Diet and Migration in Prehistoric Remote Oceania

BY

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Abstract

The human processes of food production and migration are intertwined and of utmost importance in the tropical Pacific, where generally depauperate islands predicated the need for effective cultural adaptations in order for settlements to thrive. This thesis investigates movement and diet of individuals from two prehistoric burial sites in Remote Oceania. Stable isotope analyses ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$) of bone collagen were conducted to examine diet within the last few years of an individual's life, while dentine collagen analysis provided information about childhood diet. Oral conditions (caries, macrowear, calculus, chipping, periodontitis, alveolar lesions, and ante-mortem tooth loss) were also examined as dietary indicators. Strontium analysis ($^{87}Sr/^{86}Sr$) of tooth enamel was conducted to investigate childhood residence, identify likely migrants, and consider cultural forces that may have affected movement in the past.

The first collection ($n = 28$) is from the coastal site of Bourewa in the Republic of Fiji. Bourewa contained burials dated to the Vuda phase (c. 750–150 BP), a period in which climatic fluctuations in Fiji potentially dramatically affected food resources. The second skeletal collection ($n = 126$) are from the 'Atele burial mounds on the Tongan island of Tongatapu (c. 500–150 BP). The first burial mound (To-At-1) could be classified as a commoner's burial mound while the second mound (To-At-2) was possibly used as a chiefly burial place. The possibility of diet and mobility reflecting status differences in these mounds are explored. To-At-1 and To-At-2 contained a large proportion of subadults: the bone collagen of children and adolescents yields information about the diet of those who did not survive to adulthood.

Potential differences in isotope values and oral conditions frequency are explored between the sites, burial mounds, sexes, and age groups. These findings are interpreted within the biocultural context of late prehistoric social, political, and ecological environments and compared to past Pacific studies, placing the interpretations in a wider context. Bourewa individuals relied more heavily on marine foods compared to 'Atele individuals as evidenced by significantly higher $\delta^{13}C_{bone}$ values, less severe caries, and more severe wear. Stable isotope values from the 'Atele burial mounds suggest

To-At-2 adults consumed proportionately more terrestrial foods than To-At-1 adults. Dentine and bone stable isotope values from both Bourewa and ‘Atele adults differed significantly, suggesting childhood and adult diet variation. Caries prevalence did not differ between the sexes in either site (though in ‘Atele there were significant sex-based differences in paleodietary isotope values). This lack of sex-based differences in caries prevalence is at odds with the global trend of females displaying higher caries rates.

Only one immigrant within each site was detected using $^{87}Sr/^{86}Sr$ analysis. Most displayed $^{87}Sr/^{86}Sr$ ratios expected for people living along a marine coastline. Paleodietary isotope values of a childhood diet different from the rest of the population served as supplementary evidence for pinpointing immigrants. This method identified two other Bourewa individuals who lived inland during childhood. With only one non-local in ‘Atele, religiopolitical control may have restricted who entered (and was buried on) the sacred island of Tongatapu.

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Chapter 1

Introduction

> *One does not set out in search of new lands without willing to be alone on an empty sea.*
> André Gide

The human processes of food production and migration are deeply intertwined. Population increase and subsequent dispersion into new territories are common consequences of increased food production (Bellwood, 2001; Diamond and Bellwood, 2003), and movement into new lands can lead to opportunities for access to (and control over) new food resources (e.g. Wahlqvist, 2002; Erlandson et al., 2007). These processes are of utmost importance in parts of the Pacific where generally ecologically sparse islands predicated the need for efficient colonising adaptations in order for settlements to thrive.

In this thesis, I examine movement and diet of individuals from prehistoric burial sites using multi-isotope analyses (the chemical analyses of the isotopic composition of a given compound) and oral indicators of diet. Genetic, linguistic, ethnohistoric, and archaeological research serve as supplementary information to provide a holistic understanding of movement and diet. While investigating migration and diet using paleobotany, zooarchaeology, and other archaeological techniques have yielded substantive information regarding movement, diet, and subsistence practices, examining human skeletal remains provides a direct means of understanding people who lived in the past (Larsen, 2002).

Isotope analysis is one method of understanding how prehistoric individuals moved during their lifetime (Hoefs, 2009; Bentley, 2006; Sharp, 2007). Isotope analysis of tooth enamel can determine the location where an individual spent their childhood and the large range of geological isotopic variation in the Pacific Islands (Stern, 1982) has

great potential for identifying non-local individuals in a burial assemblage. Strontium isotope analysis has already yielded interesting information regarding prehistoric human mobility in Vanuatu (Bentley et al., 2007), the Bismarck Archipelago (Shaw et al., 2010), and New Zealand (Kinaston et al., 2013c).

Prehistoric diet can be inferred using stable isotope analyses (Keegan, 1989; Hedges and Reynard, 2007). More specifically, isotope analysis of bone collagen provides information about the individual's diet within the past few years of their life (Hedges et al., 2007; Smith and Rennie, 2007). Examining the isotopic composition of tooth collagen yields insight regarding childhood diet when the tooth was forming (Fuller et al., 2003; Eerkens et al., 2011; Beaumont et al., 2013). Tooth formation is a process that is strongly genetically controlled and thus fairly precise (Ritz-Timme et al., 2000). Whether an infant was breastfed around the time of death can also be observed using stable isotope analysis and so examining the bone collagen isotopic composition in infants and children can yield insight into weaning practices in the past (Fuller et al., 2006).

Oral indicators of diet (i.e. dental wear, caries, calculus, occlusal surface chipping, periodontitis, ante-mortem tooth loss) are another strong line of evidence for understanding paleodiet within a skeletal assemblage (Hillson, 1979; Lukacs, 2012). The mouth is the first point of contact with food, and the first steps of digestion (mastication and the release of salivary enzymes) begin here. As such, examination of teeth and the surrounding bony structures provide a direct means of understanding diet and subsistence (Hillson, 2000, 2001). Oral indicators of diet provide information about proportions of foods eaten by a single individual in a less direct manner compared to stable isotope analysis, but by comparing the susceptibility of subgroups (e.g. sex, burial site) to certain oral conditions, important information about culture-specific interactions concerning access to certain types foods may be better understood (Prowse et al., 2007). Oral health studies have been conducted on prehistoric Pacific peoples since the 19$^{\text{th}}$ century (e.g. Mummery, 1870; Patrick, 1895) and so a large body of comparative research is available.

Two skeletal collections were analysed in this thesis to explore questions regarding ancient migration and diet. The first collection is from burial mounds excavated near the 'Atele College on Tongatapu, the main island of the Kingdom of Tonga (Davidson, 1969). The two burial mounds (designated To-At-1 and To-At-2) are among the largest and most complete skeletal assemblages in the Pacific ($n = 126$) which allows the opportunity to study dietary practices and mobility in the contexts of age and sex. As the two burial mounds may contain individuals of different social status (Davidson,

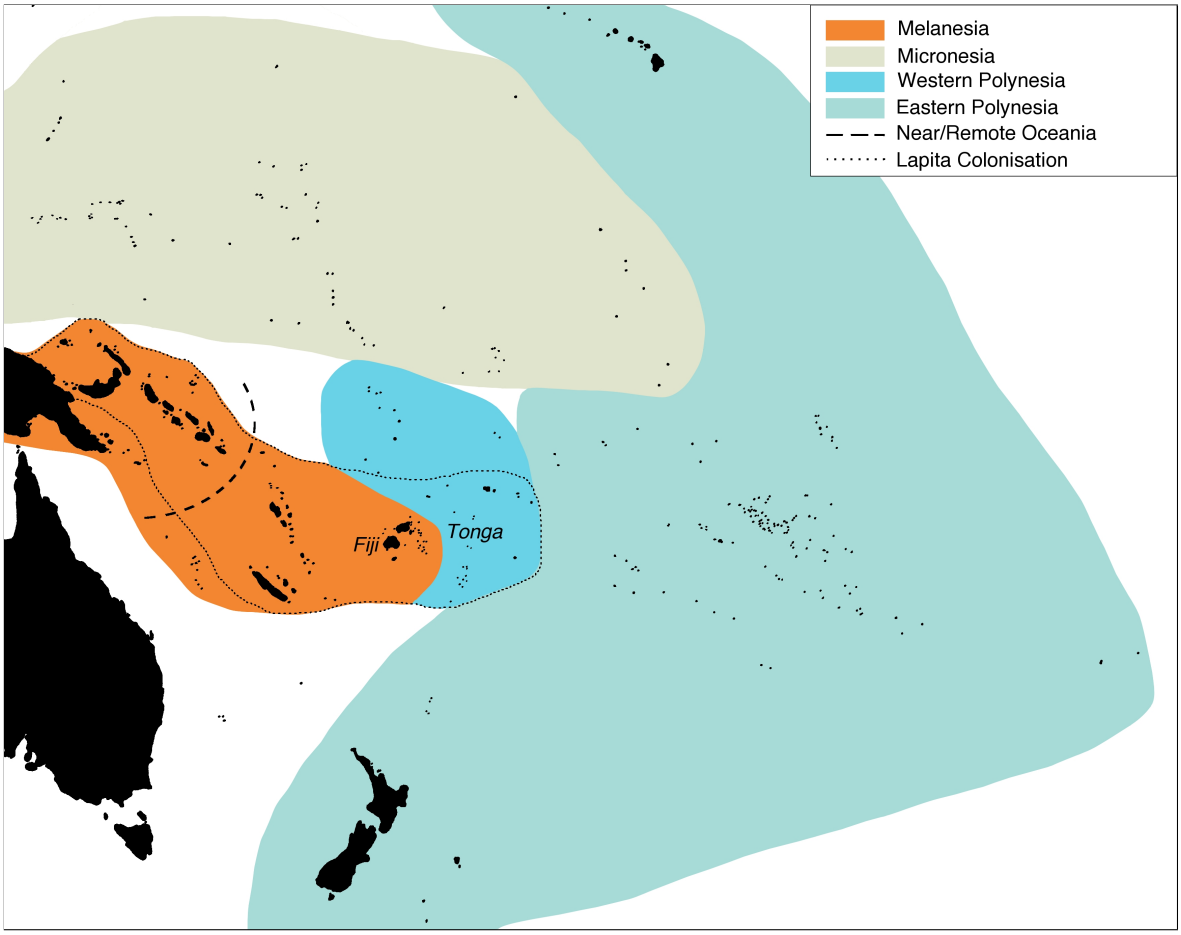


Figure 1.1. *Map showing the traditional Pacific geographic terminology (Melanesia, Micronesia, and Polynesia) and the modern geographic demarcation of Near and Remote Oceania. Tonga and Fiji, the places studied in this thesis, are labelled. Image by author, base map by Andrew Clarke.*

1969), the possibility of diet and mobility reflecting status differences is also explored. This collection also contains a large number of subadults (Buckley, 2001). As such, I can also examine weaning and childhood diet in this population.

The second collection is from the site of Bourewa on Viti Levu, the largest island of the Republic of Fiji (Nunn et al., 2004a). Compared to ‘Atele, this assemblage is smaller ($n = 28$) and consists almost entirely of adults. Isotope analyses of these individuals can be used to understand diet and mobility at the site and also to compare individuals from Fiji to Western Polynesia as represented by the ‘Atele skeletal assemblage.

1.1 Geographic terminology: defining the Pacific

The Kingdom of Tonga is located within the geographical/cultural area known as *Polynesia.* The term Polynesia designates the islands located in the southern and central parts of the Pacific Ocean, most of which are roughly within the triangle created by connecting Hawai'i, New Zealand, and Rapa Nui (Figure 1.1). The term was first used by French explorer Dumont d'Urville, who also coined the terms *Melanesia* and *Micronesia* (D'Urville et al., 2003). The geographic areas of Melanesia and Micronesia are now understood to contain multiple phyletic groups with rich cultural, linguistic, and genetic variation and thus some experts have found these terms reductionist (Kirch, 2000). As such, I will only use these two terms in reference to the geographic regions. Polynesia stands as a valid cultural group with a common genetic, cultural, and linguistic background (Bellwood, 1987). The terms Near Oceania and Remote Oceania, first introduced by Pawley and Green (1973) and further refined by Green (1991) better demarcate Oceania into broader groupings which fit the history of human occupation in the region (outlined below). Near Oceania encompasses Papua New Guinea, the Bismarck Archipelago and the Solomon Islands Archipelago, while Remote Oceania is all other Pacific islands east of this delineation.

Polynesia can be divided into two groups, Western and Eastern. Western Polynesia includes Samoa, Tonga, Tokelau, Tuvalu, and the Western outliers, which sit geographically outside of the Polynesian Triangle but are Polynesian culturally (Kirch, 1984b). Roughly 900 km east of Western Polynesia, Eastern Polynesia begins. Eastern Polynesia includes Hawai'i, New Zealand, Rapa Nui, Marquesas, Society Islands, Cook Islands, Austral Islands, Gambier Islands, Tuamotua, and Rapa (Kirch, 2000). While the Polynesian islands have a shared cultural, ecological, and linguistic history, the use of the overarching term 'Polynesia' in this thesis is meant to denote the general geographic region and shared history, and is in no way meant to generalise the rich cultural differences between the peoples located in this area.

The archipelago of Fiji, roughly 400 km west of Tonga at their nearest points, is not typically included in Polynesia and this exclusion has been the subject of discourse for decades (Howells, 1973; Frost, 1979; Hunt, 1987; Burley, 2013) and researchers have a difficult time placing Fiji in a simple cultural classification. Due to their geographic nearness (and the large distance isolating these islands from islands to the east or west) the cultures of Fiji, Tonga, and Samoa are inexorably linked (Kaeppler, 1978; Dickinson et al., 1996). Fiji is commonly paired with Western Polynesia in archaeological research (Davidson, 1977; Burley and Clark, 2003; Addison and Sand, 2008) and archaeologists

have even left Fiji out of treatises focusing on Island Melanesia (Spriggs, 1997a). However, few researchers would place Fiji as "Western Polynesia" with Tonga and Samoa, as distinctive cultural influences from the western Pacific islands came to Fiji around 2200 BP that never reached Tonga and Samoa (Green, 1995; Burley, 2013). Instead, Fiji holds its own place in the islands of the Pacific, not as Polynesia but "at the Polynesian end of a Melanesian continuum" (Bayard, 1976, 50) or "an archipelago *in Between*" (Kirch, 2000, 155). I will follow the cultural distinctions between the areas and refer to the general area as Fiji/Western Polynesia.

1.2 Introduction to Pacific Island prehistory

The story of human settlement in the Pacific is far from simple, and a rudimentary model cannot cover the challenges and questions posed in contemporary literature (Matisoo-Smith, 2007; Burley et al., 2010; Donohue and Denham, 2012). However, I will briefly review Pacific settlement to set this study within a broader context to demonstrate how influential settlement history is on subsistence and migration patterns in Remote Oceania. More detailed settlement histories of Fiji and Tonga will be provided in the following chapter.

Around 40,000 years ago, anatomically modern humans travelled from Southeast Asia to occupy parts of Near Oceania (O'Connell and Allen, 2004; Summerhayes et al., 2010). The lower sea levels during the Late Pleistocene caused New Guinea, Australia, and Tasmania to form a super-continent known as Sahul. This enabled humans to travel from Sundaland (the exposed continent consisting of modern Sumatra, Java, Borneo, and Bali) to Sahul across dry land and shallow seas using rudimentary seafaring technology (Clark, 1991; Erlandson, 2001). From what is now New Guinea, these people migrated to the Bismarck Archipelago, Solomon Islands, and the Admiralty Islands around 20,000–35,000 years ago (Allen et al., 1988, 1989; Wickler and Spriggs, 1988). In the Highlands of Papua New Guinea, an agricultural system centred on taro (*Colocasia escuelenta*) and bananas (*Musa* spp.) developed circa 10,000 BP (Denham et al., 2003; Denham and Barton, 2006).

After a long pause, a second major migration event occurred in the Pacific. Around 3300 BP, a cultural complex known as the Lapita appears in the archaeological record in Near Oceania characterised by distinctive decorated pottery, adzes, and shell fishhooks and ornaments (Kirch, 1997; Spriggs, 1997a; Denham et al., 2012). Linguistically, the Lapita likely spoke an Austronesian language (linguists generally group the other, diverse languages in Near Oceania as "Papuan" or "non-Austronesian") (Green, 1979;

Kirch, 1997; Pawley, 2007). Genetically, the Lapita appear to have carried mitochondrial lineages distinct from the original inhabitants of Remote Oceania, and varying amounts of admixture between the Lapita and the Papuan-speaking people is evident in the modern inhabitants of Near Oceania (Matisoo-Smith, 2007).

The discussion of competing theories regarding the origin, early movement, and interactions of the Lapita are outside the scope of this thesis, but Kayser et al. (2000) and Summerhayes (2001) provide succinct overviews. Regardless of the origin of the Lapita, around 3200 BP some Lapita populations moved out of the Bismarck Archipelago and into previously uninhabited islands in Remote Oceania (Spriggs, 1997a; Kirch, 1997; Clark and Anderson, 2009; Denham et al., 2012). Around 2800 BP there is evidence for the Lapita settlement of Tonga, Samoa, and Fiji (Leach and Green, 1989; Burley et al., 2012; Nunn and Petchey, 2013). From there, it is hypothesised that Lapita communities maintained contact with the founding populations to the west as evidenced by non-local materials sourced from Near Oceania (Hunt, 1987; Burley and Dickinson, 2010).

In Tonga and Samoa, contact with the Lapita populations in the west declined or were of little cultural impact as the centuries passed (Dickinson et al., 1996; Burley, 1998). Decorated pottery was replaced by plainware ceramics, and eventually pottery ceased to be manufactured altogether (Davidson, 1979; Burley et al., 2010). During these centuries (around 2600 BP) in Tonga and Samoa, the people stopped "being" Lapita and became Polynesian biologically and culturally (Best, 2002; Burley, 2007). From this Ancestral Homeland, the Polynesians began moving east, occupying the Marquesas by around 1700 BP (Bellwood, 1975, 1979). From there and possibly the Societies, the rest of East Polynesia was explored and settled over the centuries, with New Zealand colonised last, around 800 BP (Kirch, 1984a; Wilmshurst et al., 2008).

In Fiji, the settlement story changes slightly. As mentioned previously, there is evidence that Lapita populations arrived in Fiji around 2800 BP, roughly the same time as they came to Tonga and Samoa. Around 900 BP, Fijian prehistory veers from that of the Ancestral Polynesian Homeland; instead of the ceramic complex evolving to plainware and eventually disappearing, Fijian pottery exhibited an increase in incising and appliqué in addition to plainware, interpreted to be a result of a migration event or events from the west (Green, 1963b; Hunt, 1986). Linguistics also supports a significant Melanesian influence in Fijian language (Pawley, 2007). This later contact with the west may have been a single migration event (Frost, 1979), although a continuous flow of migration or interaction is more likely (Hunt, 1986).

1.3 Creating the framework of diet, subsistence, and movement

1.3.1 The research approach

In order to frame the research questions, hypotheses, and interpretations arising from this study, a biocultural approach will be used. Within a biocultural framework, the surrounding environment (social, political, economic, and ecological) must be considered as an influence on the health and choices of an actor just as the actor changes the environment he or she lives in (Levins and Lewontin, 1985; Stinson et al., 2012). The biocultural approach also considers the influence of evolution on an individual level, where the concepts of natural selection, genetic changes, adaptation, and plasticity affect population-level patterns of disease, trauma, and stress (Zuckerman et al., 2012). Issues of biological differences between sexes and ancestry groups impact disease frequency in many of the same ways social attitudes about gender and race can affect access to certain resources (Buzon, 2012).

The biocultural approach emerged in the 1960s–1980s in anthropology and was based on the ecological approach and processual theory (Goodman and Leatherman, 1998; Roberts and Manchester, 2010). These theoretical frameworks provided the goals that anthropology should use scientific rigour to understand human cultural adaptation, which are (and were) determined by environmental constraints in modern and past populations. The ecological approach, like the biocultural approach, also explores these interactions between organisms and their environments (Katzenberg, 2012).

The biocultural approach expands on these ideas, emphasizing that the interactions between human culture and the environment are inherently dynamic, as the cultural adaptations are always changing the social, political, economic, and ecological environments which in turn are always challenging the humans living within them (Levins and Lewontin, 1985; Dufour, 2006). The biocultural approach marked a significant departure from previous anthropological studies which were often typological in nature, reporting disease in single individuals without placing these individuals within their cultural, social, and ecological contexts (Temple and Goodman, 2014). There were several important exceptions, such as Hooton's (1930) population-level monograph for the Pecos Pueblo and Pearl's (1930) general call to examine the social and cultural environments people live in.

No theoretical framework is without its weaknesses. Many of the weaknesses of the biocultural approach are engrained in the nature of bioarchaeology itself (Zuckerman

et al., 2012). Qualities inherent to an archaeologically-derived skeletal assemblage (discussed more below, section 1.4) can impede the analyses of past ways of life. The lack of context (little site information or ethnohistoric records, for instance) will also make using a biocultural approach more difficult. These issues can impede any bioarchaeologist, regardless of their approach.

A biocultural approach requires the ability to compare collected data across populations in order to interpret the data within the varying contexts. Differences in collection and presentation of data hinders these comparisons. Movements for standardising data collection in bioarchaeology, especially when recording health and disease in skeletal remains, have been forwarded (e.g. Ortner, 1991; Buikstra and Ubelaker, 1994; Hillson, 2001). Databases with comparative data are growing, most notably the Global History of Health Project for the Western and Eastern Hemisphere at Ohio State University (Steckel et al., 2002).

Another challenge to using the biocultural approach is its sheer difficulty in fully conceptualizing all of the factors that can influence human adaptation systems and human health (Dufour, 2006). Many social, political, economic, and ecological variables can affect and interact human adaptation systems in ways that can be difficult to express or define. Biological anthropologists come from a variety of research backgrounds and cannot be expected to be masters of every field that affects the human experience. Broad constructs like "status" and "stress" are difficult to combine and often require viewing the phenomenon of interest within a sociopolitical context local to the culture in question, making cross-cultural comparisons of ideas like status difficult (Dufour, 2006). Operationalising variables important in a biocultural approach is also very difficult: even if we define a concept in order to assess the impact it has in a given population, making the variables that affect health concepts observable, measurable, and independent is difficult. Dufour (2006) presents stress as an example: how do we operationalise variables that affect stress, such as resource security, social support, or the individual's ability to adapt? Finally, evolutionary theory such as a biocultural approach can be difficult to utilise in a synchronic system, such as the assemblages I study (Zuckerman et al., 2012). Supplementary data such as archaeological findings or ethnohistoric texts helps alleviate those issues. Despite its weaknesses, the biocultural approach remains a holistic means of examining how human biology interacts with culture within the surrounding environment. By linking environmental process and human health in past populations, bioanthropologists can provide insight into modern societies, critical in the era of re-emerging infectious diseases, climate change, and fast-paced social changes in many parts of the world. (Morens et al., 2004, 2008; Maffi,

2008).

1.3.2 Prehistoric diet, nutrition, and subsistence patterns

Paleodietary reconstruction aims to observe three aspects of human life and health: *diet*, *nutrition*, and *subsistence*. Diet refers to the types of food eaten. Nutrition refers to the health of the individual determined by diet: caloric minimums and the balance of the proper amounts of vitamins and minerals. It is a common problem in the modern Pacific that a person can have plenty to eat but still experience malnutrition (Hughes and Lawrence, 2005). Subsistence practices are the methods of acquiring the foods eaten by a group. As such, diet can vary greatly between individuals in a culture, while subsistence patterns tend to be fairly consistent within a group of people (Danforth, 1999).

While Near Oceania is home to numerous species of mammals, land birds, and terrestrial flora, there is a sharp decline in ecological biodiversity eastwards into Remote Oceania (Stoddart, 1992; Steadman, 2006). This decline is a result of restricted plant and animal movement due to increased distance between land masses and habitat homogeneity due to decreasing environment variation (Kirch, 1979; Nunn, 1998). The reduced size and diversity of habitats leaves these island ecologies vulnerable to change, whether from climate change, catastrophic events such as volcanic activity and earthquakes, or anthropogenic alterations (Spriggs, 1997b; Nunn, 2007; Spriggs, 2010). These increasingly depauperate and fragile island ecosystems necessitated reliable and adequate food acquisition methods for colonising populations.

The acquisition of adequate nutrition is one of the central activities of any living being, and lies at the heart of human culture. Understanding the subsistence strategies and subsequent effects nutrition plays on health is important. Multiple ethnographic (Jelliffe, 1968; Jansen, 1982; Cox and Banack, 1991; Pollock, 1992) and archaeological studies (Steadman et al., 2002a; Yen, 1973) have focused on Pacific island diet, nutritional health, and subsistence patterns. It is thought that as the Lapita travelled across the Pacific Ocean they brought with them a number of plants and animals that formed an important part of their subsistence strategies wherever they lived and remained central to the subsistence economies of the cultures that followed (Kirch, 1997). This transported landscape, as well as the natural environment, greatly affects the diet and nutritional status of people in Fiji/West Polynesia into the modern day (Jelliffe, 1968; Pollock, 1992; Jones, 2009).

Diet is the main focus of this study. Stable isotope analyses will establish individual dietary profiles which can be pooled and compared between intra-population groups

(such as sex and age) and as a whole population. Oral indicators of diet will also indicate diet on an intra-population and population level. Historical accounts, ethonographic studies, and archaeological evidence of diet and subsistence will supplement the research conducted in this thesis to help interpret the dietary data produced in this study. Although the nutritional health of individuals cannot be determined using isotope analysis and oral pathologies, other studies have examined general stress and metabolic insults in these skeletal collections (Buckley, 2000, 2001) and the implications of the dietary profiles found in this study for nutritional health will be discussed in the final chapter.

There is a wealth of information regarding Polynesian/Fijian subsistence strategies and food resources provided by historical accounts, archaeological studies, and ethnographies. General diet and subsistence in this part of the Pacific will be outlined in this chapter, variations in diet and subsistence specific to Tonga and Fiji will be discussed in Chapter 2.

1.3.3 Pacific Island subsistence and diet

Two types of subsistence patterns are regularly mentioned when studying the Pacific: foraging and horticulture. Foraging, or hunting and gathering, is the oldest form of human subsistence and involves broad-spectrum consumption of wild plants and animals without direct control of the reproduction of these species (Panter-Brick et al., 2001). Aquatic foraging (which can refer to freshwater or marine foods) such as is practised in the Pacific, involves a concentrated collection of marine and lagoon resources such as fish, shellfish, and marine mammals (Ames, 2002). Compared to pedestrian foragers who rely solely on terrestrial resources, aquatic foragers tend to have more reliable, productive sources of food that allow higher population density and more permanent settlements (Ames, 2002). As pointed out by Davidson and Leach (2001), sole reliance on aquatic animals will typically result in protein poisoning and subsequent death and therefore the consumption of carbohydrates and/or fats are essential to maintaining an adequate nutritional balance.

The second form of subsistence important in the Pacific is horticulture. In Remote Oceania, horticulture mostly revolves around the cultivation of farinaceous root staples often with tree crop augmentation carried out on property borders and in forests (Kennett et al., 2006). The definition of *horticulture* is contested, especially when delineating between it and agriculture (Terrell et al., 2003; Harris, 2007; Vrydaghs and Denham, 2007). In previous anthropological work, horticulturalism in Remote Oceania was often viewed as a primitive form of agriculture (Best, 1931; Malinowski, 2012).

While both subsistence practices involve the cultivation of domesticated plants for food production and other uses, the distinctions put forth by Leach (1997) as outlined below are favoured in this study:

1. **Scale**

   Agriculturalists tend to produce on a larger scale. This is more than a matter of quantity: horticulturalists attend to every plant individually, tailoring their time and energy to fit the plant's needs. Agriculturalists will sow and harvest their crops en masse with little or no individual attention.

2. **Diversity**

   Due to the cultivation of plants on a smaller scale with more attention afforded to each plant, gardeners are more likely to identify and encourage variation in their yields. Agriculturalists, conversely, cannot often risk experimentation.

3. **Temporal Patterns**

   Agricultural fields often follow seasonal patterns of planting, harvesting, and lying fallow. Horticultural gardens host a variety of annual and perennial plants with continual care throughout the year.

4. **Material Culture**

   Just as the difference regarding cultivation is not merely a matter of scale, neither is the material culture involved in cultivation. While agricultural tools are created to attend to multiple plants at once, gardening tools are typically smaller and more individually-tailored for the horticulturalist.

The subsistence strategies of the first settlers of Remote Oceania and how they evolved are debated. One initial hypothesis, posited by Groube (1971), was that the Lapita first lived as "strandloopers" and relied almost entirely on marine and lagoon resources as aquatic foragers. When these resources became depleted, Groube argued that the population either moved to a new location or changed to horticultural subsistence practice. The coastal and offshore island settlement patterns of the Lapita, Groube stated, was chosen for easy access to maritime resources. The large-scale extinction of numerous species of iguanids and bird during early human settlement on Tonga and Fiji due to hunting and habitat destruction supports that intensive marine and terrestrial foraging strategies were practised by colonising populations throughout the Pacific islands (Pregill and Dye, 1989; Steadman, 1993; Worthy, 2000; Pregill and Worthy, 2003; Pregill and Steadman, 2004; Steadman, 2006).

Green (1976) challenged the strandlooper concept, arguing that the coastal settlements were for easy contact with other island communities; instead of a foraging subsistence model, Green held that domesticated plants and animals were the base of subsistence from first settlement and onwards (although Green notes that intensive marine foraging was still a large part of the Lapita subsistence system). In both early and late periods of Tongan settlement, domesticated animals are present in the archaeological record: the presence of chickens and pigs are evident in middens on the main island of Tonga (Poulson, 1968) and pig bones have been found in early settlements of Niuatoputapu, an island in northern Tonga (Kirch, 1978).

A more recent view on Lapita subsistence could be described as a hybrid of the two models, where the Lapita brought a suite of domesticated plants and animals and practised low-level horticultural production with intensive, broad-spectrum use of natural resources; the impact on the local environment created the necessity for later generations to increasingly rely on domesticates (Kirch, 1997; Burley et al., 2001; Kennett et al., 2006). As described by Davidson and Leach (2001), the transported landscapes of the Lapita were the "result of progressive accretions rather than an initial makeover in the style of a modern landscape-gardening professional" (119).

Flora

The bulk of flora that constitutes Polynesian/Fijian diet comes from plants imported by humans (Table 1.1). These plants can be generally divided into starchy root crops and tree crops. None of these plants are native to Remote Oceania, but originate from either Southeast Asia or New Guinea (Yen, 1980; Terrell et al., 2003; Kennett et al., 2006). The sweet potato (*Ipomoea batatas*) is unique in Remote Oceanic diet as it is not part of the initial suite of foods brought by the Lapita, likely originating from South America within the last three hundred years (Yen, 1974; Denham, 2013; Roullier et al., 2013). The coconut can naturally disperse across large bodies of water, although its distribution across the Pacific was most likely aided by humans (Gunn et al., 2011). Native plants are not part of the horticultural system but can be gathered to supplement the main constituents of island diet or in times of scarcity. A (non-exhaustive) list of edible wild species includes assorted seaweeds, seagrasses, lichens, and mosses (Yuncker, 1959; Whistler, 1991, 1992a,b; Kirch, 1997).

Fauna

Marine resources are a large contributor of animal protein in the Pacific and were in the past. Shellfish, available in marine and freshwater environments, provide relatively

Table 1.1. *Domesticated Flora of Remote Oceania. From Kirch (1997); Yuncker (1959); Whistler (1991).*

Binomial Nomenclature	**Common English Name**
Alocasia macrorrhizos	giant taro
Areca catechu	betel nut
Artocarpus altilis	breadfruit
Canarium spp.	canarium nut
Cocos nucifera	coconut
Colocasia esculenta	taro
Cordyline fruticosa	cordyline
Cycas circinalis	queen sago
Cyrtosperma merkusii	atoll taro
Dioscorea spp.	assorted yams
Inocarpus fagifer	Tahitian chestnut
Ipomoea batatas	sweet potato
Metroxylon spp.	sago palm
Musa spp.	bananas, plantains
Pandanus tectorius	pandanus
Piper methysticum	kava
Pometia pinnata	island lychee
Tacca leontopetaloides	Polynesian arrowroot
Terminalia catappa	Indian almond
Saccharum officinarum	sugarcane
Syzygium malaccense	Malay apple

easy sources of protein and the reef and inshore environments provide a wide variety of species which may be gathered for food (Szabó and Amesbury, 2011). Although there is no definitive evidence of exactly what technology was used (fishhooks, spears, nets, etc.), there is no question that fishing has been an integral part of Oceanic subsistence since the Pleistocene (Wickler and Spriggs, 1988). Approximately 50 fish species appear in the archaeological record, with the most numerous fish families listed in Table 1.2. Marine animals other than fish and shellfish were also consumed, including sea turtle, octopus, sea cucumbers, and sea mammals (Pollock, 1992).

While many of the cultivated plants were used by pre-Lapita people in Melanesia, the Lapita may have also had chickens (*Gallus gallus*) which were not present in Melanesia previous to Lapita occupation (Kirch, 2000). Pigs (*Sus scrofa*) and dogs (*Canis familiaris*) were likely already present in New Guinea previous to Lapita settlement but were further dispersed into Remote Oceania by humans (Kirch, 2000; Lum et al., 2006; Sutton et al., 2009). Likely an intended passenger on board the Lapita boats

Table 1.2. *Most numerous fish families in the prehistoric tropical Pacific. From Leach and Davidson (2000) with habitation notes from Ono (2003).*

Family (subfamily)	Common English name	Notes
Scaridae	Parrotfish	reef, rock
Serranida (Epinephelidae)	Grouper	deep waters, carnivorous
Lethrinidae	Emperors	reef bottom, carnivorous
Balistidae	Triggerfish	shallow coral reef waters
Labridae	Wrasses	reef bottom
Scombridae	Tuna	open ocean, carnivorous

rather than a stowaway (Matisoo-Smith and Robins, 2004), the rat (*Rattus exulans* or *Rattus preator* in some areas) was also transported throughout Remote Oceania as a source of protein for some societies. Not all species (faunal or floral) arrived at each new settlement: cultural preferences may have influenced food choices, species may have been lost during transport, abandoned as a source of food when maintaining breeding populations proved difficult, or failed to flourish upon arrival to a given island and were not replaced during two-way voyaging. As such, different cultures in Remote Oceania had slightly dissimilar edible toolkits available. Classic examples include the presence of only the dog in New Zealand (Davidson, 1984) and the chicken in Rapa Nui (Commendador et al., 2013) at European contact.

Wild terrestrial species were also available for exploitation. These species included land birds (such as pigeons, rails, and moas), reptiles, and bats. As previously mentioned, many species were extirpated shortly after human arrival on a number of islands in Remote Oceania, although some species were still available during early European contact and are available to this day (Steadman et al., 2002b; Steadman, 2006).

Indirect evidence of diet in Pacific prehistory

Archaeological investigations provide an important line of evidence regarding prehistoric diet. Archaeological evidence may include the means of food acquisition collection and preparation such as fish hooks, pottery, and earth ovens. The study of middens is another way of understanding domestic waste created as a result of food preparation and consumption. It is important to remember that these methods, although claiming to provide information about cultural food consumption, are actually only providing evidence of food production, processing, and waste removal. This distinction is important, as various foods will be treated differently in regards to before and after consumption and will appear in the archaeological record unevenly (Hastorf, 1988;

Leach and Davidson, 2000). Many important tropical Pacific plant foods are almost completely invisible in the archaeological record due to a lack of pollen or seeds (e.g. taro, sweet potato, banana), although plant microfossil analysis is slowly shedding light on plant use (Crowther, 2005; Horrocks and Bedford, 2005; Horrocks and Nunn, 2007; Horrocks et al., 2013; Tromp and Dudgeon, 2015).

Linguistic evidence of diet in prehistoric Remote Oceania comes in the form of comparative linguistic reconstruction. Construction of the Proto-Polynesian and Proto-Central Pacific (Polynesian with the addition of Fijian and Rotuman) languages lends clues to the diet, mode of food production and preparation, and subsistence of the ancestors of the Central Pacific (Kirch and Green, 2001; Ball, 2007). For example, the Proto-Austronesian word **kai* and its derivations (*kai* in Tongan and *ka* in some Fijian dialects) generally refers to food (Greenhill and Clark, 2011). More specifically, this word will refer to "staple" or "real" foods: starchy staples such as taro, yams, and sweet potatoes. The Proto-Polynesian word **kiinaki* and its derivatives (*kina* or *kiki* in Tongan) refers to foods that are eaten with staple foods as a relish (Greenhill and Clark, 2011). Throughout Polynesia, these attitudes towards "real" food and relish are encountered, suggesting that this is a shared ancestral tradition evidenced through linguistic analysis (Kirch and Green, 2001).

Ethnographic and ethnohistoric records can be valuable tools for providing analogies of dietary and subsistence practices before European contact. Detailed ethnographic and ethnohistoric accounts from Fiji and Tonga (e.g. Mariner and Martin, 1827; Pollock, 1992; Jones, 2009) and will be discussed in Chapter 2. However, it cannot simply be assumed that culture has not changed over time regarding subsistence, food preparation, and food choice and therefore these studies are used for further interpretation with caution.

1.3.4 Weaning and childhood diet

It is well known that subadult dietary practices greatly affect survival, growth and health throughout life (Barker et al., 1993; Gillman, 1995; Dietz, 1998; Wilson et al., 1998). Weaning foods and childhood diet are often different from the diet of adults (Danforth, 1999) and understanding these differences can yield insight into childhood nutrition. Food restrictions can occur for a number of reasons and they often affect particular members of a society (e.g. menstruating women, chiefs, children) (Barfield, 1997; Meyer-Rochow, 2009).

When a newborn is *exclusively breastfed* no foods (solid or liquid) are ingested other than human milk. When breastfed, the newborn is receiving antibodies, species-specific

hormones, and other substances that enhance infant survival and optimise development (Howie, 2002). As an infant grows, breast milk ceases to provide adequate nutritional requirements, usually around six months of age (Mahoney, 2014). To meet the needs of the growing infant, breast milk is gradually replaced with other foods in a process known as *weaning*. Culturally mediated attitudes and behaviours affect breastfeeding practices and create a range of breastfeeding strategies throughout the modern world and history (Fildes, 1986; Dettwyler, 1995a). The "natural" age of weaning is hypothesised to coincide with the eruption of the deciduous maxillary first incisor, around six months of age (Humphrey, 2010; Mahoney, 2014). *Weaning foods*, or *complementary foods*, are the foods used to gradually replace breast milk (Grueger, 2004), and are not necessarily the same foods eaten by the non-weaning members of a culture (Sellen, 2007). *Complete weaning* is the absolute cessation of breastfeeding and the timing of this process, like weaning, is culturally mediated. The natural age of complete weaning is estimated to be between 2.5 and 6.0 years from comparing the weaning age of contemporary hunter-gatherers and other great apes (Dettwyler, 1995b).

The term *weaning* can have multiple definitions (Grueger, 2004). For some, it may be the time when complementary foods are added to the infant's diet. In other literature, weaning is the process of gradually adding complementary foods to the diet (as the term is used here). For others, it is the absolute cessation of breastfeeding, synonymous with the term *complete weaning* used in this thesis (e.g. Dettwyler, 1995b; Humphrey, 2010). The very beginning of the weaning process and the point of complete weaning are two moments in an infant's life that can be separated by days or weeks, and more often months and years, and so keeping the terminology clear and precise is crucial.

Indirect evidence of weaning

Weaning is one of the more difficult aspects of ancient cultures to study due to the lack of material goods created by the process. Prior to isotope analysis, the methods of studying past infant feeding practices were indirect, through osteological evidence and ethnohistoric/modern research of weaning patterns.

Nonspecific indicators of stress, when present in children, may be related to weaning stress from decreased nutrition and increased exposure to disease (Goodman and Armelagos, 1988; Mays, 1995). Harris lines, enamel hypoplasia, porotic hyperostosis, and cribra orbitalia, all non-specific indicators of various stressors, have been suggested as evidence for childhood malnutrition and high pathogen loads (Ortner, 2003; Lewis, 2007). Specific diseases related to malnutrition can sometimes be diagnosed within the archaeological records, such as scurvy (Brickley and Ives, 2008; Buckley et al.,

2014) and rickets (Pinhasi et al., 2006). An osteological investigation is important for understanding childhood health and nutrition in past populations, but cannot provide information about age-at-weaning or the proportions of foods eaten by weaned children.

Cross-cultural comparisons of modern hunter-gatherer societies and historic records provide inferences about weaning practices in societies without written records of the process. While modern weaning practices in the Pacific Islands may not be comparable with prehistory due to cultural change, 62% of Tongan infants are breastfed exclusively for four to six months compared to the global average of 39% (UNICEF, 2003).

Ethnohistoric records provide a limited amount of information on the topic of weaning and supplementary foods in the Pacific Islands as not much was written on the subject. Throughout many of the modern tropical Pacific Islands, starchy foods that have been softened through mastication, grating, and/or pounding and the meat of coconut sprouts are common weaning foods (Pollock, 1992, 37). In the 19th century Cook Islands, Reverend Gill records Cook Island Maori as completely weaning their children before two years of age, although there are some cases of children still breastfeeding at three (Gill, 1979). However, the author also conceded that calendrical age is rarely closely recorded in the community where he lived.

A 20th century Hawaiian ethnography records infants beginning the weaning process around four months with mashed sweet potato (Handy and Pukui, 1952). Between six months and a year, fresh *poi* (fermented taro paste), soft limpets, crab juice, and other vegetables were included in the child's diet. At two years of age, all foods except those with a "strong, tart flavour" were allowed (Handy and Pukui, 1952, 256). By six years of age no food restrictions were in place. A child was not completely weaned at a certain calendrical age, instead, a ceremony in which the child was given stone or leaves representing the mother's breasts to throw away as a sign of no longer wanting its mother's milk (Handy and Pukui, 1952).

A cross-sectional nutritional survey carried out in 1972 on Tongatapu and on the island groups of Ha'apai and Vava'u reports weaning practices (Jansen, 1982). Most mothers reported breastfeeding for the first six months of their infants' lives (174/180 infants). Of the 41 infants aged between 12 to 17 months recorded during Jansen's fieldwork, six infants were still breastfed (14.6%). Whether infants were exclusively breastfed or whether complementary foods were included in their diet was difficult to determine by Jansen (1982) as questions about bottlefeeding were apparently answered in ways that did not "seem to be sufficiently reliable" (p. 205) and thus were not reported. The main weaning foods included fish, fresh fruits, shell fish, vegetables, and bananas, all of which were often mashed. These are all foods that are typical to the

Tongan diet (Pollock, 1992).

Stable isotope analysis provides direct evidence of age-at-weaning, where breast-feeding infants will display $\delta^{15}N$ values higher than their mothers (Fuller et al., 2006). Childhood diet can be reconstructed using isotope analysis and oral indicators of diet and compared to the diet of individuals who survived into adulthood (Richards et al., 2002).

1.3.5 Migration: colonisation and dispersal in prehistory

Massive movements of people today create complex interactions between migration and health and the effects of this are currently gaining attention from public health institutes worldwide (e.g. Stilwell et al., 2004; Albin et al., 2005; Gushulak and MacPherson, 2006; Baussano et al., 2013). Exploring movement in prehistoric peoples is more difficult to track. Typically, prehistoric movement is interpreted using broad cultural and demic changes as seen through material culture, linguistics, and genetics (Kirch, 2000; Gage et al., 2012). To avoid confusion, it is best to define the terms used commonly in this thesis: *mobility* and *migration*. Various researchers tend to treat these words in one of four ways:

1. These words are synonymous (Biddle and Yap, 2010)
2. Mobility refers to temporary movement, while migration is permanent settlement in a new area (Bell and Ward, 2000)
3. Mobility is movement within the boundaries of a geo-political region, while migration is movement between geo-political boundaries (e.g. the difference between moving from Auckland to Wellington and moving from London to Shanghai) (Carletto et al., 2004; Kendall et al., 2013)
4. Mobility is the capability to move, while migration is the actual movement (Borjas et al., 1992; Greenwood, 1975)

Any of these definitions are valid, but it is imperative to maintain clarity when discussing human movement. In regards to bioarchaeological research I favour the fourth option, and will use these definitions within this study to maintain consistency.

Indirect evidence of migration

Geochemical characterisation of artefacts can trace provenence and be used to infer social interaction between island societies (Weisler and Kirch, 1996; Dickinson and

Shutler, 2000; Clark et al., 2014). Similarities in artefact construction, for example, can imply cultural diffusion of ideas; the nature and distribution of Lapita pottery decoration is the most famous evidence of Lapita contact and movement in the Pacific (Spriggs, 1990; Bedford and Sand, 2007).

Linguistic analysis shows the relationships between groups of languages in order to explore linguistic changes, diffusion, and extinction (Foley, 2004; Mace and Currie, 2012). From this, the relationship between languages can be used as a proxy for population movement (e.g. Ruhlen, 1994; Currie and Mace, 2009; Diamond, 2011). The Austronesian language family, which includes Fijian and Polynesian languages, was the most widely spoken language family in the world prior to 1500 AD (Bellwood et al., 1995). Tracing the relationships and relative diversity of Austronesian languages from Taiwan to Madagascar in the Indian Ocean and the fringes of Eastern Polynesia implies the rapid widespread movement of seafaring people out of Taiwan (Gray and Jordan, 2000; Diamond, 2000). Additionally, tracing further divisions in the Polynesian language family has lent supplementary evidence to the concept of the Ancestral Polynesian Homeland (Kirch and Green, 2001).

Ancient DNA (aDNA) analysis is a useful tool for understanding broad-scale movement as interpreted via the changing genetic composition through time and space of both humans (Kayser et al., 2006; Wollstein et al., 2010; Soares et al., 2011; Jinam et al., 2012) and animals (Matisoo-Smith et al., 1998; Larson et al., 2007; Dobney et al., 2008; Storey et al., 2010; Oskarsson et al., 2012). Unfortunately, identifying similarities in populations using genetic analysis cannot be used to understand individual movement. Ancient DNA is also fragile and prone to degradation especially in hot, humid climates like the tropical Pacific (Schwarz et al., 2009; Allentoft et al., 2012).

Despite the interesting patterns that emerge in these lines of study, material culture and language are ultimately the movement of items and ideas, not people. Compared to aDNA studies, $^{87}Sr/^{86}Sr$ analysis is a fairly robust method for analysing migration with fewer issues of diagenesis and contamination (Bentley, 2006). While isotope analysis cannot examine broad-scale movement (at least, not when confined to a single PhD thesis), it possesses the unique ability to directly examine individual movement (Montgomery et al., 2005). The time period for the assemblages studied in this thesis is late prehistory in Fiji and Tonga. While the movement of entire populations to uninhabited areas was still occurring in Eastern Polynesia (Wilmshurst et al., 2011), most movement in Fiji and Tonga was on a smaller scale such as spouse exchange between islands (Kaeppler, 1978). As such, isotope analysis is a useful tool for the research questions posed in this study.

1.4 Limitations of bioarchaeological data

It is important to approach bioarchaeological research with an understanding of the limitations inherent to this particular field of research. These limitations can be broadly classified into two types: those that can be controlled or at least accounted for by researchers, and those that cannot be controlled (Pinhasi and Bourbou, 2008, 40).

Factors that can be controlled by the researcher are methods and strategies involved in excavating and analysing a skeletal assemblage. Thorough excavation techniques, careful handling and preservation practices, and accurate age and sex estimation all contribute to better evaluation of data. Whole treatises have been dedicated to arguing about "proper" excavation techniques, and the truth is that different opinions on practice (never mind mitigating circumstances and simple mistakes) leave skeletal assemblages in varying degrees of completeness and context. Less than ideal practices affecting excavation and preservation of skeletal remains, so long as they were recorded, can be recognised as possible influencing factors when addressing problems.

There are, sometimes dishearteningly, many more factors that cannot be controlled by the researcher. Importantly, bioarchaeologists cannot control the composition of their sample. Modern epidemiological researchers will typically have the benefit of choosing who they study, taking great care to choose a random sample representative of the population. Perhaps there will be factors that limit who they can choose, but most likely they will have an understanding of how these limitations have changed the demography of their sample relative to the population. In bioarchaeology, we have no such luxury. As Waldron (1994) points out, we excavate the burial sites we find and, obviously, do not uncover the ones we have no knowledge of. The individuals buried in a given location may not be representative of the entire population, as cultural factors may include or exclude certain types of people from that burial site (Pinhasi and Bourbou, 2008). We excavate however many individuals have survived the taphonomic effects and as much as the field season (and expedition funds) allow, so there is only ever a subsample of an inherently biased 'population.' And of those we discover, only a certain amount of skeletal material will withstand sharp trowels, imperfect packing methods, and careless handling. These are the *extrinsic* factors that Waldron (1994) describes, and the extent to which these factors create bias in the sample cannot be quantified.

An important *intrinsic* factor that affects the study of human skeletal remains is the fact that the individuals under investigation are dead and not living (Waldron, 1994). This is an important, if seemingly obvious, observation to make since many of

the ways in which bioarchaeologists structure their research questions and present their data follows the systems created for modern health sciences. While health and how people live is at the core of both fields, the intrinsic differences of the samples studied require bioarchaeologists to take care when presenting disease prevalence and drawing conclusions from the samples.

Wood et al. (1992) cautions that drawing conclusions about people in the past from skeletal remains is confounded by three conceptual problems: *demographic nonstationarity*, *selective mortality*, and *hidden heterogeneity*. *Demographic nonstationarity* is the concept that any given population will not be in a state of stationarity, when "closure to migration, constant age-specific fertility and mortality, zero growth rate, and an equilibrium age distribution" (Wood et al., 1992, 344). *Selective mortality* is the second issue Wood et al. (1992) outline. They state that a sample from a given burial site cannot be representative of the entire population at risk, but representative of a given group at high risk at their given age. We will never be able to correct selection bias in bioarchaeology because mortality is itself a selective process.

Selective mortality will be of great importance for the discussion of diet and weaning practices in subadults. When comparing adults and subadults in a population, one is not comparing two points in an individual's life, or comparing different life experiences within a given culture, but comparing those who survived childhood with those who did not. These subadults cannot be assumed to have had the same life experiences as those who survived into adulthood. Conversely, it cannot be assumed that all subadults were chronically sick children that were treated differently from the survivors. Many subadults in a burial site could have lived normal lives as defined by their culture until sudden death from sickness or trauma took them (Lewis, 2007).

Hidden heterogeneity, the third and final issue described by Wood et al. (1992), refers to the innumerable factors that contribute to an individual's risk of death or disease (e.g. sex, genetic background, socioeconomic status). These factors are hidden when conducting and presenting population trends if they could ever be completely determined at all.

These three conceptual issues form the basis of what Wood et al. termed the *osteological paradox*, that "better health makes for worse skeletons" (Wood et al., 1992, 356) and any analysis using skeletal collections will not be representative of living populations from which they are drawn. This rather negative view on the potential contribution of bioarchaeology to understanding past cultures stimulated debate, especially within the fields of paleodemography and paleopathology (e.g. Goodman, 1993; Jackes, 1993; Cohen, 1994; Konigsberg and Frankenberg, 1994; Cohen, 1997). Ultimately it is

understood that, despite these limitations, bioarchaeological research is the most direct means of reconstructing life in past populations (Larsen, 1995, 186). Consideration of these problems and providing alternative interpretations of the data is critical to addressing the osteological paradox (Wright and Yoder, 2003).

1.5 Research aims, objectives, and hypotheses

This study incorporates several aims and objectives that can be addressed through isotope analysis and oral indicators of diet. Initial hypotheses are presented regarding the objectives.

Aims:

- To understand individual mobility in these sites in order to consider cultural aspects affecting migration such as marriage, political control of individual mobility, and inter-island contact
- To characterise the diet of prehistoric Tongans and Fijians as diet is intricately tied with all aspects of the social landscape in Remote Oceania
- To compare inter- and intra-populational differences in diet and migration between and within the two sites to gain a more nuanced understanding of differences between late prehistoric Tonga and Fiji and certain groups within these sites such as those of different age categories, sexes, and burial mounds
- To understand age-at-weaning and weaning food practices in prehistoric Tongans, which is especially important for considering subadult health and the long-term effects of childhood diet in a person's life

Objectives:

- To detect migration using isotope analysis ($^{87}Sr/^{86}Sr$) and compare movement between subpopulations (i.e. sex, different mounds, burial sites)
- To characterise the diet of the Tongan individuals buried in 'Atele and the Fijian individuals buried in Bourewa using stable isotope analyses ($\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$) and oral indicators of diet and compare diet between subgroups in each assemblage (i.e. sex, age groups, different mounds, burial sites)
- To assess weaning patterns at 'Atele using stable isotope analysis ($\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$)

Hypotheses:

- **H_1:** As traditional society in Fiji and Polynesia is patrilocal (Nayacakalou, 1955; Aoyagi, 1966; Becker, 1995; Jones, 2009), a greater proportion of non-locals will be females as determined through $^{87}Sr/^{86}Sr$ analysis

- **H_2:** The Fijians will display greater range of $^{87}Sr/^{86}Sr$ ratios due to Viti Levu's larger island size and greater geological diversity compared to Tongatapu

- **H_3:** Non-locals from each assemblage will display different childhood diets from locals as indicated through isotope analysis and oral indicators of diet

- **H_4:** The two methods of assessing diet (stable isotope analyses and oral conditions) will agree

- **H_5:** Due to Viti Levu's larger island size, the Bourewan individuals will have a larger terrestrial component in their diet compared to the 'Atele individuals as evidenced by isotope analyses and oral indicators of diet

- **H_6:** With no previous studies finding differences between the two burial mounds at 'Atele, there will be no differences regarding diet or movement discerned in this study

- **H_7:** Adults will consume more animal protein than subadults (i.e. be on a higher trophic level)

- **H_8:** The childhood diet of adults, as inferred through isotope analysis of dentine collagen, will be on a lower trophic level compared to adults within the last few years of their lives as inferred through bone collagen

- **H_9:** The childhood diet of adults, as inferred through isotope analyses of dentine collagen, will be on a higher trophic level compared to the childhood diet of subadults as inferred through the analysis of bone collagen. In other words, the survivors of childhood (adults) will have consumed more animal protein than non-survivors (subadults)

- **H_{10}:** Using isotope analysis and oral indicators of diet, males and females will display similar diets due to the practice of communal meals in these islands as evidenced in ethnographic studies (Pollock, 1992; Jones, 2009)

- **H_{11}:** The age of complete weaning for Tongans, as interpreted through trophic level shifts in isotope analysis, will occur within the natural weaning age between 2.5 and 6.0 years (Dettwyler, 1995b)

1.6 Thesis structure

This introductory chapter served to show why reconstructing paleodiet and migration is necessary to our understanding of prehistoric life in Tonga and Fiji. I laid out the chronicle of Pacific colonisation and described the environmental and social landscapes that affect diet and movement in Remote Oceania. The limitations and complications in bioarchaeological research were discussed to establish the boundaries within which my research aims, objectives, and hypotheses were produced.

1.6.1 Academic publications

This thesis is structured as a "hybrid thesis" following the University of Otago's guidelines for including published material in a thesis (University of Otago, 2015). The core research chapters (Chapters 3 through 6) contain information that has been published or is in preparation for publication in a peer-reviewed format. Table 1.3 lists the publications included in this thesis as well as their current status at the time of submission. This information has been modified to create a more coherent, larger body of work that also includes some unpublished data and interpretations. All manuscripts were created with the help of co-authors who provided considerable aid in research design, discussion, and editing. The contributions of all co-authors for the three publications are listed in Table 1.4. Following the expectations of the University for inclusion of any published work, I am first author for all publications. In the beginning of each core chapter, any published material from which the thesis chapter integrates substantial portions are listed.

In **Chapter 2**, I review the excavation sites and any bioarchaeological studies previously conducted using these skeletal assemblages. Climate, geography, the underlying geology, and the biodiversity of Tonga and Fiji are briefly outlined. I provide a short chronicle of human settlement history for each region to place the sites in context. Ethnohistoric and archaeological evidence of subsistence and diet specific to prehistoric Tongans and Fijians are described.

Chapter 3 addresses how isotope analysis can be used to reconstruct paleodiet. The isotopes used specifically for this research project are introduced and the basic

Table 1.3. *List of published material included in this thesis.*

1. Stantis C., Tayles N., Kinaston R. L., Cameron C., Nunn P. D., Richards M. P., & Buckley H. R. "Diet and subsistence in Remote Oceania: an analysis using oral indicators of diet." **In press.** In: *The Routledge Handbook of Bioarchaeology in Southeast Asia and the Pacific*, edited by Oxenham, M. F. and Buckley, H. R., London: Routledge.
2. Stantis, C., Kinaston, R. L., Richards, M. P., Davidson, J. M., & Buckley, H. R. "Assessing Human Diet and Movement in the Tongan Maritime Chiefdom Using Isotopic Analyses." PLoS ONE, 2015, 10, e0123156
3. **in review:** Stantis C., Buckley H. R., Kinaston R. L., Nunn P. D., Jaouen, K., & Richards M. P. "Isotopic evidence of mobility and diet in a prehistoric/protohistoric Fijian coastal environment (c. 750–150 BP)." American Journal of Physical Anthropology, available online at time of submission.

bone and tooth histology necessary for understanding isotope analysis are outlined. The methods used for this study are described. The results and discussion specific to the paleodietary isotopic findings end this chapter.

Chapter 4 is devoted to the use of analysis of oral conditions as an indicator of diet. The oral conditions that have diet-related aetiologies are introduced, and the methodologies for recording these conditions are explained. Again, results and discussion specific to this section's focus close this chapter.

Chapter 5 focuses on the use of isotopic geochemistry to understand migration. Many concepts about isotope analysis from Chapter 3 are important for this section. I explain how strontium isotopes from the underlying geology end up in our bodies and how strontium isotope analysis can be used to link a person to the location of their childhood. Sample preparation and analysis specific to strontium analysis are delineated and the results are presented and then discussed.

Chapter 6 is dedicated to integrating the different types of data. The fourth hypothesis of the thesis is tested here by comparing the findings from the paleodietary isotopic data and the oral indicators of diet. The potential relationship between the paleodietary and paleomobility isotope values is explored.

The final chapter, **Chapter 7**, contains the discussion and final conclusions about how the results of the previous chapters combine to create a more refined understanding of diet, movement, and weaning in prehistoric Tonga and Fiji.

Table 1.4. *Contributions of co-authors for the three publications from which material was included in this thesis.*

	Routledge chapter (1)	PLoS ONE article (2)	AJPA article (3)
Study concept and design	CS, RLK, HRB, NT	CS, RLK, HRB	CS, RLK, HRB
Isotopic analyses	CS, RLK, MPR	CS, RLK, MPR	CS, RLK, MPR, KJ
Oral conditions data collection	CS	CS	CS
Statistical analyses	CS, CC	CS	CS
Interpretation of results	CS, RLK, HRB, NT	CS, RLK, HRB, JD	CS, RLK, HRB
Drafting of the manuscript	CS	CS	CS
Critical revision	CS, CC, RLK, HRB, MPR, PDN, NT	CS, RLK, HRB, MPR, JD	CS, RLK, HRB, MPR, PDN, KJ

Chapter 2

Materials

Civilization is a movement and not a condition, a voyage and not a harbor.
Arnold J. Toynbee

This chapter serves to place the individuals examined in this study within a biocultural context. As explained in Chapter 1, using a biocultural approach allows us to examine the dynamic relationships between humans, culture, and the environment in a hypothesis-driven approach that synthesises various types of data (Tuljapurkar et al., 2007; Zuckerman et al., 2012). Many sources of information are from the modern or the historic period, and these data are used to complement the archaeological, paleogeographical, and paleoclimatic data to create a more accurate context in which to place my study. First, the environment and geology of the islands in question will be described. The settlement history of each culture will be outlined as will the inferred subsistence patterns specific to each prehistoric group. As neither of the sites contain archaeological evidence of diet or subsistence, I will review archaeological and ethnohistoric research from other areas of Tonga and Fiji. Then, the archaeological sites of Bourewa and ‘Atele (Figure 2.1) will be described in more detail; a brief history of excavations conducted and the phases of occupation at the site as determined by artefacts, features and other archaeological methods will be outlined. Finally, the demography and preservation of the burials from Bourewa and ‘Atele will be described, and previous bioarchaeological research conducted on these assemblages is also outlined. Brief overviews of the skeletal material as relevant to this study will be presented and any interest in in-depth reports of these burials are directed to the original literature (as will be cited in-text). Appendix A of this thesis reports the census of the assemblages.

The site information and island environments for Fiji and Tonga in this chapter have been summarised in my publications, but more detailed information is given in this

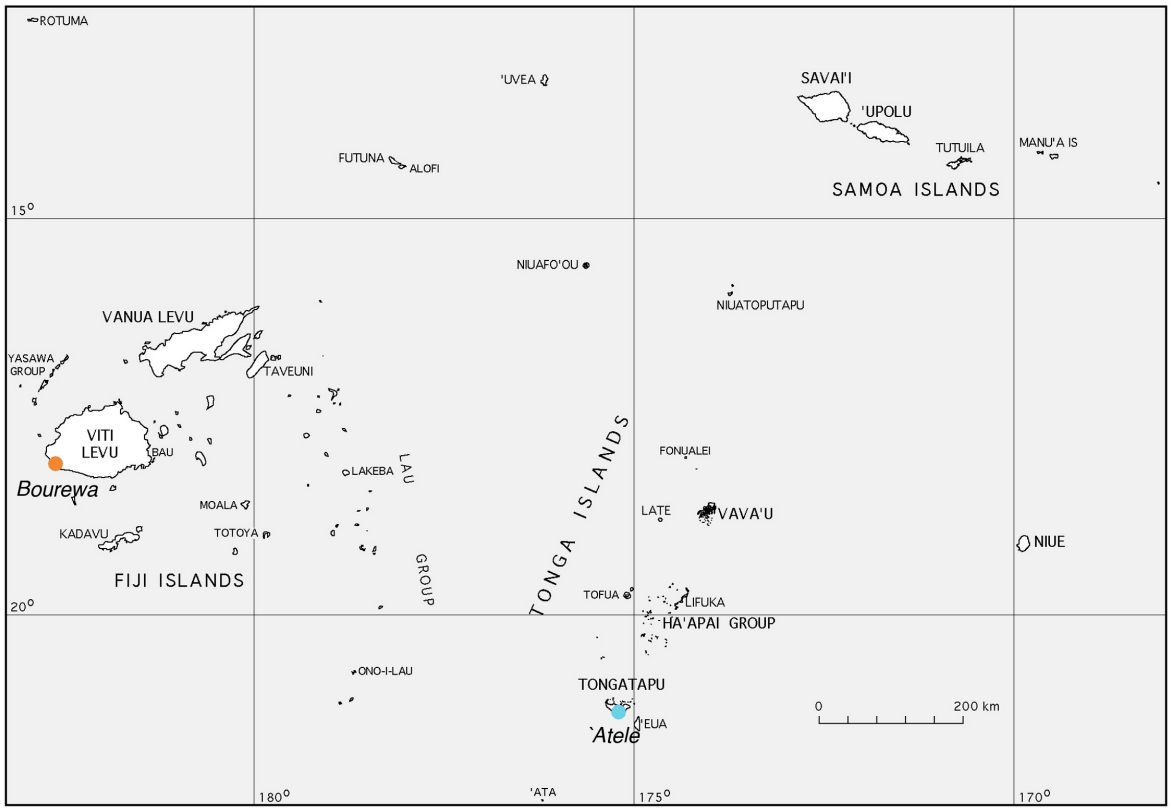


Figure 2.1. *Map of Tonga, Fiji, and Samoa with sites studied in this thesis highlighted in orange (Bourewa) and blue (‘Atele). Map courtesy of Peter Minton at EVS-Islands.*

chapter. Descriptions of the Tongan archipelago and site of ‘Atele have been described previously in Stantis et al. (2015b) and Stantis et al. (2015c). The Fijian archipelago and site of Bourewa have also been described previously, in the background sections for the Routledge chapter (Stantis et al., 2015c) and Stantis et al. (2015a).

2.1 Fiji and Bourewa

The Republic of Fiji (Figure 2.2) is an archipelago consisting of 300 to 500 islands (depending on how they are counted), 110 of which are currently occupied by humans. All together, Fiji has a total land mass of 18,272 km^2. Viti Levu is the largest island in Fiji at 10,388 km^2 and is geologically complex due to several episodes of volcanic activity and earthquakes (Rodda, 1967). Viti Levu’s large size, variable rainfall, and geological complexity creates highly varied ecosystems. Its landscape is described by some as “rugged rather than mountainous” (Anderson and Clark, 2009, 2), with a maximum elevation of 1,394 m. The mountain range runs in a north-south direction, dividing

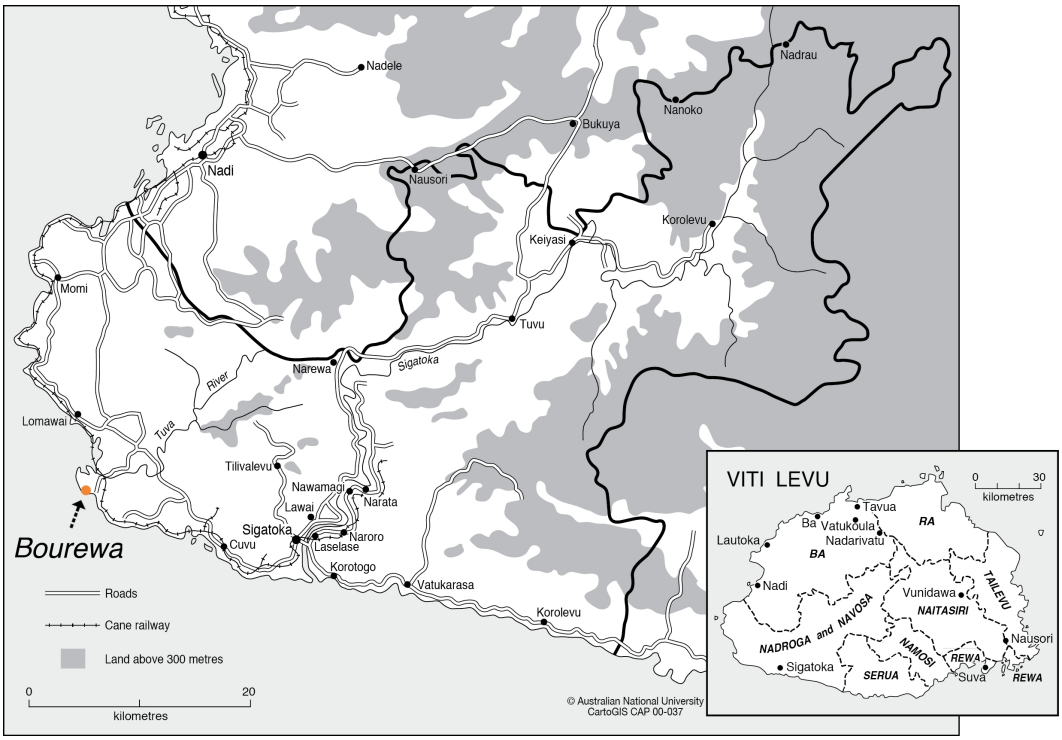


Figure 2.2. *Map of southwest coast with inset of Viti Levu, Fiji. Modified to include Bourewa site in orange. Image created by CartoGIS, College of Asia and the Pacific, The Australian National University and licensed under CC BY-NC-SA 3.0 AU.*

the island into roughly equal halves. Tradewinds blow from the east/south-east. The windward side of the island tends to be warmer and more humid, while the leeward side of the mountain divide tends to be 1 to 2 ℃ cooler (Fiji Meteorological Service, 2006). The temperature mean per month on the southwest coast varies between 22.6 and 26.4 ℃ (New et al., 2002). Average rainfall in the southwest coast per annum is 1892 mm (New et al., 2002) with more rainfall during the wet season between November to April, though rainfall is geographically highly variable on Viti Levu and heavily influenced by the tradewinds and island topography. Fiji tends to experience one cyclone per year, with two or three per decade causing serious damage (Fiji Meteorological Service, 2006). The El Niño Southern Oscillation (ENSO) is particularly devastating on Fiji as the archipelago is affected by both the high pressure system over Island Southeast Asia and the low pressure system in the eastern Pacific (Salinger et al., 1995). ENSO events are historically recorded as either bringing severe drought to Fiji or increased rain, tropical storms, and cyclones that flood valleys and devastate crops (Terry et al., 2001). In prehistory, dense tropical rainforests would have dominated the windward side while dry forests of *Casuarina* and *Pandanus* spp. would have covered most of the west and

north coast (Anderson and Clark, 2009). Fern savannas dominate many of the lowland leeward areas of Viti Levu today; anthropogenic burning is commonly attributed to the widespread nature of these habitats, though natural climatic events prior to human settlement may have encouraged their growth as well (Nunn, 1993).

2.1.1 Settlement chronology

The phases of Fijian history (Table 2.1.1) are generally defined as four phases based on ceramic design as created by Green (1963b) and modified by Frost (1979). The four-phase model is a "robust and useful interpretive tool" (Marshall et al., 2000, 5) even though the large geographic scale of Fiji and complexity of migration makes the exact timing and nature of these phases within different areas of Fiji unknown. Initial occupation of Fiji is roughly contemporaneous with that of Tonga, around 2950–3050 BP (Clark and Anderson, 2009). As the largest archipelago in size compared to Tonga and Samoa and the closest to Remote Oceania, Fiji was probably the first archipelago to be discovered and settled beyond Vanuatu (Sand, 2007, 215). Not surprisingly, the islands appear to have been settled in a west-east direction (Clark and Anderson, 2001). The Lau Islands, the easternmost island group, are a possible exception as they may have been colonised in an east-west movement from Tonga or Samoa (Burley and Clark, 2003).

The Sigatoka Phase (3000–2100 BP) is characterised by the Lapita dentate-stamped complex and coastal occupation typical of the Lapita (Davidson et al., 1990; Clark and Anderson, 2000; Burley and Dickinson, 2004; Nunn et al., 2004b). Pottery found in the Sigatoka Sand dunes were determined to be evidence of earlier occupation than the Navatu and Vuda sites excavated in the 1940s (Green, 1963a,b); Green (1967) drew the connection between the Sigatoka pottery and the Lapita pottery in the west to posit Lapita colonisation of Fiji and subsequent use as a "stepping stone" into Polynesia.

The Navatu Phase (2100–900 BP) marks the arrival of a second wave of migration from Remote Oceania as marked in the ceramic record with the advent of carved paddle impression decoration, new vessel forms, and a variant manufacturing method (Burley, 2005). Craft specialisation in the form of salt production is evident from a Navatu-era village at the Sigatoka Sand Dunes; the need for coastal salt production also implies that settlements were forming inland (Burley et al., 2011). Fortifications are established along the natural topography and are interpreted as evidence of increasing population, competition, and conflict (Field, 2004).

The Vuda Phase (900–150 BP) is marked by an increase in incising, appliqué, and plainware ceramics. An increase in contact with Western Polynesia is implied

Table 2.1. *Fijian settlement periods as defined by Green (1963b) and modified by Frost (1979).*

Time (years BP)	Period
2500–2100	Sigatoka
2100–900	Navatu
900–150	Vuda
150 BP–present	Rā/Historic

during this period from oral histories and the evidence of prestige goods being moved between these cultures (Davidson, 1977; Burley and Clark, 2003; Burley, 2013; Clark et al., 2014). Extreme environmental changes (episodic droughts and floods) that were potentially detrimental to both aquatic life and horticultural production were occurring with increased frequency during the Vuda Phase, which may explain the increased fortification as a means of protecting resources (Field, 2004, 2005). The latter stage of the Vuda Phase (500–150 BP) marks the rise of monumental architecture and increasing proximity in settlement sites and earthwork fortifications in parts of Viti Levu, indicating a further rise in population density, intergroup contact, and social hierarchy during this time period (Parry, 1987; Field, 2004).

2.1.2 Fijian subsistence

Fiji is a large archipelago with highly varied island environments. Given its size, some have argued that there have been relatively few archaeological studies on the archipelago (Nunn et al., 2003; Sand, 2007). Many of the archaeological studies have been conducted on the smaller islands east and west of Viti Levu (e.g. Cochrane and Neff, 2006; Jones, 2009; Jones and Quinn, 2009).

Unlike smaller islands in Remote Oceania, the inhabitants of Viti Levu and other continental islands routinely had access to a variety of coastal zones for shellfish gathering, not just coral reef environments: mud-flats, estuaries, sandy intertidal habitats, freshwater environments, and rocky shores (Szabó, 2001). Mollusc samples from Fijian archaeological sites spanning several landscapes and time periods display a wide diversity of species from a range of environments, which suggests broad-scale collection for consumption (Szabó, 2009).

Ethnographic observations on the Lau islands found that starchy fruits and root vegetables (*ka kana dina*, or "true food") constituted roughly 70 to 80 percent of a typical person's daily foods (Jones, 2009). Bony fish was reportedly eaten every day by those interviewed, while chicken and pig were saved for special occasions. Taro, sweet potatoes, yams, giant taro, and bananas were grown in family gardens with wild

yams available in the interior forests and breadfruit on the hill slopes and in the village gardens (Jones, 2009, 109). Turtles were eaten when caught, and tributing some portion of this highly valued meat to the chief was expected. As is typical throughout much of the Pacific, women and children were the primary collectors of inshore marine resources, while men fished for reef and deeper pelagic species (Jones, 2009).

Regarding animal domesticates and commensals, the chicken and rat were found in Lapita-era sites on Fiji (Worthy and Clark, 2009), with pigs and dogs appearing in later sites dating to 1000 BP (Clark and Anderson, 2009). The initial colonisers may have had pigs and dogs and remains simply have yet to be found, but it is also possible that these animals were not initially present in eastern Fiji or a second migration wave around 1000 BP brought these domesticates to Fiji for the first time (Worthy and Clark, 2009).

As in many areas of the Pacific, earth ovens were the most common method of cooking food. These earth ovens involved placing firewood in a stone-lined pit and once the stones were hot, placing the foods to be cooked on a bed of, or wrapped in, a bed of leaves in the pit. The food was then covered with more hot stones and then the pit covered with leaves or a mat and earth for several hours (Huebert et al., 2010). Ethnographic accounts record separate ovens made for men and women in Fiji (Pollock, 1992, 72), although Pollock only notes separate feeding patterns between men and women in Yap and Tahiti.

The late prehistoric inhabitants of Viti Levu had varied economic and subsistence specializations (Clark and Anderson, 2009) with distinct territorial boundaries (Field, 2004). Coastal inhabitants of Viti Levu could have relied more heavily on marine resources than the inland inhabitants, and the burial location of Bourewa implies these Fijians lived near the coast. The broad fringing reef near Bourewa doubtlessly provided an abundance of marine resources for the Bourewa individuals as it continues to do so today (Nunn, 2009).

Access to freshwater and arable soil is more difficult from the site, as is access to safe harbour for watercraft to a lesser degree (Nunn et al., 2004a). This implies use of the reef as the priority for any inhabitants on the Rove Peninsula compared to other subsistence practices, However, microfossil evidence of taro and yam in the Lapita-era deposits on Bourewa indicates that some horticulture was practised despite the adverse soil conditions (Horrocks and Nunn, 2007).

2.1.3 Geology and environment of Bourewa

The site of Bourewa is located on the southwestern portion of the Rove Peninsula, on the southwestern coast of the island of Viti Levu. The Rove Peninsula is composed largely of pebbly silt-clay soils with a marl and limestone bedrock (Rodda, 1967; Nunn et al., 2004a). Bourewa is approximately 40 m inland, although erosion has doubtlessly changed the shoreline over time (Nunn, 2009). The southwest coast of the Rove Peninsula is dominated by a broad fringing reef up to 3 km wide and the southeast coast contains a deepwater bay, Natadola Harbour (Nunn, 2009). Mangrove forests dominate the northern portion of the Rove Peninsula and are likely to have developed only in the second half of the last millennium (Nunn et al., 2004a; Nunn, 2009).

2.1.4 Bourewa

The site was excavated over seven field seasons beginning in 2003 (Nunn et al., 2004a). The lowest layers of the site contain the oldest known Lapita settlement in Fiji; radiocarbon dating of shell and charcoal from the lowest layers establish settlement at Bourewa by 3170 calBP (Nunn et al., 2004a). The Lapita period site may be the first settlement site of Fiji (Nunn, 2009). Cutting into the Lapita settlement are 16 burials from later periods (Figure 2.3). While ceramic, stone, and shell artefacts were recovered from the deeper layers, no apparent grave goods were associated with the burials (Nunn, 2007). Preservation was variable; some skeletons were found nearly complete with little post-mortem damage, while others were highly fragmentary due to ploughing of the topsoil.

2.1.5 Bioarchaeological studies and dating of the Bourewa assemblage

Initial skeletal analysis is credited to Professor Kazumichi Katayama from Kyoto University (Nunn, 2007), although no published findings from this skeletal assemblage have emerged to date. Instead, research has focused on the Lapita-era material in the site (Nunn et al., 2004a; Nunn and Petchey, 2013). Once AMS radiocarbon dating showed these burials were attributed to the late prehistoric/protohistoric period (Table 2.2), re-interment of many of the remains was carried out in a plot adjacent to the site (Patrick D. Nunn, personal communication, 17 June 2014). The remainder of the skeletal material are now curated at the Anthropology Laboratory in the Department of Anatomy at the University of Otago. The AMS dates of the burials in this study range

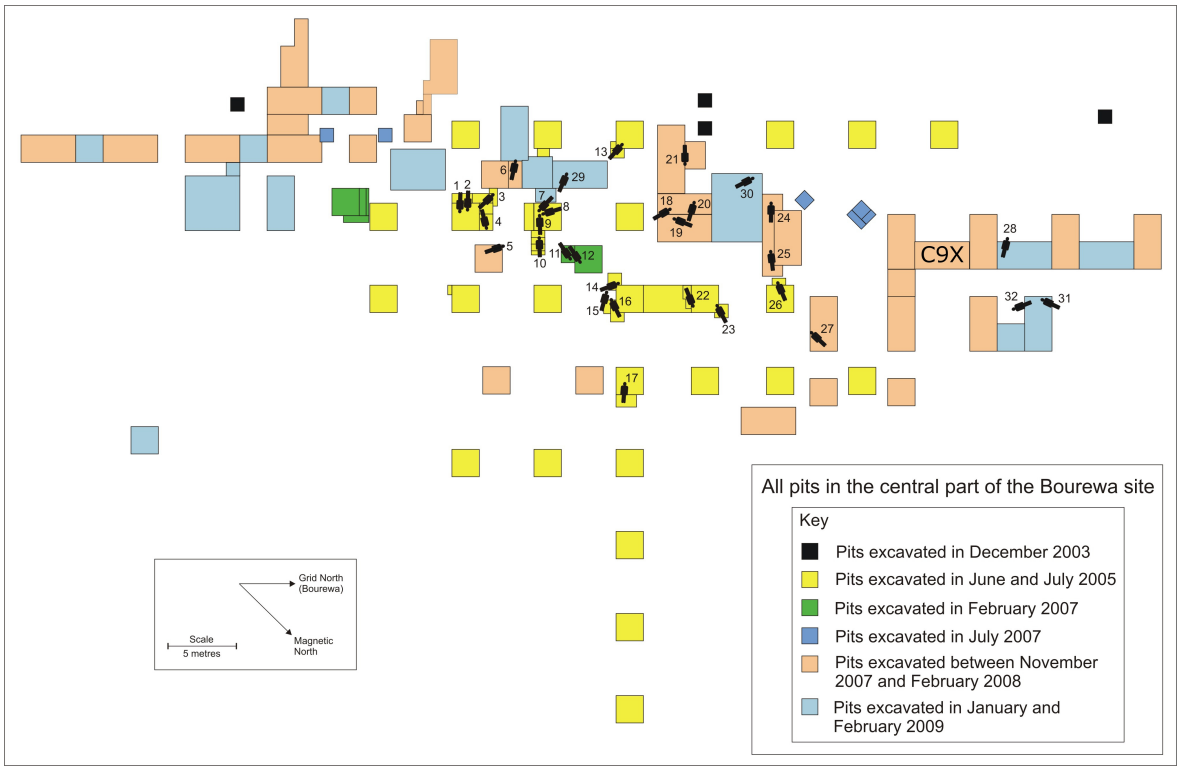


Figure 2.3. *Map of the Bourewa site with burials marked. Map courtesy of Patrick D. Nunn.*

from 790–0 BP, within the Vuda and/or Rā phases. While some of the burials are dated to the Rā period, no historic grave goods were found and there was no local knowledge of these burials, which suggests this assemblage is more likely from the prehistoric period (pre-150 BP).

2.1.6 Paleodemography

Twenty-seven individuals from the Bourewa assemblage were examined. In a box labelled "unnamed bones" two bags marked "Burial 1" and "Burial 2" contain fragmentary human material. The completeness of burials 1 and 2 in the excavation photos (Figure 2.4) and the provenence information on the lab bags placing the "unnamed bones" in pit C6A (rather than X20 where burials 1 and 2 were excavated) strongly suggests that these remains from the "unnamed bones" box are not Burial 1 and Burial 2. Thus, it appears that Burial 1 and Burial 2 were re-interred on-site and are not present in the University of Otago Anthropology Laboratory. These remains will be re-labelled in this study as Burial 33 and Burial 34 to avoid confusion.

With no previous bioarchaeological studies, I estimated sex and age for this col-

Table 2.2. *Radiocarbon dates of the burials from Bourewa examined in this study. All dates from the University of Waikato Radiocarbon Dating Laboratory corrected using marine correction factor (DeltaR) of 11±26 years (Petchey et al., 2008) and calibrated using the IntCal13 curve (Reimer et al., 2013) and a dietary correction involving $\delta^{13}C$ terrestrial/marine endpoints of -21/-12‰ (Petchey et al., 2014).*

Burial #	Laboratory #	$\delta^{13}C$	Conventional age (BP)	Calibrated age (calBP)	Probability
03	Wk-17438	-14.7	283 ± 32	250–220	95.4%
				150–0	
04	Wk-17442	-16.1	982 ± 30	790–640	95.4%
09	Wk-17451	-16.3	249 ± 35	260–180	95.4%
				150–0	
10	Wk-17452	-16.0	454 ± 30	440–120	95.4%
				10–0	
14	Wk-17443	-13.7	443 ± 32	260–0	95.4%
15	Wk-17450	-18.2	319 ± 32	310–60	95.4%
				40–0	
16	Wk-17449	-15.7	457 ± 29	430–100	95.4%
				10–0	
17	Wk-17447	-17.5	438 ± 30	480–260	95.4%
				170–150	
22	Wk-17446	-15.3	487 ± 33	440–120	95.4%
23	Wk-17439	-16.0	441 ± 30	430–90	95.4%
				10–0	
24	Wk-22827	-14.7	409 ± 37	270–0	95.4%
25	Wk-22826	-13.6	468 ± 36	280–0	95.4%
26	Wk-17437	-15.5	478 ± 32	430–100	95.4%
				10-0	

lection. Both estimations were conducted using the standards outlined by Buikstra and Ubelaker (1994). I divided the sexes into females, possible females, indeterminate, possible males, and males. Possible males and females were paired with the more confidently sexed individuals to create groups large enough for statistical testing. I used dental development (Ubelaker, 1984), dental calcification, dental eruption, diaphyseal lengths, and epiphyseal union to estimate age in non-adults. The adults were placed in the broad categories of Young (18–35 years), Middle (36–50), and Old (50+) adults following Buikstra and Ubelaker (1994). Suture closure, late-stage epiphyseal fusion, and comparative dental wear within the assemblage were used to divide adults into these categories.

I divided subadults into further categories based on chronological age (Table 2.4).

Figure 2.4. *A comparison of Burials 1 and 2 in situ and the material labelled "Burial 1"and "Burial 2". Top photo courtesy Patrick D. Nunn, bottom photos by author.*

I recognise that chronological age and physiological age (as determined using skeletal and dental development) do not always coincide (Lewis, 2007; Sofaer, 2011). It is also understood that while I used 18 years of age as the beginning of adulthood, the social categories of adulthood and childhood are fluid and variable between cultures and individuals (Halcrow and Tayles, 2011).

Twenty-one of the 27 individuals were sampled for paleodietary isotope analyses using bone. Burials 13, 33, and 34 were very fragmentary and had no cranial material; the remaining 24 individuals were examined for oral indicators of diet. Of those 24 individuals, only sixteen had the appropriate teeth for paleodietary isotope sampling (as detailed in Chapter 3). Burial 21(a) is a second individual commingled with Burial

Table 2.3. *Paleodemography of Bourewan individuals.*

	n	**Percent Total (%)**
Sex		
Female	9	36
Male	4	16
Age: Subadults		
Infant	0	0
Young child	0	0
Child	0	0
Adolescent	1	4
Subadult Total	1	4
Age: Adults		
Young adult	2	8
Middle adult	2	8
Old adult	5	19
Indeterminate adult	13	48
Adult Total	22	88
Indeterminate Age	4	15
Total	27	100

Table 2.4. *Subadult age groups. Age terminology adapted from Lewis (2007) with the "child" category further subdivided.*

Age Range (years)	**Term**
≤1	Infant
1.1 to 2.9	Young Child
3 to 13.9	Child
14 to 17.9	Adolescent
<18.0	Subadult
≥18	Adult

21, and C9X is an individual with no burial information, but was presumably found in Pit C9X (labelled on the site map, Figure 2.3).

2.2 Tonga and ‘Atele

The Kingdom of Tonga is an archipelago composed of two parallel, geologically distinct island chains that measure 748 km^2 altogether. The dual geologic systems allow the Tongans to enjoy access to a variety of materials for exploitation.The western arc island chain, the Tongan Volcanic Arc, is comprised of high islands with little to no coral reef formation (Taylor and Bloom, 1977). The lack of reefs greatly reduces the amount of marine life available around these islands, generally making these uninhabitable. Basalt, andesite, and volcanic glass from the western islands were base materials for a variety of tools, and tephra from the volcanic islands periodically falls on the eastern islands, providing good quality soil for horticultural pursuits (Burley, 1998). 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 utilising for centuries (Nunn, 1998; Taylor and Bloom, 1977). The eastern islands have been the core of Tongan settlement since Lapita colonisation as a result of the horticultural potential and rich marine environment available for exploitation (Burley, 1998).

Culturally, the archipelago is divided into four island groups: the northernmost Niuas, the Vava’u group, the Ha’apai group, and the Tongatapu island group in the south. The Tongatapu island group is the heart of the kingdom, containing the majority of the population and the capitol city, Nuku‘alofa, on the eponymous main island. Tongatapu is the largest island in the eastern chain of the Kingdom, with an area of approximately 250 km^2 (Figure 2.5) All of Tonga enjoys a relatively warm, tropical climate with two distinct seasons: a dry and cool season between May to September and a hot, wet season from November to April. The average annual temperature of Tongatapu is 23 ℃, with daily mean variation between 18 and 30 ℃. Mean total rainfall is approximately 1720 mm per annum (Tonga Meteorological Services, 2006). Tonga experiences one cyclone per year on average. El Niño Southern Oscillation events affect Tongatapu much less strongly than Fiji (Salinger et al., 1995) and so Tongatapu is comparatively less prone to climatic disturbances causing temperature and rainfall fluctuations.

The island of Tongatapu was formed by an uplifted reef complex, with the high ridges formed of ancient barrier reefs and the lowlands composed of an ancient lagoon

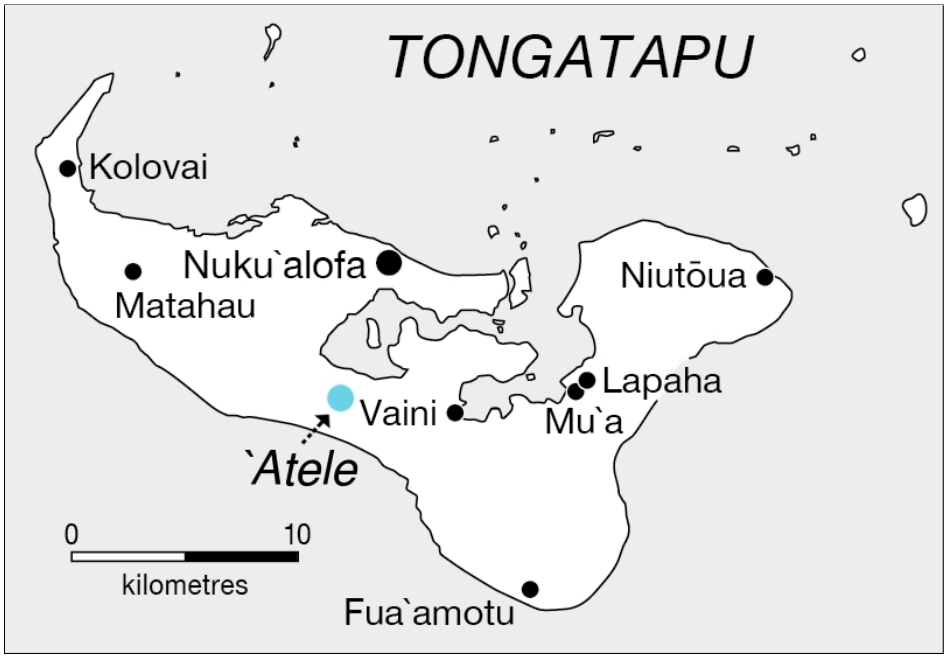


Figure 2.5. *Map of Tongatapu with ‘Atele burial mounds marked. Derivative of image by CartoGIS, College of Asia and the Pacific, The Australian National University and licensed under CC BY-NC-SA 3.0 AU.*

bed (Dickinson, 2007; Dickinson and Burley, 2007). A typical eastern island geologically, it is composed mostly of coral limestone and covered in volcanic soil (Dickinson, 2007). 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 (Taylor and Bloom, 1977; Nunn, 1998). The island is nearly bisected by the Fanga‘uta Lagoon and surrounded by a rich reef system.

2.2.1 Settlement chronology

Burley (1998) has defined five periods of Tongan settlement (Table 2.5). Tongan settlement by the Lapita is assumed to have begun on Tongatapu approximately 2838 BP (Burley et al., 2012). The “end” of the Lapita culture and the “beginning” of Polynesian culture began around 2650 BP as demarcated in the archaeological record by the loss of decorated Lapita ceramics and the rise of plain ware (Groube, 1971). Around 1550 BP the Polynesian Plain Ware Ceramic Period transformed into a near-complete loss of ceramics. This aceramic period, the Formative Period of Tonga (1550–750 BP), is a relatively unknown time in Tongan prehistory due to its scant material record (Burley, 1998).

Though the aceramic nature of the period may have stimulated less interest in some traditional archaeologists, this is an important period as the basic societal frameworks of the complex Tongan hierarchical culture began. During the Formative Period the people of Tonga developed into what some archaeologists call the "Ancestral Polynesian Culture"; alongside Samoa, the Polynesian cultural complex emerged from its Lapita beginnings and would eventually spread east (Green, 1979; Kirch, 1984a; Kirch and Green, 2001). An increase in population density, possibly to the point of full or near-full capacity, and the beginnings of chiefly ruling occur in Tonga during the Formative Period (Kirch, 1984a). No longer did the occupants of this archipelago stay along the fringes of the island like the Lapita people of the past: during the Formative Period, the inland became filled with the villages and horticultural gardens that persist to this day (Campbell, 1992).

The Chiefdom Period (750–150 BP) was the period of hegemonic control of the Tongan maritime chiefdom. At this time the Tongan paramount elite exerted their influence throughout Oceania and sent junior-ranking chiefs to outlying islands to maintain prestige and assure the flow of prestige goods (e.g. fine mats, feathers, sandalwood, barkcloth, canoes, and pottery) back to Tongatapu, the main island of the Tongan Empire (Kirch, 2000; Clark et al., 2014). Peak prehistoric population occurred at this time, with 30,000–40,000 people occupying the archipelago and the majority of the population on Tongatapu (Kirch, 1984a; Burley, 2007). During the Chiefdom Period the basic societal frameworks of the complex Polynesian hierarchical culture were fully developed (Clark et al., 2008). The concepts of rank and status, probably already engrained in Polynesian society and inherited from their Lapita ancestors (Green, 1979), created a highly stratified society. This gave the *Tu'i Tonga* (paramount chief) the capability to exert the influence necessary for monumental architecture, sweeping landscape change, and the steady extraction of surplus from the lower classes in order to support these undertakings (Kirch, 1984a; Burley, 1998).

Around 500 BP, a secular authority (the *Tu'i Ha'atakalaua*) usurped some of the Tu'i Tonga's power. By 350 BP a second secular leader (the *Tu'i Kanokupolu*) took more secular duties and influence from the Tu'i Tonga, leaving the position of Tu'i Tonga a mostly sacred one (Burley, 1998, 369). Below the Tu'i Tonga and the *hau* (the two secular Tu'i) were regional and lesser chiefs, their retainers, and skilled and unskilled workers who lived in a highly stratified and complex hierarchy (Bott, 1982). In the Chiefdom Period through to the present, stratification affects every aspect of daily life. Unlike many class structures, families did not share power and prestige: complex rules of age, sex, birth order, and lineage affected authority and ceremonial

Table 2.5. *Tongan settlement periods, as defined by Burley (1998).*

Time (years BP)	Period
2850–2650	Early Eastern Lapita Ceramic
2650–1550	Polynesian Plain Ware Ceramic
1550–750	Formative Development
750–150	Complex Centralized Chiefdom
150 BP–present	Historic

rank in different ways ensured that “no two people had the same rank” (Bott, 1981, 7).

While this highly stratified hierarchy persisted through the Historical Period (beginning 150 BP) and today, the maritime empire did not. By the 18$^{\text{th}}$ century, the empire collapsed and warfare consumed the archipelago due to incongruities with chiefly appointment, regional rivalries, increased population density, and land competition (Burley, 1998).

2.2.2 Tongan subsistence

Post-contact European accounts highlight that Tongan diet, like most Polynesian diets, centres around a starchy staple plant food (“real food” or *kai*) such as taro, yam, or breadfruit and is accompanied by side dishes (*kina*) such as animal flesh and grated coconut to provide flavour variety (Pollock, 1992). Most plants eaten in Tonga today and in the past were likely imported by the initial colonizers and include root crops and fruit and nut trees (Kirch, 1984a, 1997). Terrestrial native plants are not part of the Tongan horticultural system but could be gathered in times of food scarcity, such as after extensive cyclone damage to gardens (Kirch, 1984a, 1997; Whistler, 1991).

Unlike in Fiji, where irrigation and terracing can support water-reliant species, the fast draining soil of Tongatapu does not lend itself to swamp taro (*Cyrtosperma merkusii*). Tongatapu soil is instead better suited to the cultivation of yams and taro. Swidden farming is practised to clear areas for root vegetable cultivation, while tree crops are maintained at garden boundaries and in forests (Pollock, 1992).

Midden evidence from a Tongan site (To-Pe-1) suggests shellfish were the most common sources of protein in the Tongan diet (Poulson, 1987). There is scant evidence for exploitation of marine fauna outside of molluscs and fish at this site, though Poulson (1987) found evidence of marine turtles (*Chelonia mydas* and *Caretta caretta*). These turtle species can weigh around 200 kilograms each, a significant hunting victory in any period of time. A small number of porpoise bones were also excavated (Poulson, 1987), although there is no ethnographic or historical evidence for how porpoises would

be exploited in the tropical Pacific. Beached whales were not typically eaten, only butchered for the valuable teeth to be made into beads. (Mariner and Martin, 1827, 250).

Mariner mentions eating dogs, but it is not clear whether dogs were available in Tonga before European contact, or if Europeans introduced the Tongans to dogs (Mariner and Martin, 1827, 215). Captain Cook wrote that Tongans, when given dogs as gifts by the captain, were already familiar with the species and had a specific word for them, a word Cook notes is the same in the "New Zealand language", *kuli* or *kuri* (Cook, 1967a, 262). Anderson, the ship's surgeon and naturalist during the *Resolution's* second voyage, records the presence of a growing population of dogs of mixed stock between Cook's gifts on the previous voyage and dogs from Fiji (Anderson, 1967). While dog bones have not been found in archaeological excavations on Tongatapu, they have been found in Lapita and Plain Ware era sites on Lifuka Island, part of the Ha'apai group of islands (Steadman et al., 2002b).

Regarding Tongan rat populations, Poulson's excavations on Tongatapu found Polynesian rat (*Rattus exulans*) bones in the archaeological records, especially in middens and pit infill sites that have been suggested as food storage areas (Poulson, 1987, 247). Mariner reports rat as a food source among the lower classes in the 19th century as well as prey for sport hunting amongst the chiefly class (Mariner and Martin, 1827, 225).

There is no mention of eating reptiles in Post-Contact sources, but this does not exclude the use of lizard as a food source before European arrival. Iguana bones (*Brachylophus fasciatus*) were found in midden excavations, and Poulson suggests that people resorted to lizard-hunting during times of near-starvation (Poulson, 1987, 241). Relatively large bones of a *Brachylophus* iguanid have also been found on the island of Lifuka of the Ha'apai island group (Pregill and Dye, 1989). Like the molluscs, the lizard remains seem to be larger than modern ones, possibly as a result of overhunting. This idea is supported by the hypothesis that the Lifuka island iguanid bones belonged to a species that was hunted to extinction around the Plain Ware periods (Pregill and Steadman, 2004).

While pigeon snaring was a popular sport for the chiefly class (Burley, 1996), pigeons may or not have been eaten. A very small number of wild avian bones were present in excavated Lapita-era middens (Poulson, 1987). This suggests that land birds were not a common source of food for prehistoric Tongans, but might have still been eaten in small amounts.

The elite class of Polynesia were routinely tributed garden foods (e.g. taro, yams)

by the rest of society and, in Tonga, a large proportion of these tributes were kept by elites for consumption during feasts (Mariner and Martin, 1827; Kirch, 2000). Modern and historic ethnographic writings record that these foods could then be changed in complex and labour-intensive ways such as puddings or fermentation to increase the foods' social value (West, 1835; Oliver, 1989; Pollock, 1992; Leach, 2003).

2.2.3 ‘Atele burial mounds

In 1964, Janet Davidson led an excavation of two burial mounds on the Tonga College grounds in the ‘Atele area (Davidson, 1969). Typically the disturbance of the dead is *tapu* (taboo) on Tonga. However, the Honourable Ve‘ehala, Keeper of the Records at the time, and current occupants of nearby villages had no recollection of the people buried in the ‘Atele mounds and thus excavation was permitted. The grounds of Tonga College held several mounds. Three mounds, the largest in size, are named and were still used for interment at the time of excavation. Eleven other mounds, unnamed and with no record of use, were located on the grounds which showed evidence of use as burial mounds due to the presence of white coral sand scattered on the surface. These eleven mounds could be roughly divided into two size groups, and one of each were chosen for excavation. The main research focus of the original excavations was to determine 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 centres and on edges of the mounds were dug instead. Only 2.9% and 13.6% of the possible areas were excavated for the mounds (designated To-At-1 and To-At-2), respectively.

To-At-1

The first burial mound excavated was designated To-At-1 using the archaeological naming system for Tonga (island-area-number). The mound was approximately 40 m in diameter and relatively low, 80 cm at maximum height. The centre of the mound was intercut by the more recent occupations so that the original layers were largely destroyed, and the edges of the mound were disturbed by modern ploughing. In other parts of the mound Davidson found five main layers corresponding to four separate periods of occupation. The layers were labelled in descending order, with the base layer of the mound labelled Layer 5. The layers were described by Davidson as follows:

> “Layer 5– A brown garden soil, similar to that in the surrounding fields, which overlay the clay subsoil. It filled several deep postholes.

Table 2.6. *To-At-1 occupation stages. From Davidson (1969, 257–258).*

Stage 1	First stage of human use. Holes dug on site; possibly either postholes or yam planting holes
Stage 2	More holes dug, two fire pits present in this stage. Possible house structure present, but the thinness of layer 4 suggests a short duration of occupation in this stage. Midden material found in this stage.
Stage 3	First burials made on site. The ground surface (layer 4) is dug into in order to place the bodies, and white sand covers the bodies. More postholes present- a house may have been present before the burials, or a special structure might have been built over the bodies
Stage 4	The mound is constructed during this final phase of human use. The mound is constructed using spoil from a surrounding trench (open to the north) and then burials are placed. A few postholes exist filled with layer 1 material; a special structure might have been built over these burials.

> Layer 4– A thin layer of blackened soil, shell, burned coral oven stones and considerable charcoal. Several postholes were filled with this material, and one large fire pit and one smaller one were cut from it into layer 5.
>
> Layer 3– A thin layer of mixed soil and white sand, which filled a few postholes. The earliest burials on the site were derived from this layer, and the burial pits were partially filled with similar material.
>
> Layer 2– Sterile clay and soil used on the construction of the mound.
>
> Layer 1– Mixed soil and sand very similar to layer 3. Burial pits dug from the surface of the mound were filled with similar material." (Davidson, 1969, 257–8)

Davidson proposes four stages of occupation for this area, outlined on Table 2.6. Other than the burials, postholes (or possibly holes for planting yams) and two firepits without oven stones were features found in To-At-1. Some shell and pottery (all plain) were found in the lower levels. There were no grave goods, although black soil staining is evident around some burials. Davidson (1969) interpreted this as potentially caused by black tapa cloth used for wrapping the dead, a practice still used in Tongan burials. Davidson reports excavating 46 individuals from 38 separate interments. Most burial pits were oval or rectangular and between 30 to 80 mm deep. The majority of individuals were primary, single burials in the supine position (lying on their backs). Intercutting of older burials for newer burials was obvious in some cases. One burial (29) was a secondary burial of the disarticulated remains of an adult and two subadults. Orientation and position (all supine or side burials with extended legs) were variable

Table 2.7. *Rough chronological order of burials in To-At-1. The groups are divided into those below the mound and those in the mound, and subgroups are arranged in order from oldest to most recent. Adapted from Davidson (1969), 260.*

Prior to mound construction	
subgroup 1 (oldest)	34, 30, 29
subgroup 2	27, 28, 24, 23, 22, 21, 20 (27 and 28 are contemporaneous)
subgroup 3	16, 17, 18, 19
subgroup 4	10, 11, 12, 13, 14
From the surface of the mound	
subgroup 5	8, 9, 36, 37
subgroup 6	2, 3, 5, 7, 32, 33, 35
subgroup 7 (most recent)	1, 4, 6, 31, 25, 26

with no discernible patterns regarding age, sex, or time of burial. With intercutting, reburial of disturbed bone, and the large number of individuals in a relatively small space, chronological order of interment was difficult for Davidson, but the rough sequence of burial is presented in Table 2.7.

To-At-2

To-At-2 is larger than To-At-1, approximately 25 m in diameter and 2.5 m high with a shallow ditch encircling the edges. Davidson described six layers in this mound:

> “Layer 6– A thick layer of dark brown soil, which filled a large shallow pit and at least one posthole beneath the mound itself. In the main trench, two subdivisions of this layer could be identified, a harder browner zone at the base, and a softer bloacker zone nearer the surface. This layer contained most of the potsherds found in the mound, and very occasionally shell and fragments of turtle bone.
>
> Layer 5– A thin layer of mixed white sand and soil.
>
> Layer 4– A mixed fill of dark brown soil and more orange clay derived from excavation in the immediate vicinity.
>
> Layer 3– A mixed layer of white sand, and material similar to layer 4.
>
> Layer 2– A fill consisting of hard orange subsoil won from the surrounding ditch and forming the upper layer of the mound.
>
> Layer 1– Mixed clay, soil, and white sand.” (Davidson, 1969, 266)

Table 2.8. *To-At-2 stages of occupation. From Davidson (1969, 267–268).*

Stage 1	A shallow pit of unknown utility and at least one posthole indicates initial human use not associated with burial
Stage 2	The first burials occur in this stage. Burials are placed in pits, covered with white sand, and filled.
Stage 3	A small mound is created from spoil from a surrounding ditch; new burials are placed. This surrounding ditch has been refilled over time.
Stage 4	A larger mound is created using spoil from the larger second ditch surrounding the mound; more burials are placed.
Stage 5	More burials are placed in the sides of the mound and in the ditch. Davidson proposes these may have been placed "hastily and unceremoniously" (p. 268).

Table 2.9. *Rough chronological order of burials in To-At-2. Adapted from Davidson, 1969, p. 271.*

Period 2 (oldest)	26, 27, 39, 40, 41
Period 3	5, 6, 20, 21, 22, 23, 25, 28, 29, 37, 38
Period 4	1, 2, 3, 4, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 30, 31, 32, 33, 35, 36
Period 5 (most recent)	24, 34, 42

Five stages of occupation were proposed (Table 2.8). Later research on the interments reported a total of 42 burial interments excavated from this mound, comprising of 53 individuals (Pietrusewsky, 1969). An adze fragment was found in the outer ditch fill, and shell and unidentified non-human bone were found in the lowest layer and fill. Unlike To-At-1, there was no evidence of occupation in the lower layers except the unknown pit. The only feature present other than burials was a pit from the first period of occupation. Davidson (1969) could offer no interpretation for what this pit might have been.

As in To-At-1, there were no grave goods, only black staining around some of the individuals potentially indicative of black tapa mats. The burials were more spaced out in To-At-2 compared with To-At-1, so less disturbances of earlier burials were present. Most individuals were buried in pits filled with white sand, like To-At-1, though thirteen burials lacked sand or a recognisable pit. Once again, orientation was variable and most primary burials were supine or lying on their sides with extended legs (sometimes the knees were slightly bent). The decreased density of these burials made the creation of a sequence more difficult, nonetheless Davidson placed the To-At-2 burials into major periods (Table 2.9).

Tonga Burial Mound Classification

In 1929, an examination and classification of the different mound types in Tonga was conducted (McKern, 1929). McKern defined three types of burial mounds:

- *langi*, a mound with a coral stone overlay reserved for the Tu’i and their families
- *fa‘itoka*, a large mound with a surrounding ditch for the lesser chiefs and their families and retainers
- *tanu‘anga*, a small, shallow mound for commoners

Following McKern’s classification system, the two ‘Atele 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 *tanu‘anga* and To-At-2, the taller mound (2.5 m high) with a shallow encircling ditch, would be a *fa‘itoka*. Davidson (1969) was critical of this classification for the ‘Atele burial mounds, as there were no discernible differences regarding mound construction or method of interment between To-At-1 and To-At-2.

Dating

Two bone samples from To-At-2 provided sufficient collagen for radiocarbon dating in the 1960s (Davidson, 1969); the results (770 ± 200 BP and 390 ± 110 BP), along with the material goods recovered and size and construction of burial mounds, prompted Davidson to place mound use firmly in the Late Formative Period/Early Chiefdom periods. Ceramic findings in the ‘Atele mounds were sparse (75 potsherds total in both mounds), and none of the sherds were decorated (Poulson, 1987). There were also no European artefacts. Given this evidence, Poulson (1987) agreed with the placement of the mounds in the Formative Period.

However, recent AMS dating places the interments between c. 500–200 BP, which corresponds with the Chiefdom Period in Tonga (Table 2.10). These dates are markedly different from the original radiocarbon dating cited in the report. The increased accuracy of modern dating methods (de Laeter, 1998) and expanded understanding of how marine reservoir offsets affect estimations (Petchey and Clark, 2011) probably account for this discrepancy. While the radiocarbon range could place some of the burials within an early historic timeframe, this is unlikely given that there was no recollection of these burials by the community and there were no artefacts indicative of European contact found in the mounds.

Table 2.10. *Radiocarbon dating results for 'Atele burial mounds. AMS dating from Waikato Radiocarbon Dating Laboratory. The $\delta^{13}C$ values were measured on prepared graphite using the AMS spectrometer due to the small size of the samples, and so the radiocarbon dates have been corrected for isotopic fractionation. However, the AMS-measured $\delta^{13}C$ values can differ from the $\delta^{13}C$ of the original material and are not listed. Dates are corrected for a lagoon reservoir using a R value of 273 (Petchey and Clark, 2011) and calibrated using the IntCal13 and Marine13 curves (Reimer et al., 2013) in OxCal v4.2.3 (Ramsey, 2009). Data originally presented in Stantis et al. (2015b).*

Burial #	Laboratory #	$\delta^{13}C$	Conventional age (BP)	Calibrated age (calBP)	Probability
To-At-1/06	Wk-38144	—	278 ± 21	254–215	95.4%
To-At-1/34	Wk-38145	—	489 ± 22	323– -2	95.4%
To-At-2/04	Wk-38146	—	232 ± 23	256–7	95.4%
To-At-2/24	Wk-38147	—	220 ± 23	255–10	95.4%
To-At-2/26	Wk-38148	—	280 ± 22	248– -2	95.4%

2.2.4 Bioarchaeological studies of the 'Atele assemblage

Pietrusewsky (1969) was the first to examine the To-At-1 and -2 skeletal remains in a laboratory setting, recording a general skeletal inventory of 99 individuals. An assessment of dental health has been conducted on 52 individuals from the 'Atele assemblage, recording carious lesions, dental calculus, macrowear, and periapical cavities (Taylor, 1971). The results of this dental census will be discussed in more detail in this study's chapter on oral indicators of diet (Chapter 4).

Macroscopic indicators of disease in the 99 individuals from the 'Atele skeletal collection have been examined as a comparative sample to Taumako, an assemblage from the Solomon Islands (Buckley, 2001). The main aim of Buckley's thesis was to address the role of malaria in the Soloman Islands and compare Taumako to Tonga, an area historically unaffected by malaria. Buckley (2001) found that, compared to Taumako, the 'Atele subadults were more affected by non-specific disease although Taumako individuals had an increased prevalence of yaws and the mortality profiles of the two sites were similar. Although differences in health between the two sites may have been caused by malaria, Buckley (2001) concludes that the data cannot unequivocally support this hypothesis and diet and environment may have been a significant contributor to the disease prevalence in Tonga. In addition to comparing the two sites, Buckley also compared To-At-1 and To-At-2 for mortality and morbidity, but found no differences between the mounds. A detailed report of skeletal pathologies

in subadults within the mounds is reported by Buckley (2000). In subadults, Buckley noted a high rate pathological lesions and concludes that comorbidity of infectious disease and nutritional deficiency was the most probable cause. Although no statistical tests were conducted in Buckley (2000), there are no differences in childhood health between the two burial mounds in a qualitative comparison.

Evidence of entheseal changes and osteoarthritis have been examined as an indicator of gendered divisions of labour, though no significant differences between the sexes were found in the ‘Atele assemblage (Foster, 2011). Foster (2011) also found no differences in activity between the two burial mounds of ‘Atele. Robb et al. (2012) examined nonspecific stress using cortical bone thickness and femoral length to examine whether different Pacific Island assemblages, including ‘Atele, display different adaptational responses to Pacific environments. While sexual dimorphism and age influenced cortical bone thickness and femoral length, there are no relationships between these measurements and non-specific stress or the temporal/spatial distributions of the different sites (Robb et al., 2012). Scott and Buckley (2014) explored skeletal trauma and interpersonal violence within the assemblage, finding a number of “parry” fractures in radii and ulnae but few instances of cranial trauma. This led Scott and Buckley (2014) to conclude that ritualised acts of violence such as sporting events may be the cause rather than warfare. Neither Robb et al. (2012) nor Scott and Buckley (2014) compare the two burial mounds in their studies, and instead examined the ‘Atele assemblage as a whole.

2.2.5 Paleodemography

Individuals are labelled by their mound and burial number and, in the case of interments with multiple individuals, a letter follows the burial number to differentiate the individuals. For this study, 100 labelled individuals were examined. Some individuals were stored without any indication of burial location. This may be the result of unfortunate curation practices, although Davidson noted that some bones from To-At-2 were unassigned during excavation as crumbling on the sides of the excavation trench caused some burials to be inadvertently revealed and moved (Davidson, 1969, 270). Pietrusewsky (1969) noted these unlabelled bones and presented an inventory, but no one to date has analysed them. These unnumbered individuals were also separated into cranial and postcranial boxes without suggestion of association between the separated materials. As such, cranial and postcranial material could not be assumed to be associated in these unnumbered individuals, but were still included in this research in order to better understand the Tongan diet on a population level and increases the final sample size to 126 individuals. The age-at-death and sex estimation for this collection were conducted

Table 2.11. *Paleodemography of 'Atele assemblage. The 26 unlabelled individuals (all unknown age, unknown sex) are not included except in combined total.*

	To-At-1	To-At-2	Overall
Sex			
Female	11	16	27
Male	7	11	18
Age: Subadults			
Infant	9	4	13
Young child	6	2	8
Child	4	6	10
Adolescent	2	4	6
Subadult total	**21**	**16**	**37**
Age: Adults			
Young adult	8	8	16
Middle adult	5	6	11
Old adult	0	7	7
Indeterminate adult	10	15	25
Adult total	**23**	**36**	**59**
Indeterminate age	2	2	4
Total	**46**	**54**	**126**

by Buckley (2001). For subadults, Buckley employed dental development (Ubelaker, 1984), dental calcification, dental eruption, diaphyseal lengths, and epiphyseal union. For adults, differential preservation of postcranial material made estimation using epiphyseal unions and pubic symphyseal degeneration difficult; seriation by degree of dental attrition was the primary method of assigning adults to age groups (Lovejoy, 1985). Sex estimation of adults was determined using the standards outlined in Buikstra and Ubelaker (1994). Buckley divided the sexes into females, possible females, indeterminate, possible males, and males. For this study, the "possible" categories were paired with the more confidently sexed individuals to create groups large enough for statistical testing. Buckley's system of dividing adults into three age categories (Young, Middle, and Old) will be used here. However, her system will be modified slightly so that individuals aged 18 years and over will be categorised as adults, rather than 20 and over.

The paleodemographic distributions for the 'Atele mounds are presented on Table 2.11. Due to the different levels of completeness, not all skeletons had both dental material (for dental markers of diet and isotope analysis) and post-cranial skeletal

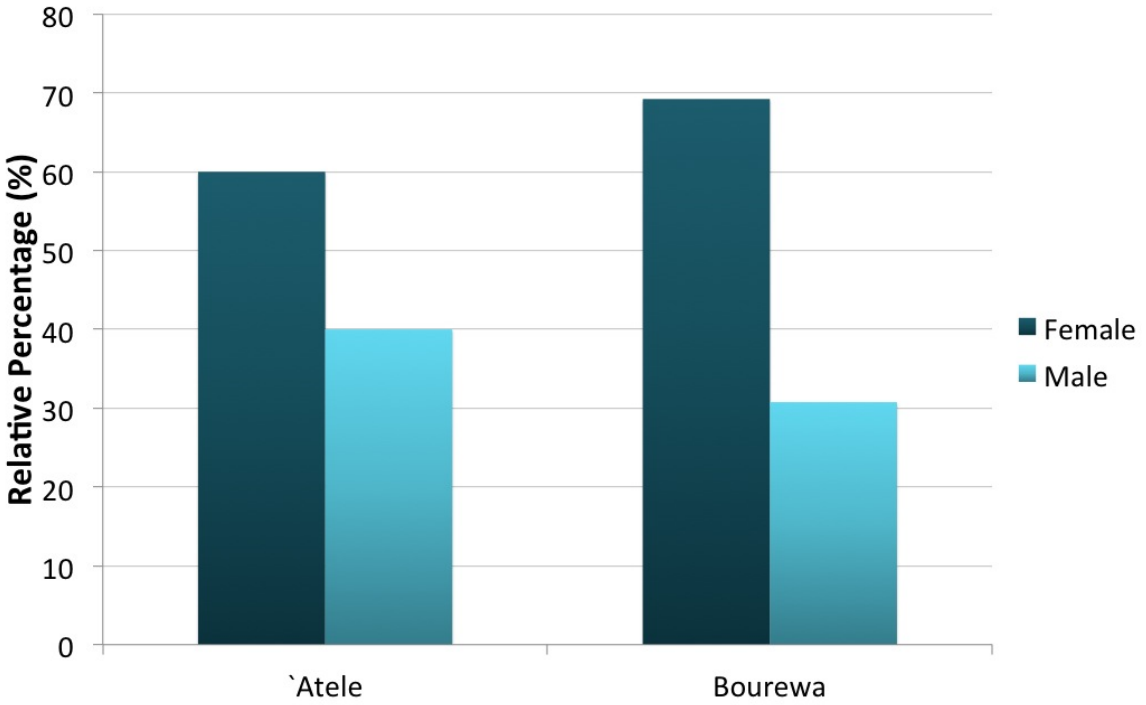


Figure 2.6. *Relative percentage of males and females at ʻAtele and Bourewa.*

material (for isotope analysis). If no assumption is made about pairing cranial and postcranial material (and none was for this study), 126 Tongan individuals in total were examined. Eighty-nine individuals were included for dental markers of diet and 43 individuals for isotope analysis of teeth. Regarding postcranial material for isotope analysis of bone, 93 individuals were included.

2.3 Comparing the two assemblages

As neither of the excavations were carried out with excavation of human remains as a primary goal, assuming that either assemblage is representative of the living population demographically is unwise (Waldron, 1994). Both assemblages have more females than males, as seen on Figure 2.6. Despite the small sample sizes within categories for the Bourewa assemblage, there were no significant differences regarding distribution of males and females between the two sites when the ʻAtele burial mounds are combined, $\chi^2(2) = 0.37, p = 0.546$. There were also no significant differences regarding adult age categories (Young, Middle, and Old adults) between sites, $\chi^2(2) = 4.41, p = 0.110$, though Bourewa has a much larger relative percentage of old adults (Figure 2.7). With only one subadult in the Bourewa assemblage (an adolescent) and 37 subadults in the

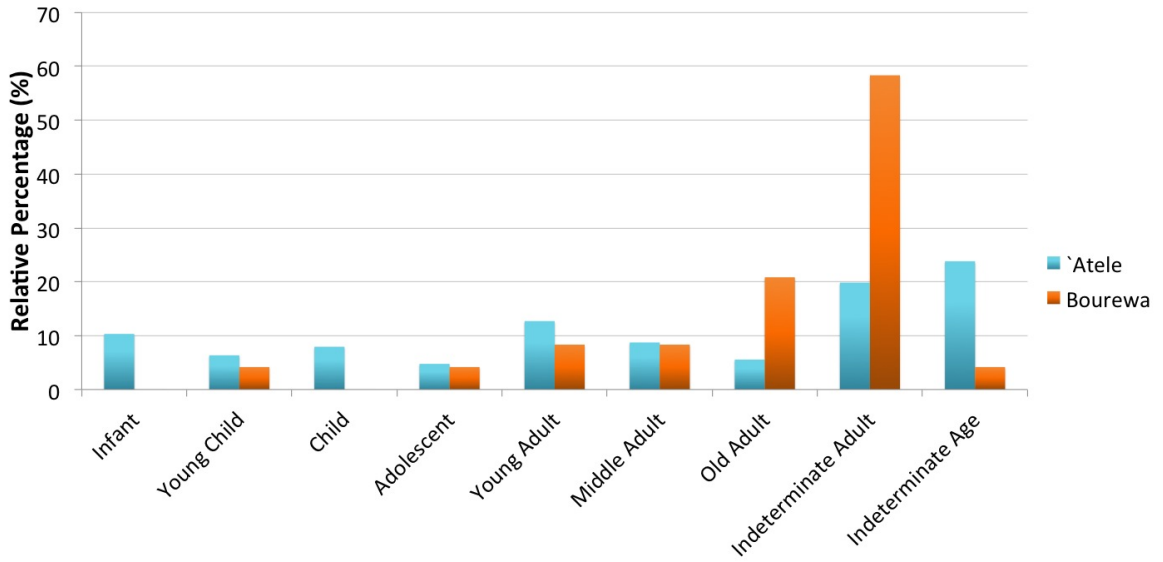


Figure 2.7. *Relative percentage of age categories ʻAtele and Bourewa individuals.*

ʻAtele assemblage (Figure 2.7), the ʻAtele assemblage will provide more information about childhood diet in non-survivors.

Figures 2.8 and 2.9 display the demography of the ʻAtele burial mounds by age categories and sex. Between burial mounds, there were no differences regarding sex ($\chi^2(1) = 0.03, p = 0.901$). There were also no significant differences regarding the distribution of subadults and adults, $\chi^2(1) = 3.32, p = 0.068$, or between adult age categories, $\chi^2(2) = 5.51, p = 0.063$.

2.4 Summary

The assemblages of Bourewa and ʻAtele are among the largest skeletal assemblages in Fiji and Tonga and serves as representations of life in late prehistory for this study. Examining the isotopic composition and oral indicators of diet of the individuals from these sites will address the first three aims of this thesis: to understand individual mobility, to characterise the diet, and to compare inter-and intra-population differences between and within Tonga and Fiji. Rudimentary statistical comparison showed no significant differences in population composition between the two sites regarding sex or age categories, suggesting the adults can be grouped as a single cohort when comparing the two sites. Although the Bourewa assemblage has only a single adolescent and no infants or children, the subadults who were interred in the ʻAtele burial mounds will provide information for addressing the last aim, to understand age-at-weaning and weaning food practises in prehistoric Tongans, and its associated hypotheses.

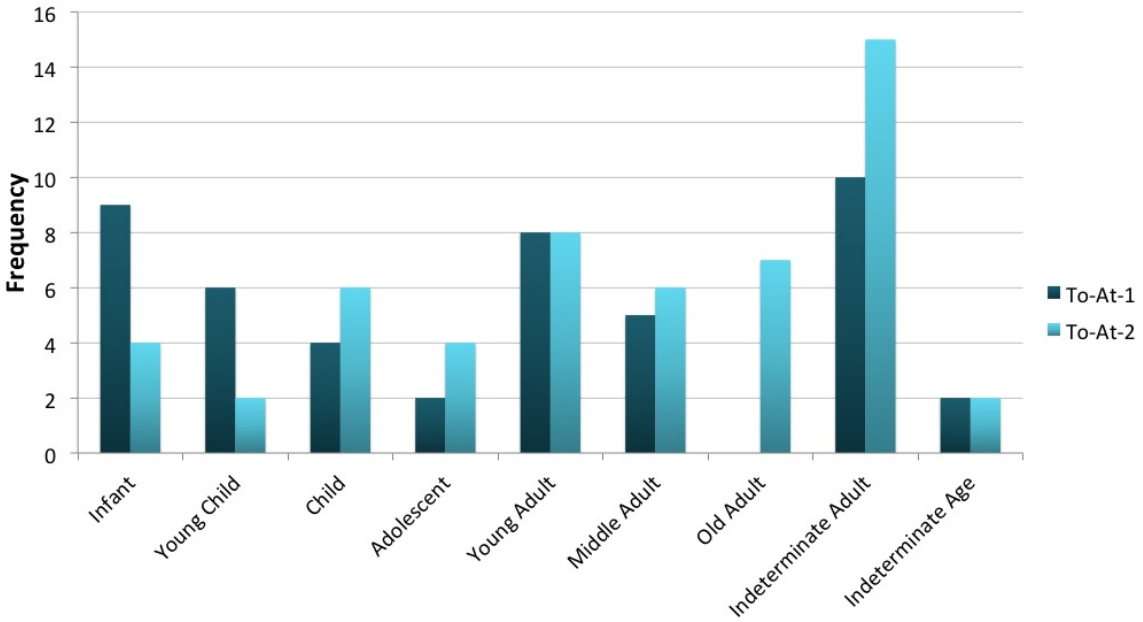


Figure 2.8. *Age categories of individuals in 'Atele burial mounds.*

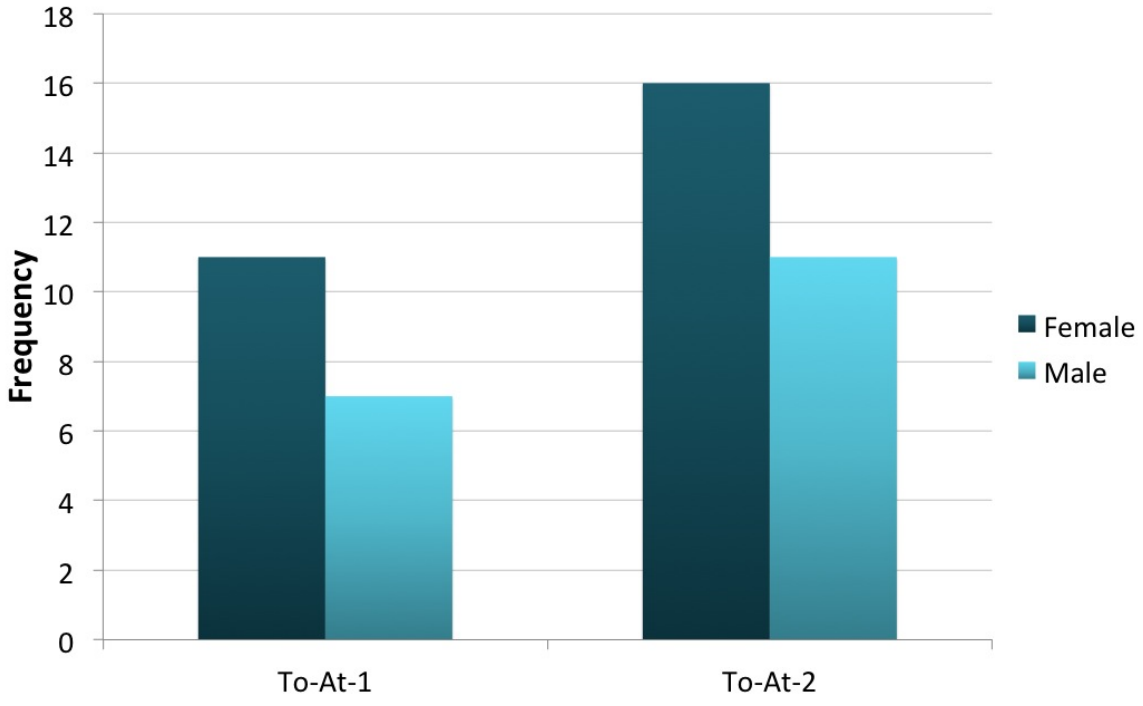


Figure 2.9. *Sex of individuals in 'Atele burial mounds.*

Chapter 3

Stable Isotope Analyses of Diet (δ^{13}C, δ^{15}N, and δ^{34}S)

First we eat. Then we do everything else.
M. F. K. Fisher

The main purposes of this chapter are to review the concepts of isotope analysis in bioarchaeological research, to present the isotope analyses used for paleodietary reconstruction, and discuss the interpretation of these analyses. The first section of this chapter summarises the basic principles of isotope analyses, focusing on the stable isotopes used for this portion of the study (carbon, nitrogen, and sulphur). The second part of this chapter reviews concepts of bone and tooth anatomy that relates to these isotope analyses (the isotopes and skeletal tissues relevant to understanding migration are reviewed in chapter 5). Then, the ways in which stable isotope analysis can be used to understand the diet of individuals excavated from archaeological sites is outlined. Issues regarding diagenesis, food webs, metabolic pathways, and other factors which alter isotopic compositions in animal tissue are explored. An overview of past isotope studies exploring prehistoric Pacific island diet is presented before the methodology used for this study is outlined, along with an explanation (and justification) of the statistical methods used for interpreting isotopic values. Finally, I present and briefly discuss the results specific to my paleodietary isotope analyses. These results are discussed in more detail, with the other lines of evidence ($^{87}Sr/^{86}Sr$ analysis, oral indicators of diet) integrated into a holistic discussion about diet and mobility, in the final two chapters of this thesis.

This chapter integrates substantial portions of the methods, results, and discussion sections from Stantis et al. (2015b) and Stantis et al. (2015a).

Table 3.1. *The isotopic compositions of the elements examined in this thesis. Some elements have more than two naturally occurring isotopes; only the isotopes used for this study are listed. From Berglund and Wieser (2011); Böhlke et al. (2005).*

Element	Isotope	Number of protons	Number of neutrons	Relative atomic mass	Natural abundance (%)
Carbon	^{12}C	6	6	12	98.93
	^{13}C	6	7	13.003354	1.07
Nitrogen	^{14}N	7	7	14.003074	99.64
	^{15}N	7	8	15.000109	0.36
Sulphur	^{32}S	16	16	31.972071	94.99
	^{34}S	16	17	33.967866	4.25

3.1 Principles of isotope analysis

Isotopes are atoms of an element which have the same number of protons and electrons but the number of neutrons differ (Sharp, 2007). The difference in the number of neutrons creates variation in atomic mass between isotopes (Table 3.1). Isotope analysis is based on the principle that isotopes of the same element, due to their difference in atomic mass, will behave differently during physical reactions (Hoefs, 2009). The chemical properties of these isotopes remain largely the same as chemical reactions generally involve electron activity rather than neutrons (Urey, 1947; Sharp, 2007)

Heavier isotopes have a lower vibrational frequency relative to lighter isotopes; this results in a proportional decrease of energy and velocity in the heavier isotope (Sharp, 2007). The lower energy results in stronger covalent bonding when the heavier isotope forms a molecule, but increases the amount of energy necessary for the molecule with the heavier isotope (the heavier *isotopologue*) to react. As such, lighter isotopologues preferentially diffuse out of a system, leaving the heavier isotopologues in the reservoir. These differences in reaction rates between isotopologues, also known as *kinetic isotope effects* or *fractionation*, dictate the ratio of isotopes in a sample. These differences in isotope ratios can be observed using a mass spectrometer (Hoefs, 2009).

Some isotopes are deemed *stable* as they are not known to undergo radioactive decay, a stochastic process resulting in an atomic loss of energy that can transform an atom into a different element (Hoefs, 2009). A classic example of radioactive isotopes is radiocarbon (^{14}C), which is constantly formed in the Earth's atmosphere by cosmic radiation and decays into stable ^{14}N. Understanding radiocarbon's rate of decay permits accurate dating of archaeological material (Libby, 1946). As stable isotopes do not

decay over time, the stable isotope ratio in an organism will remain constant after death (barring diagenetic effects). Most stable isotopes are *primordial*: they were created by cosmic forces and have existed in their current state since before the Earth was formed. Other stable isotopes are *radiogenic* (like ^{14}N) and were created by the radioactive decay of another nuclide but are not themselves radioactive (Hoefs, 2009).

3.1.1 δ and ‰: presenting isotopic data

Presenting isotope data as absolute isotope abundances tends to provide long, unwieldy ratios with no guarantee to the reader that the sample has been compared to international reference standards. In most studies, the absolute isotopic ratio is of less interest than knowing the differences between samples. To easily compare these differences, an equation is used and the result is designated by delta notation (δ). To determine the δ value of a sample, the isotopic composition of a sample is compared to the international reference standard (Stuiver and Polach, 1977; Rundel et al., 1989). This is done by presenting the ratio of the sample over the ratio of the international reference standard, and then multiplying by 1000:

$$\delta = \left(\frac{R_{sample}}{R_{standard}}\right) - 1 \times 1000‰ \tag{3.1}$$

For this study, R is $^{13}C/^{12}C$, $^{15}N/^{14}N$, or $^{34}S/^{32}S$. Since the fractionation processes typically cause very small changes in ratios, these isotope ratio values are reported as per mil, or parts per thousand (‰). A sample with a positive δ value contains more heavy isotopes relative to the international reference standard and a negative δ value indicates the sample has more lighter isotopes relative to the international reference standard (Hoefs, 2009).

3.1.2 Reference standards for isotope analysis

A standard is material of known isotopic value used as a reference to allow very precise comparisons within and between laboratories (Sharp, 2007). Two types of standards are used: international and internal.

International standards are samples used to calibrate isotopic compositions in laboratories to ensure reliable and accurate measurements for all researchers in the world. These agreed-upon international standards are very scarce (and very expensive), and not used in every-day laboratory procedures. The international standards are given a δ value of 0‰, and all other materials are measured against this value (Sharp, 2007).

Table 3.2. *International Reference Standards for Isotopic Analysis From Meier-Augenstein (2010).*

Element	**International reference standard material**	**Isotope ratio of international reference**
Carbon	VPDB (Vienna Pee Dee Belemnite)	0.0112372 $^{12/13}C$
Sulphur	VCDT (Vienna Cañon Diablo troilite)	0.0450045 $^{32/34}S$
Nitrogen	AIR (atmospheric gas)	0.0036765 $^{14/15}N$

The international standards relevant for this study are shown on Table 3.2. The first international reference standard for $\delta^{13}C$, Pee Dee Belemnite (PDB), was a Cretaceous-era fossil (*Belemnitella americana*) from the Pee Dee region of South Carolina, USA. Cañon Diablo troilite (CDT) was the iron sulphide portion of a meteorite from the Barringer Crater of Arizona, USA. CDT was used as an international standard for sulphur. Both international standards have been depleted for four decades (and the Cañon Diablo troilite had problems with isotopic homogeneity), so new standards have been created that are identical for practical purposes, named VPDB and VCDT (so named as the new standards were adopted at a conference in Vienna) (Gröning, 2004). AIR is the Earth's air, which has a constant $^{15}N/^{14}N$ ratio and has yet to be depleted (Junk and Svec, 1958).

Internal standards, or working standards, are samples of known isotopic composition in relation to international standards. Internal standards are available in greater quantity than international standards (and less expensive). By carefully calibrating the internal standards to the international standards, internal standards can be analysed alongside samples throughout day-to-day laboratory routines to ensure consistency of the analytical instruments and allow samples of unknown isotope composition to be compared to international standards (Taylor et al., 2004). Laboratories might purchase standards from chemical suppliers to ensure consistent purity, or provide references through other channels. For example, the NERC Isotope Geochemistry Laboratory in the United Kingdom uses two internal standards for oxygen isotope analysis: ACC-1, synthetic apatite acquired from the Aldrich Chemical Company, and SME, enamel from a mastodon tooth excavated by a researcher (Chenery et al., 2012). Generally, any material can be used as an internal standard as long as it is homogeneous and stable (Taylor et al., 2004). The internal standards used by the laboratories in which I conducted my analyses will be listed in the methodologies section of this chapter.

3.2 Skeletal biology

Isotope analysis could potentially be conducted using virtually any body tissue as almost all tissues reflect the diet and origin of the individual. However, due to the rarity of soft tissue survival in an archaeological setting, bone and teeth are most often sampled. In addition, as different tissues have different metabolic pathways, the relationship between the isotopic composition of an organism's diet and the isotopic composition of its tissue (the *diet-tissue spacing*) varies depending on the tissue (DeNiro and Epstein, 1981; DeNiro, 1987). Thus, it is imperative to understand the physiology of these tissues and how they reflect an individual's life and the diet-tissue spacing for calcified tissues has been extensively studied in laboratory settings (DeNiro and Epstein, 1978; Tieszen et al., 1983; Ambrose and Norr, 1993).

In order to maximise strength and resistance to deformation without brittleness and with minimal mass, osseous and dental tissues are heterogeneous materials composed of organic and inorganic matter (Ettinger et al., 2013). As the organic and inorganic matter are formed using different metabolic pathways, these materials must be separated when preparing samples for isotope analyses to ensure the stable isotope values are providing information about diet. The organic portion of skeletal tissue is composed primarily of collagen with other proteins, polysaccharides, and lipids present in smaller quantities (Suchanek and Yoshimura, 1998). Most collagen in skeletal tissue is Type I (Niyibizi and Eyre, 1994). Type I collagen, along with Types II, III, V, and XI, is categorised as fibrillar collagen (Viguet-Carrin et al., 2006). A key feature of fibrillar collagen is that it consists of a long, continuous triple helix with highly organised fibrils joining together end-to-end to form long fibres. This contributes to the high tensile strength of Type I collagen, which is invaluable in the skeleton's role of structural support of the body and teeth's ability to resist forces during mastication (Buehler, 2006).

The inorganic portion of skeletal tissue is mostly carbonated hydroxyapatite, a.k.a apatite or bioapatite (Currey, 2002). Hydroxyapatite ($Ca_5[PO_4]_3[OH]$) is the calcium-containing mineral constituent of bone and teeth. Carbonate ions, derived from bicarbonate (HCO_3^-) in the blood, often substitute the phosphate or hydroxide ions (Shore et al., 2013). Biological hydroxyapatite is less pure than most geological forms, with impurities of potassium, magnesium, strontium, sodium, and fluoride (Shore et al., 2013). During tissue formation, collagen fibres form and then become mineralised as the plate- or needle-shaped hydroxyapatite matrix is deposited parallel to the fibres (Palazzo et al., 2007; Kalita, 2008). This creates a stronger material than either of

the components on their own. Without collagen, bone and teeth are brittle and lose resistance to shearing or compressive forces (Viguet-Carrin et al., 2006); without mineral, skeletal tissue lacks the ability to resist deformation (Currey, 2002; Roschger et al., 2008).

As an added boon for bioarchaeologists, the mineral matrix can protect and preserve the organic portion of calcified tissues with little to no alteration over hundreds or even thousands of years depending on the burial environment (Dobberstein et al., 2009). Though collagen does not last as long as apatite on a geological timescale, it is resistant to degradation for up 200,000 years in some circumstances (Jones et al., 2001). With collagen's resistance to degradation, relative abundance in calcified tissue, and the presence of well-established collagen quality indicators (described below, section 3.3.1), the paleodietary isotope analyses conducted in this thesis use these proteinaceous portions of skeletal tissue. Extraction of this material (detailed in the methods section of this chapter) involves the denaturation of collagen, leading to the triple helix relaxing and unravelling; the final product, though often called "collagen," would be more properly referred to as "gelatin" or "protein remnants" (Brown et al., 1988; Brock et al., 2013) since the final product is a collection of protein aggregates that are mostly derived from collagen but also consists of some non-collagenous proteins. As described in the methodology section of this chapter, the use of ultra-filters helps reduce the amount of non-collagenous contaminants from the final sample before analysis (Brown et al., 1988).

Metabolic processes of collagen and apatite

Macronutrients (carbohydrates, lipids, and proteins) are preferentially routed to the synthesis of different body tissues, and thus isotope analysis using only one type of tissue (e.g. collagen) does not necessarily represent the whole diet (DeNiro and Epstein, 1978; Tieszen et al., 1983). Krueger and Sullivan (1984) suggest dietary carbohydrates and lipids are metabolised for energy and their carbon is used for mineral synthesis. Dietary amino acids are metabolised for collagen production (Krueger and Sullivan, 1984; Lee-Thorp et al., 1989). Modern routing models estimate that $\delta^{13}C_{collagen}$ is mostly derived from protein with a small contribution from carbohydrates and lipids (Fernandes et al., 2012). As such, isotope analysis of diet using collagen will yield information about the protein portion of diet, but low-protein foods may be under-represented (Ambrose and Norr, 1993).

The $\delta^{13}C$ values of the inorganic portion of skeletal tissue, bioapatite, is more representative of the whole diet (Ambrose and Norr, 1993). Carbonate in the inorganic

portion of skeletal tissue (substituted in the phosphate position of hydroxyapatite or adsorbed on crystal surfaces) represent dietary fats and carbohydrates (Lee-Thorp et al., 1989; Ambrose and Norr, 1993). The $\delta^{13}C$ of carbonate from dental apatite has yielded values closer to the isotopic composition of the whole diet in controlled studies (Balasse et al., 2003; Passey et al., 2005). However, as carbon is only found in hydroxyapatite when carbonate substitutes phosphate or hydroxide, the relative amount of carbon in bioapatite is much smaller than in collagen (Kalita, 2008) and thus more sensitive equipment (accelerator mass spectrometers or AMS) or larger samples of enamel are required to examine $\delta^{13}C$ values in apatite (Zazzo, 2014). There are also no means of determining tissue integrity as established as the collagen integrity indicators available (DeNiro, 1985; Ambrose, 1990; Ambrose and Norr, 1992; Nehlich and Richards, 2009). In addition, $\delta^{15}N$ and $\delta^{34}S$ analysis cannot be conducted using apatite as these elements are not in hydroxyapatite. As such, collagen sampling was chosen as the method of examining paleodiet instead of apatite for this study, though it is certainly an interesting avenue in future research.

3.2.1 Osseous tissue

Bone is roughly 10% water, 60% inorganic, and 30% organic by weight and 35% water, 40% inorganic, and 30% organic by volume (Shore et al., 2013). Calcium phosphate in the form of hydroxyapatite or amorphous calcium phosphate constitutes most of the inorganic material (Suchanek and Yoshimura, 1998) and 85–90% by weight of organic material is composed of collagen (Brock et al., 2013). Osseous tissue can be divided histologically into two types, cortical bone (a.k.a. compact bone) and cancellous bone (a.k.a. spongy or trabecular bone).

Cortical bone is so named as it forms the cortex (outer layer) of bones. In cortical bone, collagen fibres are arranged as thin plates (lamellae) in concentric rings around a Haversian canal which channels blood vessels and nerves (Thomson and Caballero, 1998). The dense, even microstructure of cortical bone makes it resistant to physical stress and is thus found in all parts of the skeleton that are subjected to higher physical stress: parts of the skeleton that provide leverage for movement or support (e.g. the shaft of long bones) or are key for protecting soft organs (e.g. the inner and outer layers of many cranial bones) (Shore et al., 2013).

Cancellous bone is found in the epiphyses of long bones, inside ribs and vertebral bodies, and enclosed between the cortical layers of flat bones. Cancellous bone is formed of open rod-like and sheet-like structures (trabeculae). Compared to cortical bone, trabeculae are less resistant to physical stresses compared to cortical bone on a

microstructural level (Rho et al., 1993). Cancellous bone is also less dense and contains more "open" space, though the heterogeneous nature of trabeculae distribution makes comparing bone strength between the two types of bone difficult (Currey, 2003). The non-bony spaces of trabecular bone are also more suitable for exchanging metabolic materials and holding red bone marrow for red blood cell production (Kieser, 2012).

Bone turnover

When the skeletal system is first taking shape, bone undergoes the process of *osteogenesis*. Osteogenesis occurs as two processes: endochondral and intramembranous (Boyce et al., 2013). During endochondral ossification, long bones are formed when osteoblasts replace a calcified hyaline cartilage mound with osseous tissue. In flat bones and during the radial growth of long bones, intramembranous ossification occurs via osteoblasts within vascular fibrous membrane sheets. In both instances, osteoblasts form trabeculae. Subsequent remodelling replaces the trabeculae with lamellar bone in certain parts of the skeletal system (Boyce et al., 2013).

After osteogenesis, bone is in a continuous process of resorption and remodelling, where the organic and inorganic portions are broken down into their component materials, dispersed, and then used to form new bone tissue (Kieser, 2012). By constantly rebuilding itself, bone can morphologically adapt to compressive and tensile stresses placed upon it, repair damage, and release stored minerals back into the bloodstream (Kieser, 2012). During remodelling, osteoclasts digest the old bone matrix in pockets or trenches along the bone surface. Osteoblasts then synthesize new layers of organic matrix which become mineralised before the osteoblasts become resting bone-lining cells (Boyce et al., 2013).

Through remodelling, collagen is constantly (albeit slowly) replaced in bone throughout a person's life. Due to the remodelling process, bone collagen is not representative of the diet consumed by an individual when the bone was first formed but within the last years of their life. The ^{14}C bomb peak (the increased concentration of atmospheric radiocarbon after nuclear weapons testing in the 1950s and 1960s C.E.) can serve as a reference point to try to understand the exact rates of collagen turnover (Hedges et al., 2007). Hedges et al. (2007) found that adult human femoral mid-shafts had a collagen turnover of $\leq$4% per year. As such, collagen from the femur represents an average of roughly the last ten years of life. Adolescent (10–15 years of age) turnover was faster, 5–15%/year. Both Geyh (2001) and Hedges et al. (2007) noted that, in addition to age, individual variation affected turnover rates. Szulc et al. (2000) caution that variation in turnover rates in subadults can be affected by malnutrition, premature

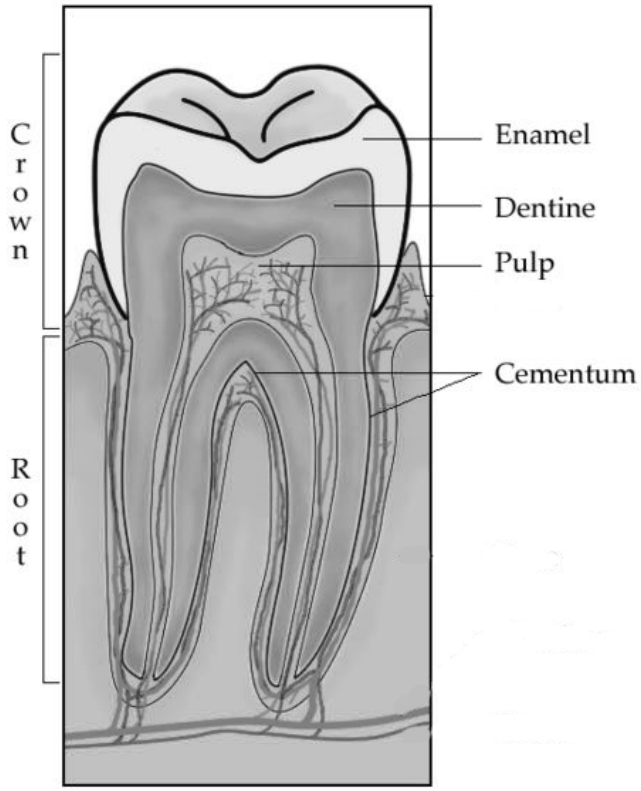


Figure 3.1. *Cross-section of a tooth, with different tissues (enamel, dentine, cementum, and pulp) and anatomical areas (crown and root) labelled. Original digital image by Sam Fentress licensed under CC BY-SA 2.0.*

growth, and disease. Bone collagen turnover is greatly increased in subadults relative to adults: the bones of infants and young children undergo complete turnover in less than a year (Bryant and Loutit, 1964; Rivera, 1965; Szulc et al., 2000). Geyh (2001) found a turnover of less than 1.5% per year in those above 19 years of age and a faster turnover in adolescents (under 19) around 5%/year.

3.2.2 Dental tissue

Teeth are composed of four different tissues: enamel, dentine, cementum, and pulp (Figure 3.1). Cementum and pulp are not used in isotope analyses and will not be further described. Enamel is largely inorganic (Hillson, 1996) and not suitable for collagen analysis. However, enamel is used for $^{87}Sr/^{86}Sr$ analysis in this thesis and will be discussed in the chapter focusing on isotope analysis of movement (Chapter 5).

Dentine is approximately 20% organic, 10% water, and 70% mineral by weight and 30% organic, 20–25% water, and 40–45% mineral by volume (Hillson, 1996). Primary

dentine is formed between enamel and the pulp chamber in the crown, and between the cementum and pulp chamber in the root. During dentinogenesis, cells known as odontoblasts secrete dentine until the tooth becomes functional or the apex closes (Linde and Goldberg, 1993). Unlike bone, primary dentine does not remodel once tooth formation is complete (Hillson, 1996). Approximately 90% of the organic portion of primary dentine is type I collagen (Goldberg et al., 2011). After primary dentinogenesis, odontoblasts continue to secrete secondary dentine throughout life at a slower rate (Nanci, 2013). Secondary dentine is peripheral to the pulp chamber, filling the area where the pulp was as the pulp chamber recedes through a person's lifetime. Tertiary dentine is reactive to physical insults to the tooth, whether from carious lesions, attrition, or trauma (Nanci, 2013). Care must be taken to avoid including secondary or tertiary dentine when sampling for isotopic research as examining primary dentine provides information about a person's childhood, while secondary and tertiary dentine complicate those results (Sealy et al., 1995).

3.3 Diagenesis of collagen

The two component types of calcified tissues (organic and mineral) undergo different processes of *diagenesis*, the alteration of the chemical and physical properties of material over time due to processes within the environment (Goffer, 2007). The main factors involved in the diagenesis of organic materials, namely collagen, will be briefly outlined in this section. In Chapter 5, diagenesis as it relates to apatite will be discussed as $^{87}Sr/^{86}Sr$ analysis utilises the mineral component of bone.

The main cause of organic loss in ancient bone appears to be microbial attacks from microorganisms in the soil (Hedges, 2002). Bones buried in waterlogged anoxic environments (such as bogs) and extremely cold environments may not experience microbial activity (Child, 1995a,b). Microbial enzymes might not degrade collagen on their own, but the restructuring and demineralisation of the inorganic portions may leave collagen susceptible to degradation. In warm environments and over time, collagen is also vulnerable to temperature-related degradation (Hedges, 2002). While generalities about time and location in relation to diagenetic processes can be forwarded, there is high variability in the intensity of diagenetic processes even when these factors are recognised (Sandford, 1993). Small-scale variations in soil geochemistry and physiological variation between skeletons can also greatly affect the extent of diagenesis within a site (Radosevich, 1993).

While the sites examined in this thesis come from late prehistory and so have been

exposed to the environment for a relatively short period of time (approximately 750 years maximum), the heat and humidity in the tropical Pacific could have altered the collagen from the skeletal remains so that isotope analyses do not yield meaningful results. There are a few methods of determining collagen integrity when conducting stable isotope analyses that were used in this study, and these will be outlined in the methodology section (below).

3.3.1 Methods for assessing collagen preservation

In order to ensure the isotope analysis results from purified collagen are reliable, accurate, and not altered by contamination, several methods have been developed to assess collagen preservation.

A common method of assessing collagen preservation is collagen yield. Collagen yield is the percent mass of purified collagen compared to the original sample mass:

$$Collagen\ Yield\ \% = \frac{mass\ purified\ collagen}{mass\ original\ sample} \times 100\% \tag{3.2}$$

The original sample mass is measured just before the demineralisation step with HCl, and the purified collagen is measured after freeze-drying. It is assumed small collagen yields are indicative of collagen degradation (Ambrose, 1990). While straightforward, this method of assessing collagen preservation is problematic. Due to the ultrafiltration steps of the modified Longin method used in this study, the collagen yield will be much smaller than should be expected (Jørkov et al., 2007; Müldner and Richards, 2007). Collagen yields were not used to assess collagen preservation in this study. Instead, other methods were used in this study to test collagen preservation: %C, %N, and %S by weight (Ambrose, 1990; Ambrose and Norr, 1992; Nehlich and Richards, 2009) and atomic C:N ratio, C:S ratio, and N:S ratio (DeNiro, 1985; Richards et al., 2001; Nehlich and Richards, 2009). All of these methods require no extra analytical procedures; all of this information is provided from elemental analysis conducted just prior to mass spectrometer analysis.

The first method developed for assessing collagen integrity is still among the most trusted: the ratio of the mass of carbon to the mass of nitrogen, or C/N ratio (DeNiro, 1985). Atomic ratios are determined by dividing the percentages by weight of two atomic elements in the sample and then multiplying by the atomic weight ratio. For

example, one can determine the C:N ratio using this equation:

$$\frac{Carbon}{Nitrogen} = \frac{\frac{\%_C}{\%_N}}{\frac{AtomicWeight_C}{AtomicWeight_N}} = \frac{\%_C}{\%_N} \times 1.1\overline{66} \tag{3.3}$$

Similar equations determine C:S and N:S (Nehlich and Richards, 2009). DeNiro (1985) observed that fresh bone had a C/N ratio within 2.9 and 3.6 and posited that archaeological samples within that range will be adequately preserved. Higher ratios may be indicative of carbon rich/ nitrogen poor humic soil contamination and lower C/N ratios are likely the result of ammonia and other amines (Masters, 1987). Modern collagen displays C/S ratios of approximately 780, although ancient samples can be expected to display lower ratios (Richards et al., 2001). C:S ratios of 600 ±300, N:S ratios of 200±100, and a %S by weight of 0.15–0.35% are criteria for acceptable sulphur results of mammal bone Nehlich and Richards (2009).

Determining percentage by weight is a straightforward procedure; the % element by weight for each sample is measured then compared to the normal range of modern bone. Any samples outside of the normal range of variation are considered for exclusion; modern bone samples have %C values between 15% and 47%, and %N values fall between 5% to 17% (Ambrose, 1990; Ambrose and Norr, 1992). Poorly preserved and/or contaminated archaeological samples will have %C and %N values outside of these ranges. Percentage by weight of sulphur in modern mammalian bones was 2.8% ±0.07 although significant differences in the percentage of sulphur could be observed between marine and terrestrial mammals (Nehlich and Richards, 2009).

3.4 Interpreting paleodiet using stable isotope analyses

3.4.1 Food webs

The complex feeding connections present in an ecological community could be depicted as a food chain, where an autotrophic species (any organism which can produce biomass from light energy or chemical energy) is consumed by a primary heterotroph who is consumed by a secondary heterotroph and so on. A food web, an interconnected and elaborate depiction of predator-prey relationships, is composed of all the known food chains in an environment and better depicts the complex connections between species. Understanding how food webs can differ in varying environments (especially between terrestrial and marine environments) aids with interpretation of isotope analyses (Zanden and Rasmussen, 2001). Ecologists have been using isotope analyses to understand food

webs for decades (Rundel et al., 1992; Boecklen et al., 2011). As with ecological studies, bioarchaeological studies using isotope analyses aim to place the organism studied within the feeding connections in an ecological community.

Placing an organism within a food web involves establishing its trophic level: understanding what it eats and who eats it (e.g. Cortés, 1999; Borrell et al., 2011). In a simple food chain, autotrophs (a.k.a. primary producers) are the first trophic level, with herbivorous species on the second trophic level, the carnivores that eat the herbivores are on the third, and the apex predators that eat the third-level carnivores are on the fourth. The trophic level can continue on as long as the food chain continues. Trophic level is usually not so simple in actual ecological communities (Polis, 1991; Williams and Martinez, 2004). For example, omnivorous species occupy multiple trophic levels by consuming both autotrophic and heterotrophic species, two species may consume each other, and juveniles of a species may eat at a different trophic level from its adult form (Pimm and Lawton, 1978).

There is a fractionation effect between the isotopic compositions of what an organism consumes and its own tissues (DeNiro and Epstein, 1978, 1981; Tieszen et al., 1983; Tieszen and Boutton, 1989). Understanding the extent of isotopic enrichment for the different dietary isotopes (discussed for each isotope, below) allows researchers to place an organism within a food web.

Marine environment food webs

As humans are often within both terrestrial and marine food webs, understanding the differences between these two ecological systems is necessary to explore prehistoric human diet. Isotopic analyses can differentiate between marine and terrestrial foods, as will be explained below. There are two key differences between terrestrial and marine food webs. First, primary producers vary greatly between marine and terrestrial environments (Roff, 2013). Terrestrial autotrophs tend to be large in size with large lifespans and slow growth. Large portions of their biomass are typically conserved from the feeding chains (e.g. wood in trees). Marine primary producers, compared to terrestrial primary producers, are typically smaller (microscopic in the case of many phytoplanktons), consumed wholly (whether phytoplanktons or macrophytic marine plants) and have a short lifespan and quicker reproductive rate (Roff, 2013). The second key difference is that marine food webs tend to be larger and more complicated then terrestrial food webs, containing more trophic levels (Roff, 2013). This is especially true in pelagic zones (open waters not near the shore or near the ocean floor), where there tend to be several levels of carnivorous animals feeding off the lower levels (Roff, 2013).

3.4.2 Carbon ($\delta^{13}C$)

Trophic level

The difference between autotrophs and the whole body of herbivores averages about 1‰, but due to fractionation within an animal's body, bone collagen from herbivores will generally display $\delta^{13}C$ values around 5‰ higher than the plants they ate (DeNiro and Epstein, 1978; Tieszen et al., 1983). There are small amounts of trophic level spacing in animals; bone collagen from a carnivore is expected to have a carbon isotopic composition between 0‰ and 2‰ higher than the herbivores it consumes, but this spacing is too small to use $\delta^{13}C$ analysis to examine trophic level variation except in controlled studies (Bocherens and Drucker, 2003). With so little stepwise enrichment between trophic levels, carbon isotope analysis can instead be used to understand other aspects of a food web, such as what type of primary producers are forming the basis of a given ecosystem (Schoeninger and DeNiro, 1984).

Photosynthetic pathways

Carbon primarily enters the food web through primary producers, and thus most of the differences in $\delta^{13}C$ values between food webs arise from the varying $\delta^{13}C$ values of primary producers (Lee-Thorp et al., 1989; Sharp, 2007). The most drastic differences result from how plants conduct carbon fixation, the process of converting carbon dioxide from the air to organic compounds. Different species of terrestrial plants have acquired varying biochemical pathways for improving the amount of carbon captured during respiration. The three types of carbon fixation are: C_3, C_4, and CAM. In the 1960s it was noted that radiocarbon dating maize was providing dates inconsistent with other plant material (Hall, 1967). It was determined that maize exhibits different carbon isotope ratios from many other plants in the United States, because most local plants are C_3 while maize is a C_4 plant. The different ways in which plants fixate carbon is a major reason for variation in $\delta^{13}C$ values between different types of terrestrial autotrophs.

C_3 plants use the Calvin cycle to fixate carbon (Bassham et al., 1950). During the Calvin cycle, ^{12}C-containing CO_2 is preferentially routed into the plant through the stomata due to the slower movement of the heavier ^{13}C. ^{13}C-containing CO_2 is further discriminated in C_3 plants during the carboxylation of RuBP (ribulose-1,5-bisphosphate) by the enzyme RuBisCo (ribulose bisphosphate carboxylase/oxygenase) (Marshall et al., 2007). The significant isotope separation in C_3 plants results in a typical $\delta^{13}C$ range between -33 to -23‰ (Sharp, 2007, 155).

However, plants using the Calvin cycle have a problem: as temperatures increase, the enzyme RuBisCo increasingly causes the oxygenation of RuBP rather than carboxylation (Sharkey, 1988). The release of CO_2 and resulting increased stomatal conductance results in increased water loss, a deleterious consequence in hot and/or arid environments (Raines, 2006). In 1966, an alternative to the Calvin pathway was discovered using $^{14}CO_2$ as an isotopic tracer through leaf segments of sugar cane: the C_4 pathway (Hatch and Slack, 1966). Unlike the three-carbon acid RuBP in the C_3 pathway, the C_4 pathway (sometimes called the Hatch-Slack pathway) produces four-carbon acids such as oxaloacetate and malate. These four-carbon acids concentrate CO_2 during photosynthesis, minimising photorespiration and water loss. The increase in plant fitness explains why, even though only about 0.32% of extant terrestrial plant species are C_4 plants, they contribute approximately 18% of global oxygen production (Sage, 1999). C_4 plants dominate tropical and savannah landscapes; however, the C_4 pathway is less energy efficient, so areas with cooler climates tend to mostly be populated with C_3 plants. The C_4 pathway causes less depletion of the heavier ^{13}C isotope, resulting in a typical $\delta^{13}C$ range between -16 to -9‰ (Sharp, 2007, 155).

Crassulacean acid metabolism, or CAM, is the third type of carbon fixation in terrestrial plants. Photosynthesis can be divided into two separate reactions: a light-dependent reaction (which requires light energy to create chemical energy) and a light-independent reaction. At night, the stomata of CAM plants open to allow carbon dioxide to enter during the light-independent reaction and produce 4-carbon acids (Yamori et al., 2014). The carbon dioxide-containing acids are stored in the plant cells until day, when they are released and the light-dependent reaction involving a C_3-like metabolism takes place. CAM is especially suited for arid climates as the stomata close during the day to prevent excess water loss and thus many succulents use the CAM pathway (Ranson and Thomas, 1960). As CAM plants alternate between two types of photosynthetic reactions, they display a wide range of $\delta^{13}C$ values, between -10‰ and -20‰ (Pérez-Harguindeguy et al., 2013). This carbon stable isotope range makes it difficult to distinguish between CAM plants and C_3/C_4 plants within an ecosystem when using solely $\delta^{13}C$ analysis (O'Leary, 1988; Marshall et al., 2007; Pérez-Harguindeguy et al., 2013).

Marine flora follow C_3 or C_4 pathways, but as marine autotrophs rely more on the ocean's carbon reservoir rather than atmospheric carbon, they display different $\delta^{13}C$ values compared to terrestrial plants. The ocean's carbon reservoir in the form of bicarbonate has a higher $\delta^{13}C$ value compared to atmospheric CO_2: Hoefs (2009) reports dissolved ocean carbon at 0±3‰ compared to the atmospheric value of -9±2‰,

while Schwarcz and Schoeninger (2012) describe marine flora as generally 7‰ higher than terrestrial flora. This enrichment places marine flora generally between C_3 and C_4 plants, overlapping terrestrial C_4 ranges (Kelly, 2000; Sharp, 2007). Due to this large difference in carbon isotope compositions between marine and terrestrial food systems, many of the first isotope studies of past humans focused on understanding the role of marine foods in prehistoric diet (Chishom et al., 1982; Schoeninger et al., 1983).

Differentiating between food from freshwater environments and other environments is difficult. Freshwater food webs draw from a variety of carbon sources including atmospheric CO_2, dissolved CO_2, bicarbonate from the soil, and carbon from organic detritus (Zohary et al., 1994). Freshwater fish bones have yielded $\delta^{13}C$ values between -12.9 and -24.6‰ (Katzenberg and Weber, 1999).

The differences in isotopic composition between marine and terrestrial plants allows researchers to examine the relative proportions of these types of foods in paleodietary analysis, although caution must be taken when studying people who may have been consuming C_4 plants. The inclusion of both C_4 plants and aquatic organisms in a diet shifts the carbon isotopic composition of a person's tissue towards a higher $\delta^{13}C$ value compared to a C_3-based diet, so shifts cannot be solely attributed to either of these plant types (Chisholm et al., 1983). There are only two C_4 plants in the Pacific that may have been consumed by prehistoric people, sea grapes (*Cawlerpa racemosa*) and sugar cane (*Saccharum officinarum*), and neither are dietary staples in the prehistoric Pacific though some researchers have predicted high sugarcane consumption as the cause of less negative $\delta^{13}C$ values in some sites (Ambrose et al., 1997). With no ethnographic accounts of Tongans or Fijians consuming high proportions of these foods, any patterns toward higher values in this study may be cautiously attributed to marine organism consumption rather than C_4 plants or terrestrial animals who eat C_4 plants.

Other factors influencing plant $\delta^{13}C$ values

Plant-environment interactions are complex, and there are secondary effects on $\delta^{13}C$ values to consider beyond photosynthetic pathways. In a forest environment, a vertical ^{13}C gradient exists in which canopy plants exhibit up to 5‰ higher $\delta^{13}C$ values than ground plants (Broadmeadow and Griffiths, 1993; Bonafini et al., 2013). The causes behind this phenomenon are not known, though reassimiliation of ^{13}C depleted CO_2 by plants below the canopy has been hypothesised (Bonal et al., 2000; Dawson et al., 2002). Light density may also influence the carbon isotopic composition of plants, with plants in lower light environments displaying lower $\delta^{13}C$ values (Ehleringer and Cerling, 2001). This trend is known as the *canopy effect* and causes significantly different $\delta^{13}C$

values between forest plants and those in open areas (Heaton, 1999; Krigbaum, 2005). This effect has even been utilised for paleoenvironmental studies in Paleolithic Europe to determine whether herbivores were living in closed canopy systems or in open plant environments (Bocherens et al., 1999).

Climate also influences the $\delta^{13}C$ values of plants, thus affecting the $\delta^{13}C$ values of the entire food web in a given area. Climatic conditions such as temperature, rainfall, and humidity have been shown to influence the $\delta^{13}C$ values of Holocene-era charcoal, wood, and bone samples from Europe (van Klinken et al., 1994, 2000). The relationships between $\delta^{13}C$ and climate were small, approximately 0.18‰ per ℃ and -0.06 per % humidity in bone samples (van Klinken et al., 1994, 447), but climatic variation on a larger temporal and/or spatial scale could theoretically cause wider isotope variation. Plants grown in drier soils or soils with higher salinity tend to display higher $\delta^{13}C$ values (Tieszen, 1991). Altitude is another factor affecting $\delta^{13}C$ values in plants. Decreasing air pressure causes increased uptake efficiency of carbon dioxide, causing higher $\delta^{13}C$ values in alpine plants compared to lowland plants of the same genus (Körner et al., 1988).

3.4.3 Nitrogen ($\delta^{15}N$)

Nitrogen typically enters an ecosystem in one of two ways. The first is via nitrogen fixation, the process wherein relatively inert atmospheric N_2 is converted into more reactive molecules such as ammonium (NH_4^+) or nitrate (NO_3^-) (Keeney and Hatfield, 2001). Prokarya that can fixate nitrogen are known as *diazotrophs*. Diazotrophs in marine and freshwater environments tend to be colony-forming cyanobacteria (Bergman et al., 2013). Many terrestrial species of diazotrophs are in a symbiotic relationship with plants, often forming colonies in root nodules and providing nitrates for their host (Fisher and Newton, 2002). The most common hosts (known as nitrogen-fixing plants) are from the family *Fabaceae*, which includes peas, beans, soybeans, and clover. Non-nitrogen-fixing plants have to rely on a second form of nitrogen transfer: the breakdown of nitrogen-containing matter in the soil by free-living bacteria (Schoeninger and Moore, 1992). Nitrogen-fixing plants display $\delta^{15}N$ values +2‰ higher than non-nitrogen-fixing plants on average, though the values tend to overlap (Virginia and Delwiche, 1982; Schoeninger and Moore, 1992).

Primary producers express a wide variety of $\delta^{15}N$ values due to nitrogen-fixation, differences in the nitrogen composition of different soils, and the systematic enrichment of deep-rooted plants compared to short-rooted plants; values between -8‰ and +18‰ have been reported (Kelly, 2000). There are differences when examining the average

$\delta^{15}N$ values between marine phytoplankton and terrestrial plants (+7‰ and +3‰ respectively), but the ranges overlap (Schoeninger and DeNiro, 1984; Ambrose and Norr, 1993). Thus, it is difficult to use nitrogen stable isotope analysis to understand the different proportions of primary producers in the same manner as carbon stable isotope analysis (and one of the reasons it is so beneficial to conduct carbon and nitrogen stable isotope analyses in conjunction).

The main utility of nitrogen isotope analysis is for understanding the trophic level of an organism (Kelly, 2000). The primary source of nitrogen for most animals is from dietary protein. Due to fractionation within the body, an animal's $\delta^{15}N$ value is approximately 3–6‰ higher than the food it eats (DeNiro and Epstein, 1981; Minagawa and Wada, 1984). Thus, herbivores will have a $\delta^{15}N$ value 3‰ higher than the average $\delta^{15}N$ of the plants it eats, while the carnivore that eats the herbivore will have a value approximately 6–12‰ higher than the plants the herbivore ate; an omnivore who eats both plants and the original herbivorous species will fall in between the other two animals. As such, stepwise enrichment can be observed between $\delta^{15}N$ values and trophic level when plotting a baseline within an ecosystem.

There have been controlled diet studies indicating a wide range of variation in the degree of stepwise enrichment; diet-collagen enrichment has been suggested by researchers as falling anywhere between +1.5‰ to 6‰ (Bocherens and Drucker, 2003; Perkins et al., 2014). Given the range of variation, it is best not to treat 3‰ or any other value as definite spaces in a food chain. Instead, 3–6‰ will be used as a general guideline.

This phenomenon allows one to determine the trophic level of an animal using stable nitrogen isotope analysis (DeNiro and Epstein, 1981; Minagawa and Wada, 1984). As marine ecosystems tend to have more trophic levels than terrestrial ecosystems and the $\delta^{15}N$ value of marine primary producers is slightly higher than terrestrial primary producers, one can differentiate between marine and terrestrial diets. While there is some overlap in $\delta^{13}C$ values between marine and terrestrial animals, Schoeninger and DeNiro (1984) found that carnivorous terrestrial animals display an average $\delta^{15}N$ value of 8.0‰, while carnivorous marine animals display an average $\delta^{15}N$ value of 16.5‰, with no overlap in range, demonstrating the utility of differentiating between marine and terrestrial ecosystems.

Stress factors may also affect $\delta^{15}N$ values. Increased water stress in mammals may increase the $\delta^{15}N$ values in their tissue (Ambrose and DeNiro, 1986; Ambrose, 1991, 1993), though this theory has been questioned (Hartman, 2011). Extreme nutritional stress can also increase $\delta^{15}N$ values in mammals as the body may catabolise its own

proteins when there is insufficient dietary protein (Hobson et al., 1993; Hatch, 2012; Reitsema, 2013). Robertson et al. (2014), when analysing the $\delta^{13}C$ and $\delta^{15}N$ values of collagen and $\delta^{13}C$ values of apatite in rats fed 45% of their ad libitum diet, found a significant increase in $\delta^{15}N$ values but no significant change in $\delta^{13}C$ values within their bone collagen. However, the rationed group's mean $\delta^{15}N$ values in Robertson et al.'s study were only 0.1‰ elevated compared to the control group.

Similarly, Hatch et al. (2006) found no nitrogen enrichment among people with bulimia and demonstrates that sufficient protein intake, even in incredibly restricted diets, does not result in catabolisation. Elevated $\delta^{15}N$ have been found in animals living in especially cold climates (Fernández-Mosquera et al., 2001), though aridity may have been the underlying cause. Waters-Rist and Katzenberg (2010) theorised that different rates of growth could potentially affect $\delta^{15}N$ values in subadults, affecting diet-to-tissue spacing and subsequently rendering the interpretation of infant and young child feeding practices difficult. However, Waters-Rist and Katzenberg (2010) found that growth stress appears to have no effect on $\delta^{15}N$ values, as evidenced by comparing the $\delta^{15}N$ values of diaphyses, metaphyses, and epiphyses in subadults and finding no significant differences.

3.4.4 Sulphur ($\delta^{34}S$)

Carbon and nitrogen isotopes are typically studied together in order to understand diet in a comprehensive manner (e.g. Ambrose, 1990; DeNiro and Epstein, 1981). Unlike carbon and nitrogen, there is little isotopic discrimination during sulphur uptake in autotrophs; primary producers will have essentially the same $\delta^{34}S$ values as their sulphur source (Kennedy and Krouse, 1990; Trust and Fry, 1992). The sulphur sources of different types of plants (i.e. marine, terrestrial, and freshwater), however, vary greatly in isotopic composition, and studies are proving that sulphur isotope analysis is another useful tool to help differentiate between the consumption of marine, terrestrial, and freshwater foods in past populations (Richards et al., 2001, 2003; Craig et al., 2006; Privat et al., 2007; Buchardt et al., 2007; Nehlich et al., 2010, 2011; Kinaston et al., 2013b, 2014a).

Marine autotrophs display $\delta^{34}S$ values similar to the oceanic sulphate reservoir (+20.99‰), between +17 to +21‰ (Rees et al., 1978; Peterson and Fry, 1987). Terrestrial plants draw upon sulphur in the soil, underlying bedrock and atmosphere and will display more $\delta^{34}S$ variation than marine plants, typically within a range of -5 to +10‰ (Peterson and Fry, 1987; Nriagu et al., 1991). Sea-spray (salt-water aerosols from crashing waves or high winds) and marine-derived precipitation may alter $\delta^{34}S$

values in coastal regions, creating homogeneous "marine" values in human tissue even when terrestrial foods are the main form of subsistence (Richards et al., 2001). By examining δ^{13}C and δ^{15}N values simultaneously with δ^{34}S values, differentiating between sea-spray effect and marine diet is feasible. Freshwater plants vary greatly and produce values roughly analogous to terrestrial primary producers, making comparison between freshwater and other food sources difficult (Peterson and Fry, 1987; Privat et al., 2007). Interestingly, plants in mangrove marshes can display δ^{34}S values 20‰ lower than the aqueous sulphate (Nriagu et al., 1991); this is attributed to preferential uptake of sedimentary sulphides by estuarine plants (Fry et al., 1982).

Sulphur is present in animals in the amino acid methionine, which contributes about 0.46% of collagen by weight in animal bone (there is another sulphur-containing amino acid, cysteine, but it is only present in trace amounts in bone collagen) (Brosnan and Brosnan, 2006). As animals display roughly the same δ^{34}S values as the foods they eat (Peterson et al., 1985; Peterson and Fry, 1987; McCutchan et al., 2003), sulphur analysis is not useful for understanding trophic levels like nitrogen analysis, but it is a relatively straightforward process to trace an animal's sulphur isotope value back to their environment.

3.4.5 Breastfeeding and weaning

The most common method used for understanding the feeding practices of infants and young children in the past is nitrogen stable isotope analysis (Tsutaya and Yoneda, 2015). Milk from lactating mammals has a similar nitrogen isotopic composition to their flesh, 3.0–3.6‰ higher than their diet (Steele and Daniel, 1978). As such, a subadult consuming its mother's breast milk is one trophic level higher than her own tissues. Due to this stepwise nitrogen enrichment, breastfeeding practices and age-at-weaning can be extrapolated from nitrogen isotope analysis (Dupras and Tocheri, 2007; Williams et al., 2005).

Stepwise nitrogen enrichment from being breastfed has been confirmed in living populations. Fogel et al. (1997) demonstrated isotopic shifts from breastfeeding through the analysis of fingernail clippings from mother and infant pairs. Breastfeeding infants displayed 3‰ higher δ^{15}N values than their mothers on average. These differences were not observed by Fogel et al. (1997) until the infants were two to three months of age, which was linked to the time necessary for nails to grow from cuticle to fingertip. When infants were introduced to complementary foods, the isotopic values declined to within 1‰ above their mothers' δ^{15}N values. Fuller et al. (2006) confirmed Fogel et al's findings using hair and fingernail samples in infants who were exclusively breastfeeding,

Figure 3.2. *Expected curve of $\delta^{15}N$ values when examining breastfeeding and weaning practices. Explanation of letters below in-text. Adapted from Schurr, 1997, 920.*

exclusively formula-feeding, or mixed-feeding. Exclusively breastfed infants displayed the +3‰ δ^{15}N and +1‰ δ^{13}C values expected in infants one trophic level higher than their mothers, while exclusively formula fed infants displayed no significant differences in isotopic composition compared to their mothers. The stable nitrogen isotope values of mixed-feeding infants fell somewhere in-between breastfed and non-breastfed infants.

Katzenberg et al. (1993) conducted the first study of prehistoric humans to observe elevated δ^{15}N values in infants relative to the adult population, and many others have utilised nitrogen isotope analysis to understand infant and young child feeding practices and death (e.g. Schurr, 1997; Fogel et al., 1997; Prowse et al., 2008; Kinaston et al., 2009). Contrary to the findings of Fuller et al. (2006), several archaeological studies of subadults have found infant δ^{15}N values indistinguishable to the population or adult female mean (Jay et al., 2008; Kinaston et al., 2009; Tsutaya et al., 2013). *In utero* stress and/or restricted diets were hypothesised by the researchers as the underlying causes in these archaeological sites, although little is known about how isotopic values are affected by foetal and perinatal stress.

Schurr (1997, 920) provides a thorough review of the factors that create an idealised breastfeeding and weaning curve (seen on Figure 3.2). He points out that newborns should have bone collagen isotopic compositions similar to their mothers (point *A* on the graph). The initial high slope of the curve (*B*) is created as protein turnover replaces that synthesised *in utero* with protein synthesised while breastfeeding. If the whole

body protein turnover rate remains fairly constant, the upcurve and downcurve (C) will be similar, provided weaning were an instantaneous event (i.e. breastmilk were completely replaced by other foods in one event). If not (which is often the case), the slope of the weaning curve would be affected by the rate of weaning and the isotopic compositions of the replacement/complementary foods. The equilibrium level (D) at the right end of the curve would be determined by the childhood diet after weaning is complete and may or may not be similar to the adult $\delta^{15}N$ mean (Schurr, 1997). By plotting the $\delta^{15}N_{bone}$ values and estimated age-at-death of subadults in an assemblage, the general pattern of the weaning process can be estimated.

Carbon isotope analysis has also been used to examine the types of complementary foods used during weaning. If the complementary foods were different types of food from those in a typical adult's diet, weaning children will have displayed different $\delta^{13}C$ values as well as elevated $\delta^{15}N$ values. Katzenberg et al. (1993) used carbon isotope analysis in their study, where elevated $\delta^{13}C$ values in infants relative to the adult population were interpreted to be from using maize (*Zea mays*) as a complementary food in a prehistoric southern Ontario population.

In this thesis, both carbon and nitrogen isotope analyses will be examined in infants and young children to understanding feeding practices in prehistoric Tonga. Sulphur stable isotope analysis will also be used for understanding the types of complementary foods introduced during the weaning process. With no infants or young children in Bourewa, the reconstruction of prehistoric Fijian breastfeeding and weaning practices cannot be explored using the available assemblage from this site.

There are several issues when trying to recreate age of weaning in a population using bone collagen from infants and young children. First, these are subadults who died during childhood and may not have experienced weaning and feeding practises similar to those who survived (Lewis, 2007). The issue that non-survivors of childhood may have different diets to those who survived is the basis of the ninth hypothesis of this thesis.

Second, the creation of a weaning profile using cross-sectional data relies on the accuracy of ageing methods for precision (Reynard and Tuross, 2015). Ageing skeletal material using epiphyseal fusion, long bone length, and dental development has a degree of error (Scheuer and Black, 2000). If the ageing error is not directional (i.e. does not consistently age younger or older than their chronological age), then a large enough sample size will correct the standard error. It is difficult to arrive at a minimum number of samples to account for ageing error, but the 21 infants and young children in the ʻAtele assemblage is most definitely not large enough.

An important assumption when reconstructing weaning patterns in prehistoric populations is that the methods used to estimate age are accurate and reliable (Reynard and Tuross, 2015). This assumption is important when considering any age-based differences, but the finer scale of examination required when reconstructing weaning patterns compared to what is necessary for investigating adult age groups differences (a scale of months and years rather than decades) makes accurate and reliable age estimation methods all the more important. There is a general paucity of ageing standards specific for non-European subadults (Halcrow et al., 2007) and there are currently no ageing standards specific to Pacific or Polynesian populations. The possibility of inaccurate estimations due to populational differences is understood, but this issue cannot be remedied within this thesis.

3.4.6 Establishing a dietary baseline

When interpreting paleodiet, it is important to establish a dietary baseline specific to the region of interest. There are slight but significant variations around the globe for carbon, nitrogen, and sulphur isotope values of plant and animal life due to variable rainfall, soil conditions, climate, and other factors (Casey and Post, 2011). The difference in carbon and nitrogen values has even been used to consider childhood place of origin in past populations (Schroeder et al., 2009), and the highly varied sulphur values in environments have been utilised in ecological studies to track human and animal migrations and diet (Peterson et al., 1985; Hesslein et al., 1991; Thomas and Cahoon, 1993; Richards et al., 2001).

A dietary baseline is created by analysing the stable isotope values of plants and animals that may have constituted part of the local human diet from a region. These floral and faunal samples can come from modern sources or archaeological excavations. Modern species might be altered by fertilisers, pollution, and other anthropogenic soil contaminants, and care must be taken not to sample species that were not present in the past. Alternatively, archaeological samples may be difficult to obtain due to poor preservation. Regardless of provenance, samples are usually taken from the edible portions of plants and the bones of animals that would have been consumed by the population being studied.

Modern samples are also affected by changes of the carbon isotopic ratios in the Earth's carbon cycle due to recent anthropogenic activity (Keeling, 1979). Essentially, carbon emissions, radioactive decay, and other human activities have changed the carbon isotopic ratios in the Earth's carbon reservoirs and all modern terrestrial samples will display carbon values 1.5‰ lower than pre-Industrial samples; this is known as the

Suess effect (Tans et al., 1979). The oceanic carbon reservoir is more resistant to change, and modern marine organisms display smaller changes than pre-Industrial samples (0.86‰) (Tieszen, 1991; Beavan Athfield et al., 2008). The Suess effect needs to be corrected for when integrating modern plant and animal species into a dietary baseline.

Archaeologically derived faunal samples are often only calcified tissues due to the degradation of soft tissues. Additionally, sometimes bone is easier to collect and preserve in the field for dietary baseline than flesh. Since it is typically the flesh of an animal that humans consume, the isotopic ratios from the collagen samples can be converted into the tissues consumed in order to create comparable units if interpreting the whole diet. Mammalian bone collagen displays $\delta^{13}C$ values 2‰ higher than flesh (Lee-Thorp et al., 1989). There are no discernible differences in the $\delta^{15}N$ values between flesh and bone (DeNiro and Epstein, 1981; Sealy et al., 1987). The differences in sulphur isotopic composition between tissues, like the variation between trophic levels, is small (Peterson et al., 1985; Richards et al., 2001). Fish tissues undergo different depletion effects compared to mammals (Beavan Athfield et al., 2008). Nitrogen and sulphur isotopic composition still changes a negligible amount, but Beavan Athfield et al. (2008) alter fish bone isotopic values to flesh by converting the $\delta^{13}C$value -3.7‰ . These values are not absolute, and there is variation between species, local biogeochemistry, and individual organism biochemistry (Layman et al., 2012).

Another way of placing human bone values within the local foodweb is to leave the faunal bone stable isotope values unaltered, and adjust the human bone values for trophic level, approximately -1‰ for $\delta^{13}C$ and -3‰ for $\delta^{15}N$. With this method, all bone values in the dietary baseline do not need to be altered, which removes the additional level of error introduced by adjusting all bone collagen values for flesh-to-bone corrections and then diet-to-tissue spacing. The inclusion of bone collagen values of animals can serve as dietary proxies. Kinaston et al. (2014b) and Kinaston et al. (2014a) achieve this by including fruit bat bone samples that represent the stable isotope values of a mammal consuming an entirely terrestrial diet, and marine organisms (reef fish, deep water fish, and sea turtles) consuming entirely marine-based diets on various trophic levels. This method of placing prehistoric humans within their environment will be used here.

There are a few studies that have isotopically analysed archaeologically-derived material to form a dietary baseline (Allen and Craig, 2009; Field et al., 2009). A large body of modern dietary baseline data for the tropical Pacific are also available (e.g. Fry et al., 1983; Ambrose et al., 1997; Yoshinaga et al., 1991, 1996; Leach et al., 2003; Beavan Athfield et al., 2008; Jones and Quinn, 2009; Valentin et al., 2010). However,

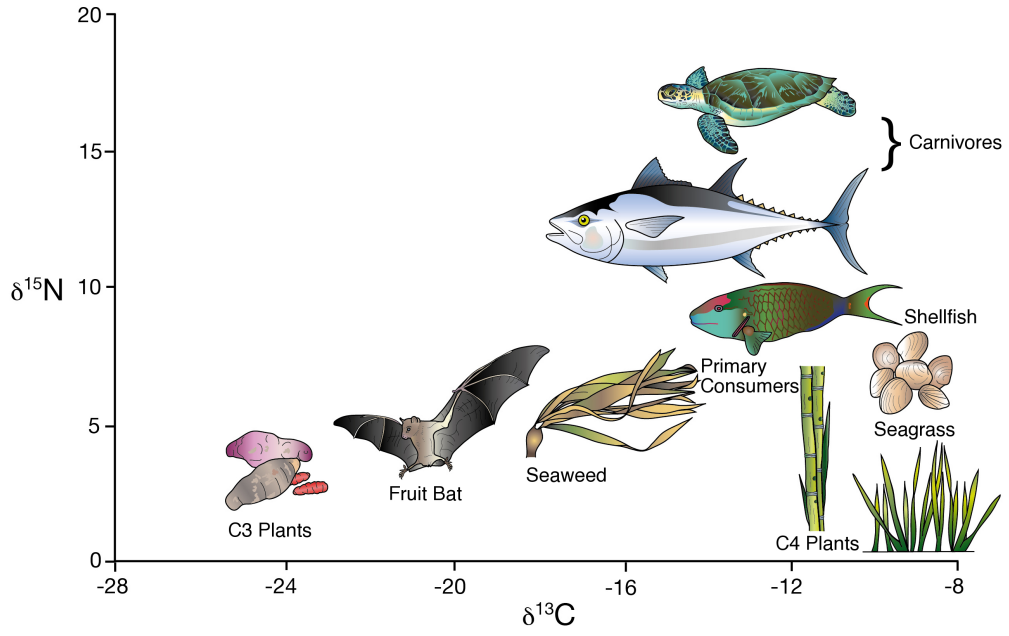


Figure 3.3. *Illustration of the typical food web $\delta^{13}C$ and $\delta^{15}N$ values in Remote Oceania. Data from Kinaston et al. (2014b), illustration by Robbie McPhee.*

using these baseline data must be done with caution as these studies did not include defatting protocols or are unclear about their defatting protocols. While some reviews have found small differences between bone samples that underwent lipid extraction protocols and those that did not (Kelly, 2000), analysing only one tissue type is critical due to different metabolic fractionation between lipids, proteins, and carbohydrates (Sotiropoulos et al., 2004; Kiljunen et al., 2006; Kinaston et al., 2013b). Furthermore, the acquisition of many of the samples were from New Zealand where fertilisers could have been used which make these samples doubly unsuitable for the creation of a baseline (Leach et al., 2003).

Establishing a comprehensive dietary baseline requires sampling dozens of flora and fauna; this is outside the scope of this thesis. However, an opportunity arose during my studies to collect some baseline samples from the island of Atiu in the Cook Islands. The data from these samples and from previously published research with similar defatting protocols (Kinaston et al., 2014b) can be used to quantify the foodweb structure of the tropical Pacific (Figure 3.3).

Following Kinaston et al. (2014b), marine organisms (i.e. fish, seaweed, turtle) and freshwater fish from previous tropical Pacific island baseline studies using modern and archaeologically-derived samples (Leach et al., 2003; Ambrose et al., 1997; Allen and

Craig, 2009; Field et al., 2009; Richards et al., 2009; Casu et al., 2009; Yoshinaga et al., 1991) were also included in the aggregated baseline used to place the Bourewa and 'Atele individuals within the foodweb. This was necessary as the modern plant and animal samples collected for this study and in Kinaston et al. (2014b) did not include very many aquatic organisms. The baseline data from Kinaston et al. (2014b) and the data from this study will be statistically compared in this chapter to explore whether the data are similar or if the ecologies found in tropical Pacific islands are too variable to use aggregated baseline data.

3.4.7 Techniques for placing consumers in the food web

There are complex analytical techniques for placing consumers within their food web such as linear mixing models (notably IsoSource, Phillips et al., 2005) and Bayesian mixing models (e.g. Moore and Semmens, 2008). The analytical approaches that can be used for dietary studies are thoroughly reviewed by Layman et al. (2012). The use of these types of models have had success in some isotope analyses of past human groups (e.g. Beavan Athfield et al., 2008; Coltrain and Janetski, 2013; Colonese et al., 2014; Arcini et al., 2014). These models require large bodies of baseline dietary data (Layman et al., 2012) and cannot be supported with the current corpus of tropical Pacific island baseline data. In order to address this thesis' aims, we do not require the proportion estimations of certain foods consumed that modelling provides. Instead, the Bourewa and 'Atele individuals will be examined within the available baseline data, and their place in the foodweb will be inferred with qualitative assessments and comparisons of the assemblages to past stable isotope studies of prehistoric Pacific people.

3.5 Paleodietary reconstruction using stable isotope analyses in Fiji/West Polynesia

Isotopic analyses of prehistoric human diet in Oceania are a growing field. Kinaston and Buckley (2013) provide a thorough review of the published literature that has used isotope analyses of archaeologically-derived human remains throughout the Pacific. I will briefly review all stable isotope studies that have been conducted on populations from Fiji and Western Polynesia, as well as any studies conducted after Kinaston and Buckley (2013). The Fijian and Western Polynesian studies are summarised in Table 3.3.

The first study to use paleodietary isotope analysis on Fijian/ Western Polynesian

Table 3.3. *Paleodietary isotope studies of prehistoric Fiji and Western Polynesia. Modified from Kinaston (2010,42)*

Reference	Analyses	Site(s)	Location(s)	Time Frame (BP)	Sample Size	Comparisons analysed?
Leach et al. (2003)	$\delta^{13}C$, $\delta^{15}N$, & $\delta^{34}S$	To-At-1 and To-At-2	Tongatapu, Tonga	500–200	8 (To-At-1) 12 (To-At-2)	
Leach et al. (2003)	$\delta^{13}C$, $\delta^{15}N$, & $\delta^{34}S$	Wakea, Qaranipuqa rock shelter	Lakeba, Fiji	2600–500	4 (2 from each site)	
Leach et al. (2003)	$\delta^{13}C$, $\delta^{15}N$, & $\delta^{34}S$	Natunuku	Viti Levu, Fiji	c. 2000	1	
Leach et al. (2003)	$\delta^{13}C$, $\delta^{15}N$, & $\delta^{34}S$	To-Pe-1	Tongatapu, Tonga	prehistoric Post-Lapita	1	
Leach et al. (2003)	$\delta^{13}C$, $\delta^{15}N$, & $\delta^{34}S$	Sigatoka	Viti Levu, Fiji		1	
Valentin et al. (2006)	$\delta^{13}C$, $\delta^{15}N$	Korotuku burial mound	Cikobia, Fiji	c. 150	9	Sex, status
Field et al. (2009)	$\delta^{13}C$, $\delta^{15}N$	Y2-39 and Y2-25	Waya Island, Fiji	2758–2503 (Y2-25) 760–250 (Y2-39)	14 human samples	Temporal, spatial
Field et al. (2009)	$\delta^{13}C$, $\delta^{15}N$	Nokonoko and Bukusia	Viti Levu, Fiji	1500–280 (Nokonoko), 527–4 (Bukusia)	3 human samples	Temporal, spatial
Jones (2009)	$\delta^{13}C$, $\delta^{15}N$, & $\delta^{13}C_{apatite}$	Seven sites from four islands	Lau Island Group, Fiji	2760–420	9	Temporal
Kinaston (2010)	$\delta^{13}C$, $\delta^{15}N$, & $\delta^{34}S$	Six sites from four island groups	Papua New Guinea, Vanuatu, Solomon Islands	3200–300	251	Temporal, spatial, sex, age
Valentin et al. (2011)	$\delta^{13}C$, $\delta^{15}N$	Three sites	Tutuila, Samoa	1000–150	14	Temporal, spatial
Phaff (2012)	$\delta^{13}C$, $\delta^{15}N$	Sigatoka	Viti Levu, Fiji	1750–150	23	Temporal
Kinaston et al. (2013c)	$\delta^{13}C$, $\delta^{15}N$, & $\delta^{34}S$	Namu burial ground	Taumako, Solomon Islands	750–300	99	Sex, age
Fenner et al. (2015)	$\delta^{13}C$, $\delta^{15}N$, & $\delta^{13}C_{apatite}$	J28 and To-At-36	Tongatapu, Tonga	late prehistoric/ protohistoric	12 (J28) 5 (To-At-36)	Spatial, status

prehistoric individuals was Leach et al. (2003). Leach et al. (2003) conducted a wide sampling strategy, analysing $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ on individuals from 21 assemblages throughout the Pacific. Nineteen individuals from the 'Atele assemblage were included, as well as the Tongatapu site of To-Pe-1 (originally designated To-1 by Poulson, 1987). Fijian individuals from the Sigatoka Sand Dunes and Natunuku sites on Viti Levu and sites on Lakeba Island were also included. While these sites were compared visually to the other Pacific assemblages, no statistical comparisons were conducted. Instead, most of Leach et al.'s (2003) study focused on dietary reconstruction using the New Zealand assemblages analysed.

Nitrogen isotope analysis was conducted on the cortical bone of nineteen individuals from 'Atele, and three of those nineteen were also analysed for carbon and sulphur by Leach et al. (2003). Unfortunately, the carbon, nitrogen, and sulphur analyses for the 'Atele individuals by Leach et al. were conducted in different laboratories, and so reliable indicators of collagen integrity (described in detail in the methodology section, below) cannot be determined from their published data. In addition, most of the nitrogen results from 'Atele individuals by Leach and colleagues analysed whole bone powder rather than purified collagen (as this study used) and are thus doubly incomparable. As such, these previous analyses were not used, and all 'Atele individuals with cortical bone present for sampling were analysed in this study.

A study of nine individuals, possibly elites, from Cikobia Islands, Fiji (c. 150 BP) found no differences in isotopic values between the sexes (Valentin et al., 2006). The Fijians displayed $\delta^{13}C$ and $\delta^{15}N$ values consistent with a diet mostly consisting of terrestrial C_3 plants with a significant contribution of marine foods. This was interpreted as consistent with a high-status diet, although Kinaston and Buckley (2013) point out that no comparisons were made by Valentin et al. (2006) between these supposed elites and any Fijian commoner burials.

Field et al. (2009) reported the isotopic compositions ($\delta^{13}C$, $\delta^{15}N$) of human bone from Waya Island and Viti Levu, Fiji. The bones sampled were all found as "incidental encounters" when excavating middens and fortifications, not systematic excavations of burial sites (p. 1548). As such, Table 3.3 lists these as "samples" rather than individuals as commingling may have been an issue. When examining temporal changes in diet, Field et al. (2009) found a shift to an increased reliance on horticultural foods rather than marine resources. Though the samples collected by Field et al. (2009) were small in number, this subsistence pattern corroborates with findings from other parts of the tropical Pacific (Kinaston et al., 2014a).

Jones (2009) proposed that dietary reconstruction from isotope analysis implies

a diet unlike that suggested by traditional archaeological and ethnographic research from the Lau Islands: the prehistoric Lauans seem to have relied heavily on root crops (approximately 60% of total diet), with inshore marine and terrestrial animal foods providing the remainder rather than a large proportion of the diet coming from offshore resources. They also note temporal shifts in dietary proportions with the earlier group displaying a greater reliance on marine resources. Resource depletion related to climatic shifts was cited as the underlying cause of these dietary changes (Jones, 2009).

Kinaston's PhD thesis (2010) is the largest examination of prehistoric Pacific individuals after Leach et al. (2003). With assemblages spanning thousands of years and just as many kilometres, comparing the diet of Lapita-associated individuals with post-Lapita diet in the Western Pacific Islands was one of the main aims of Kinaston's study. The largest post-Lapita assemblage in her study is the Namu burial ground from the Polynesian Outlier, Taumako (Solomon Islands). $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ analyses (n = 114 bones, 72 teeth) reveal a high reliance on marine foods in all assemblages. In the Taumako assemblage, Kinaston found no differences in the bone or tooth collagen isotopic results between the sexes or adult age groups (Young and Mid/old combined). The tooth collagen (from the apical half of first molar roots) displayed significantly lower $\delta^{13}C$ values than adult bone collagen. Subadults aged four years and above display significantly lower $\delta^{15}N$ and higher $\delta^{34}S$ values than the adult cohort. Kinaston posited that the older subadults may have been consuming less animal protein or more protein from a very different source. Though the sample size of those aged $\leq$0 years of age is too small for reliable statistical testing ($n = 4$), these infants display higher $\delta^{13}C$ and $\delta^{15}N$ values than the females in the assemblage. Kinaston postulated these values in infants as a potential consequence of *in utero* stress.

Petchey et al. (2011) re-analyse several Pacific samples from the Leach et al. (2003) study and other studies of Papua New Guinea and New Caledonia sites. The main focus of Petchey et al.'s (2011) study was not paleodietary reconstruction, but the examination of how the consumption of marine foods affect radiocarbon dating. As the samples analysed by Petchey were repeated analyses of the Leach et al. (2003) data, they are not included in Table 3.3.

Valentin et al. (2011) provide the only isotope study to date to examine prehistoric Samoa. Fourteen individuals (11 adults, 2 young children, 1 child) excavated from three sites on Tutuila, the largest island of the Samoan Islands archipelago, were analysed. The two young children (both approximately two years of age) display elevated $\delta^{15}N$ values compared to the others, most likely as a result of breastfeeding. Three distinct sites with different occupation histories (c. 1000 BP, 500 BP, and 250 BP) are examined,

though the sample size was too small to make any meaningful comparisons.

An unpublished master's thesis, Phaff (2012) examined diet in the individuals from the Sigatoka Sand Dunes on Viti Levu, Fiji using δ^{13}C and δ^{15}N analysis. The assemblage spans several phases of Fijian occupation, from the Plainware to the Ra phases (c. 1750–150 BP). Though Phaff compared status groups, she did not use inferential statistics to compare groups. She also did not use inferential statistics to compare males and females, although she asserted that there are no differences between them as determined by isotope analyses. Using data from Phaff's dissertation and the demographic information from Visser (1994), there are no differences between the sexes regarding δ^{13}C, $t(13) = 0.14$, $p = 0.893$, or δ^{15}N, $t(13) = -0.38$, $p = 0.710$.

Kinaston et al. (2013b) analysed 99 adults from the Taumako assemblage (the 80 adults Kinaston examined in her 2010 thesis and an additional 19 samples collected after). Kinaston et al. explore sex-, age-, and status-related differences using δ^{13}C δ^{15}N and δ^{34}S values alongside a "wealth index," a processual-style enumeration of grave goods created by Leach and Davidson (2008) and used for status or rank differentiation. Males from Taumako appear to have eaten from higher trophic levels (as evidenced by significantly higher δ^{15}N values) and higher status individuals (the top 20% as scored using the wealth index) displayed significantly higher δ^{13}C and δ^{15}N values, regardless of sex. These dietary differences were interpreted as the consumption of valued meat products such as pelagic fish, marine turtle, and pig. This is the first published isotope study to examine δ^{34}S values in prehistoric Polynesia (though Kinaston et al., 2013a was the first in the prehistoric Pacific). Unlike δ^{13}C and δ^{15}N values, δ^{34}S displayed no sex- or status-related trends in the Taumako site. There is a significant, negative correlation between δ^{34}S and % sulphur by weight in the Taumako samples, which Kinaston et al. (2013b) interpret as diagenetic alteration. Volcanic deposition is suggested as the cause, and Kinaston et al. (2013b) caution that their samples were within the acceptable parameters for sample integrity proposed by Nehlich and Richards (2009). No other study has examined the relationship with δ^{34}S and % sulphur by weight.

While Kinaston et al. (2013c) explored diet within the temperate Pacific (New Zealand) rather than the tropical Pacific, their study identified Polynesian adaptation strategies in island environments. The Wairau Bar site examined by Kinaston et al. (2013c) contains individuals from the earliest settlement period of New Zealand. The individuals from Group 2/3 (the later burials) consumed a wider range of foods as evidenced by more variable δ^{13}C and δ^{15}N bone collagen values. Group 1 may have been a founding population, and Group 2/3 practised a more diverse subsistence pattern as they increased their range from the initial settlement area to other parts of the

island and began consuming more wild food plants available in New Zealand. The mobility data ($^{87}Sr/^{86}Sr$ analysis) also supports this (Kinaston et al., 2013c), and will be discussed more in Chapter 5.

Though $\delta^{13}C$ values in apatite have been analysed previously (Bentley et al., 2007), Kinaston et al. (2014b) used $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ ratios from bone collagen from 49 individuals excavated from the site of Teouma. Located on Efate Island in Vanuatu, Teouma is the oldest-known Pacific cemetery (c. 3000 BP) (Bedford et al., 2009). Kinaston et al. (2014b) compared the $\delta^{13}C$ and $\delta^{15}N$ results from Teouma to previous studies (Ambrose et al., 1997; Valentin et al., 2006; Kinaston et al., 2013b), the Teouma individuals displayed a relatively wider range of values, suggesting more broad spectrum foraging. When comparing the sexes, males displayed significantly higher $\delta^{15}N$ values and a wider range of values. This more variable diet with higher trophic level protein in males was evaluated by Kinaston et al. (2014b) as possibly being a result of sexual division of food acquisition, or the preferential distribution of more socially-valued animal flesh to men.

The small island of Uripiv (<1 km^2) in Vanuatu provided burials from all periods of prehistoric/ early historic human occupation (c. 3000–150 BP) for paleodietary reconstruction (Kinaston et al., 2014a). Kinaston et al. (2014a) compared the Uripiv individuals to the early Lapita burials from the Vanuatu site of Teouma (the oldest cemetery in the Pacific). The Uripiv individuals from all time periods consumed a greater proportion of terrestrial foods compared to those from Teouma, as evidenced by the significantly higher $\delta^{15}N$ and $\delta^{13}C$ values in Teouma individuals. There was a pattern of decreasing $\delta^{13}C$ and $\delta^{15}N$ bone collagen values as time progressed on Uripiv, suggestive of increasing reliance on terrestrial foods. This pattern is identified by Kinaston et al. (2014a) as supporting the archaeological model of settlement patterns in the Pacific, where horticultural practices became more established as time progressed.

The most recent isotopic investigation in human paleodiet comes from the same island as To-At-1 and To-At-2, Tongatapu (Fenner et al., 2015). Fenner et al. (2015) examined two burial mounds. J28 (traditionally known as Aponima) is a stone-slab lined tomb in Lapaha, on the northeast part of the island. Lapaha was the central place of rule during the Chiefdom Period, and the district is home to several *langi* and other structures for chiefly use (Clark et al., 2008). AMS dating places those interred in J28 as late prehistoric/protohistoric (c. 290–150 BP). Following the same logic as Davidson (1969) employed for ‘Atele, the lack of oral tradition regarding J28 led Fenner et al. (2015) to posit that the earlier dates are more likely. The second burial mound, To-At-36, is located near the ‘Atele College in the same general area as To-At-1 and

To-At-2 (Fenner et al., 2015). Like J28 and To-At-1 and To-At-2, there is no community knowledge of who is interred in To-At-36. Structurally, To-At-36 is similar to To-At-1 in that it is a low earth mound 1m high (compared to To-At-1's 80 cm height) and 20 m in diameter (compared to To-At-1's 40 m) (Fenner et al., 2015). AMS dating has not been conducted on those interred in To-At-36, but the initial excavator of the site (Dirk H. R. Spenneman) places the construction of the mound sometime within the last 700 years, during the Chiefdom Period (Spennemann, 1989). With J28 and To-At-36 appeared to be a *langi* and a *fa'itoka*, respectively, Fenner et al. (2015) compare the two as an opportunity to compare potential elite and non-elite individuals.

Fenner et al. (2015) found no differences in $\delta^{13}C_{bone}$, $\delta^{15}N_{bone}$or $\delta^{13}C_{apatite}$ between J28 and To-At-36. $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ analyses were also conducted, and will be described in the chapter on movement. Fenner and colleagues concluded that status did not affect diet in prehistoric Tonga. J28 and To-At-36 were combined and compared to Leach et al.'s (2003) 'Atele data, despite the issues with the Leach et al. data as outlined above. No differences in $\delta^{13}C_{bone}$ values between the two mound groups (To-At-1/2 and J28/To-At-36) were found by Fenner et al. (2015), but To-At-1 and -2 did display significantly higher $\delta^{15}N$ values, about 1‰ higher. These results were tied into the vastly different $^{87}Sr/^{86}Sr$ ratios between the mounds and interpreted as To-At-1 and To-At-2 potentially interring exclusively immigrants who consumed a different diet from locals. The interpretation of To-At-1 and -2 individuals as immigrants will be discussed more in section 5.4.

3.6 Methodology

All sample preparation for the 'Atele collection was carried out personally. For the Bourewa assemblage, I conducted the dentine collagen preparation and the bone collagen was prepared by Dr. Rebecca L. Kinaston (RLK) using the same protocol. I also performed the baseline sample preparation for the Cook Islands samples. All sample preparation for the 'Atele collection and dentine collagen preparation was conducted at the University of Otago Department of Anatomy. Bone collagen preparation for Bourewa was conducted by RLK at the Max Planck Institute for Evolutionary Anthropology (Leipzig, Germany).

Mass spectrometer analysis was conducted at two different laboratories. The 'Atele samples and Bourewa bone collagen were analysed at the Max Planck Institute for Evolutionary Anthropology. The Bourewa dentine and baseline samples, prepared later, were analysed by Iso-Analytical Limited (Cheshire, United Kingdom) when scheduling

conflicts made analysis at Max Planck difficult. Sulphur stable isotope analysis was not conducted for the Bourewa collection.

3.6.1 Choosing, isolating, and cleaning bone samples

The first step of sample preparation was isolating the material from the skeleton that was sampled. The goal was to isolate one bone sample and one tooth from every individual, but this proved impossible due to differential preservation. From the 'Atele collection, bones were sampled from 93 individuals and teeth were sampled from 43 individuals. From the Bourewa assemblage, 21 bones and 16 teeth were sampled from 24 individuals total. Table 3.4 displays the demographic information of the individuals sampled for bone and teeth. This information was presented in Chapter 2, but is repeated here for clarity.

Bones displaying evidence of pathologies were avoided, as changes in the metabolic pathways of diseased tissues may alter the isotopic composition (Katzenberg and Lovell, 1999; Olsen et al., 2014). Any bones displaying evidence of any adhesive were avoided whenever practical to prevent contamination. For the Tongan individuals, ribs were primarily chosen. There are three reasons for using ribs:

- They are generally present
- They are easy to work with in later stages of sample preparation due to their simple three dimensional shape
- If the articular surfaces and sternal ends are not included, ribs are usually of little use to other bioarchaeological research

If there were no ribs present, long bone fragments were sampled.

After photographing the bones, they were either broken by hand or cut with a Dremel® 300 Series rotary tool with a 545 Diamond Wheel. It was preferred to break by hand or with a hammer, because cutting the bone with a rotary tool results in burning of the collagen due to the heat the wheel generates. This destroys the collagen along the cut. This complication, combined with the inherent loss of material when abrading through the bone with a rotary tool, results in the loss of a larger amount of bone than if broken with a hammer or by hand. The diamond wheel, collet, and collet nut of the Dremel® were all sonicated in distilled water for three minutes in between samples to prevent contamination. The rotary tool itself was wiped down with ethanol (70% v/v) between samples. The work area was lined with aluminium foil, which was replaced between samples.

Table 3.4. *Demographic distribution of bones and teeth sampled for paleodietary analysis.*

	# of bones sampled	# of teeth sampled
Sex		
Bourewa females	7	6
Bourewa males	4	3
ʻAtele females	23	23
To-At-1	9	10
To-At-2	14	13
ʻAtele males	18	9
To-At-1	7	5
To-At-2	11	4
Adult/Subadult		
Bourewa adult	18	
Bourewa subadult	1	
Tonga adult	49	
To-At-1	17	
To-At-2	32	
Tonga subadult	33	
To-At-1	20	
To-At-2	13	
Adult age groups		
Bourewa young	2	2
Bourewa middle	2	2
Bourewa old	4	1
ʻAtele young	15	14
To-At-1	8	8
To-At-2	7	6
ʻAtele middle	10	8
To-At-1	5	4
To-At-2	5	4
ʻAtele old	7	4
To-At-1	0	0
To-At-2	7	4
Total		
Bourewa	23	16
ʻAtele	93	43
To-At-1	38	21
To-At-2	47	22

Special care was taken when finding suitable samples from the ‘Atele collection due to handling by past researchers. Many bone fragments were glued using cyanoacrylate adhesives and/or taped together with masking tape. These contaminants will add their own unique isotopic values if included (Moore et al., 1989), so avoidance of samples with glue or tape was a necessity. Unfortunately, three long bone samples (To-At-1/11, To-At-1/16, and To-At-1/07) were sawed before realising that glue was bonded to the broken end of the shaft. For these three samples, a Dremel® 109 Engraving Cutter was used to remove the glue. The cutter, collet and collet nut were cleaned in the same manner as the diamond wheel, above.

The bones were then sandblasted using a BEGO EasyBlast sandblaster with Shera Aluminium Oxide (99.7% purity, 110my grain size) at a pressure of 3 bar. Sandblasting removed the outside layer of bone, which may have impurities from taphonomic processes that occurred during burial. Sandblasting also served to remove any India ink that marked the burial designation on some ‘Atele bones. Once the bones were cleaned by sandblasting, collagen extraction could begin.

3.6.2 Choosing, isolating, and cleaning tooth samples

For the tooth samples, I chose and cleaned the teeth for both assemblages. Several criteria were considered when choosing a tooth for isotope analysis. I wanted to choose teeth whose roots were forming roughly between five and ten years of age. Permanent second molars (maxillary or mandibular, any side) were preferentially chosen as the primary sample over any other tooth type. If second molars were not available, permanent premolars (second, then first) were chosen, followed by first molars. Permanent second molars and the premolars have similar formation and eruption times (Hillson, 1996). First molars form earlier than second molars and premolars. Deciduous teeth were excluded from this study, as deciduous teeth begin formation in utero (Hillson, 1996) and would be influenced by the maternal isotopic composition (Wright and Schwarcz, 1998).

For first molars, the root half ($R_{1/2}$) with the apex (A) was used for isotope analysis; for the premolars and second molar I used the $R_{1/2}$ closer to the cementoenamel junction (CEJ). This created a roughly equivalent time span captured in each root, as seen on Table 3.5. While some bioarchaeological and zooarchaeological studies have used smaller increments of dentine to examine smaller age ranges (Zazzo et al., 2006; Britton et al., 2011), I chose to forgo serial section sampling for this project. That approach would not have provided more information about diet on a population level or between population groups.

No isolated teeth were used for sampling to prevent multiple sampling of the same individual. For the 'Atele collection, the individuals without any contextual information were excluded. Only teeth with fully formed roots were used for this study; as such, only individuals approximately 11 years of age and older were included in isotopic sampling.

Teeth with visible cracks and heavy wear were excluded from candidacy for isotope analysis due to risk of soil contamination. Teeth with signs of serious trauma or gross carious lesions (advanced dental carious lesions that have destroyed a large portion of the tooth) were excluded on the basis that tertiary dentine formation would be a present contaminant. While teeth without glue were preferred, previous researchers had glued many of the 'Atele teeth using cyanoacrylate adhesives. As some individuals only had teeth glued into the sockets, the presence of adhesive could not be a cause for exclusion. Teeth with minimal amounts of glue were chosen in these cases.

Like the bone samples, teeth were photographed for preservation. Unlike the bones, tooth crowns were also moulded using Kerr Take 1® Advanced™ vinylpolysiloxane (VPS) impression material. This high-resolution moulding material will allow future researchers to conduct microwear analysis on the teeth. After moulding, the outer surface of the tooth root was ablated with a 109 Engraving Cutter using a Dremel® 300 Series rotary tool in order to remove soil, cementum, and glue. Then, the tooth was cut at the CEJ with a 545 Diamond Wheel. The root was then cut in half with the diamond wheel. The root half to be used for carbon and nitrogen analysis was sonicated in distilled H_2O for three minutes while the crown was put aside for $^{87}Sr/^{86}Sr$ sampling. All leftover tooth material was bagged and returned with the rest of the skeletal material in the original box. Contamination reduction procedures concerning the work area and rotary tool were identical to those followed during bone sampling. Photographing, moulding, and cutting of the tooth roots were conducted in the University of Otago Anthropology Laboratory.

Table 3.5. *Sampling plan for tooth roots. Each tooth type included in the isotope analysis had different areas sampled to create age ranges as close together as possible (Hillson, 1996).*

Tooth type	Area sampled	Expected age range (years)
1st Premolar	CEJ–$R_{1/2}$	6.4–9.3
2nd Premolar	CEJ–$R_{1/2}$	7.3–10.1
1st Molar	$R_{1/2}$–A	5.5–8.5
2nd Molar	CEJ–$R_{1/2}$	7.6–10.6

3.6.3 Collagen extraction

In all but the oldest of bone, age is of little consequence when considering collagen diagenesis (Dobberstein et al., 2009). Rather, humic contaminants due to interment in the soil and contamination from preservation procedures such as glue are the main causes of concern; removal of contaminants is of utmost importance prior to putting samples through a mass spectrometer. For this study, collagen extraction and purification were carried out using the Longin method (1971) as modified by Brown et al. (1988) and Collins and Galley (1998).

The samples were weighed, and 1200–1400 mg of each sample was put in a 50 mL labelled glass test tube. Although the samples can be powdered for quick demineralisation, intact collagen fibres are more likely to be retained in non-powder form (Schoeninger et al., 1989; Collins and Galley, 1998). Thus, the samples were kept in as large of pieces as would fit in the test tube. Samples that would not readily fit in the test tube were broken with a hammer. Demineralisation and the removal of carbonates, phosphates, and fulvic acids from the samples occurred by soaking samples in 15 mL of 0.5 M HCl at 4 °C under an aluminium foil "tent" (to prevent contamination) until demineralised. Replacement of the acid occurred every 48 hours until the demineralisation process was complete. EDTA could be used in place of HCl for the demineralisation step (Jiang et al., 2007), but HCl demineralises tissue quicker and requires less replacement steps. In addition, HCl has the added bonus of causing swelling of the collagen matrix and increasing Type I collagen's solubility (Collins and Galley, 1998).

The samples were determined to be ready for the next step by visual examination. According to Kinaston (2010, 86), sample demineralisation is determined by examining the solution and sample. The sample may be completely demineralised if it is:

- Soft and pliable when gently probed.
- Floating, rather than lying at the bottom of the test tube.
- Slightly translucent.

Additionally, a solution surrounding completely demineralised material will be:

- Still, rather than bubbling, as there is no longer any inorganic matter for the HCl to react with (this sign needs to be interpreted cautiously, as it may simply be the case that the HCl has been "exhausted" and needs to be replaced)
- Clear, rather than yellow-brown and/or cloudy. Murkiness indicates dissolved inorganic material.

After demineralisation, the samples were rinsed three times in distilled water so as to remove all remaining HCl. In order to solubilise the samples, approximately 8 mL of 3.00 pH HCl solution was added. Tight aluminium foil "caps" were added to prevent evaporation, and the samples were then heated in a 70 °C oven for 48 hours.

Next, the samples were transferred to a new 50 mL test tube, with any large solids left in the original test tube to be discarded. The samples were then filtered using a 5–8 µm Elkay Ezee® mesh filter to remove too-large particles. The filtered solutions were transferred to another, labelled 50 mL test tube.

The next step of collagen extraction is ultrafiltration, a step first introduced to the Longin method by Brown et al. (1988). Ultrafiltering removes peptides less than 30 kDa NMWL (Nominal Molecular Weight Limit); these peptides of lower molecular weight are likely humic contaminants. The ultrafilters (Amicon Ultra-0.5 Centrifugal Filter Units with Ultracel-30 membranes) were first cleaned to remove exogenous carbon (in the form of glycerine in the ultrafiltration membranes) by centrifuging distilled water three times in a Heraeus Cryofuge 6000i. The samples were then centrifuged through the ultrafilters at 3008 rcf. The material remaining in the ultrafilters were pipetted to 4 mL microcentrifuge tubes and placed in a 25–35 °C freezer until completely frozen, at least 24 hours. The lids of the tubes were punctured with a dental tool (cleaned between samples with 70% v/v ethanol) in order to prevent over-pressurisation during freeze-drying. Finally, the samples were freeze-dried for 48 hours.

Freeze-drying produces the final form of the sample, slightly-translucent and ranging from white to yellowish-brown, with an appearance similar to finely spun sugar. Some samples appeared to contain small amounts of a light powder. When Ambrose ran blanks alongside the collagen during extraction, he also found white residues in his blanks (Ambrose, 1990). Ambrose describes that the residues "tasted like table salt" (1990, 437). I did not confirm his findings by tasting any residues, but Ambrose estimates any powder in samples were small amounts of sodium chloride from impurities in the acids that may have been present, but did not alter the isotopic results.

3.6.4 Collecting baseline samples

Geographical data (using animal proxies) and dietary baseline data are already being collected for Tonga (Michael P. Richards, personal communications, 21 June 2013). Baseline data from Atiu (Cook Islands) were collected for this study. The samples were air-dried on-site, and then packed in silica gel. Although Atiu is a small island, GPS coordinates were marked for every sample, to conform with previous Pacific baseline studies (Kinaston et al., 2014b) and determine any geographic variation present, however

unlikely.

For the dietary baseline, plants that would have been eaten by prehistoric people were collected. While any part of a plant would be acceptable, it was preferred to collect the edible portion for sampling. Plants that may have been fertilised with commercial fertilisers were avoided. All plants were collected on land with the permission of the landowners.

Modern domesticated fauna were not sampled, as they are fed or scavenge imported food. Rats were also excluded for this reason. In addition, the use of domesticates from other islands or time periods would have to be interpreted with caution as different husbandry practices can create vastly different diets for these animals (Oliver, 1989; Kinaston and Buckley, 2013). Fish bones were from identifiable fish caught by locals. No samples were collected from endangered species.

Biosecurity export clearance was granted by the Cook Islands Ministry of Agriculture (Biosecurity Service). Import into New Zealand was granted using the University of Otago's Anthropology and Archaeology Departmental import permit (permit #2013049508). The samples were inspected and granted clearance by the Ministry of Agriculture and Forestry (MAF) and were transported immediately to the Anthropology and Archaeology transitional facility upon arrival to Dunedin.

3.6.5 Preparing baseline samples

The plant and animal samples from the Cook Islands were prepared at the University of Otago Department of Anatomy following the de-fatting protocol outlined by O'Connell et al (2001). Bones were rinsed with distilled water, soaked in a methanol/chloroform solution (2:1 by volume) and sonicated for three hours. The solution was changed five times during the ultrasonic bath. The bones were then rinsed with distilled water and demineralised following the same modified Longin method used for the archaeological bone and teeth.

Animal flesh and plant samples were rinsed in distilled water and placed in the methanol/chloroform solution in polypropylene centrifuge tubes. Samples were rotated and solvent was replaced every 24 hours until the solution was clear (approximately five days). The samples were then rinsed again in distilled water, placed in microcentrifuge tubes, and left to dry. Finally, all baseline samples were lyophilised (freeze-dried).

3.6.6 Analytical procedure by mass spectrometer

Max Planck Institute

At the Max Planck Institute for Evolutionary Anthropology (Leipzig, Germany), the following analytical technique was used for the 'Atele samples and Bourewa bone samples. The freeze-dried collagen was weighed into tin foil capsules. For carbon and nitrogen analysis, 0.45 to 0.55 mg of collagen is ideal. Owing to the much smaller proportion of sulphur in bone collagen, 10 to 11.1 mg of collagen is necessary for sulphur analysis. In addition to the collagen, 1 mg of vanadium pentoxide (V_2O_5) was added for sulphur analysis. Without the vanadium pentoxide, recovery of sulphur in the mass spectrometry array is very low; the presence of vanadium pentoxide with the sample during combustion allows near-complete recovery of sulphur. Previous methods of increasing sulphur recovery were much slower, although they had the advantage of not using a highly toxic compound like V_2O_5 (Hagerman and Faust, 1955). Carbon and nitrogen were measured in duplicate. Sulphur was measured in duplicate whenever feasible; unfortunately, small collagen yields of some samples meant sulphur was sometimes only weighed once, if at all.

Carbon and nitrogen isotope values were measured simultaneously using a Flash EA 2112 coupled to a DeltaXP continuous-flow isotope-ratio-monitoring mass spectrometer. Sulphur isotope composition was measured by combusting the samples in SO and SO_2 gas in a HekaTech EuroVector elemental analyser coupled to a Delta V Plus 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. For sulphur, IAEA-S-1 (silver sulphide), IAEA NBS-127 (barium sulfide), IAEA-SO-5 (barium sulfide), SRM 1577b and IVA-001 (casein protein) were interspersed.

Iso-Analytical Limited

Iso-Analytical Limited used the following analytical procedure for the Bourewa dentine collagen and Cook Islands baseline samples, which I quote verbatim from their laboratory report (Ian Begley, personal communication, 9 May 2014):

> "The technique used for analysis was Elemental Analysis-Isotope Ratio Mass Spectrometry (EA-IRMS). In this technique, samples and references

are weighed into tin capsules, sealed, and loaded into an auto-sampler on a Europa Scientific elemental analyzer, from where they are dropped in sequence into a furnace held at 1000 ℃ and combusted in the presence of oxygen. The tin capsules flash combust, raising the temperature in the region of the sample to ∼1700 ℃. The combusted gases are swept in a helium stream over combustion catalyst (Cr_2O_3), copper oxide wires (to oxidize hydrocarbons), and silver wool to remove sulfur and halides. The resultant gases, N_2, NO_x, H_2O, O_2, and CO_2 are swept through a reduction stage of pure copper wires held at 600 ℃. This removes any oxygen and converts NO_x species to N_2. A magnesium perchlorate chemical trap is used to remove water. Nitrogen and carbon dioxide are separated using a packed column gas chromatograph held at a constant temperature of 65 ℃. The resultant nitrogen peak enters the ion source of the Europa Scientific 20-20 IRMS first, where it is ionized and accelerated. Nitrogen gas species of different mass are separated in a magnetic field then simultaneously measured using a Faraday cup collector array to measure the isotopomers of N_2 at m/z 28, 29, and 30. After a delay, the carbon dioxide peak enters the ion source and is ionized and accelerated. Carbon dioxide gas species of different mass are separated in a magnetic field then simultaneously measured using a Faraday cup collector array to measure the isotopomers of CO_2 at m/z 44, 45, and 46.

Both references and samples are converted to N_2 and CO_2 and analysed using this method. The analysis proceeds in a batch process by which a reference is analysed followed by a number of samples and then another reference.

The reference material used for $\delta^{13}C$ and $\delta^{15}N$ analysis of your collagen samples was IA-R042 (NBS-1577B, powdered bovine liver, $\delta^{13}C_{\text{V-PDB}}$ = -21.60 ‰, $\delta^{15}N_{\text{AIR}}$ = 7.65 ‰).

IA-R042, a mixture of IA-R005 (beet sugar, $\delta^{13}C_{\text{V-PDB}}$ = -26.03 ‰) and IA-R045 (ammonium sulfate, $\delta^{15}N_{\text{AIR}}$ = -4.71 ‰) and a mixture of IA-R006 (cane sugar, $\delta^{13}C_{\text{V-PDB}}$ = -11.64 ‰) and IA-R046 (ammonium sulfate, $\delta^{15}N_{\text{AIR}}$ = 22.04 ‰) were run as quality control check samples during analysis of your collagen samples.

The reference material used for $\delta^{13}C$ and $\delta^{15}N$ analysis of your plant samples was IA-R001 (wheat flour, $\delta^{13}C_{\text{V-PDB}}$ = -26.43 ‰, $\delta^{15}N_{\text{AIR}}$ = 2.55 ‰).

IA-R001, a mixture of IA-R005 and IA-R04 and a mixture of IA-R006 and IA-R046 were run as quality control check samples during analysis of your plant samples.

IA-R042 and IA-R001 are calibrated against and traceable to IAEA-CH-6 (sucrose, $\delta^{13}C_{V\text{-}PDB}$ = -10.43 ‰) and IAEA-N-1 (ammonium sulfate, $\delta^{15}N_{AIR}$= 0.40 ‰). IA-R005 and IA-R006 are calibrated against and traceable to IAEA-CH-6. IA-R045 and IA-R046 are calibrated against and traceable to IAEA-N-1. IAEA-CH-6 and IAEA-N-1 are inter-laboratory comparison standards distributed by the International Atomic Energy Agency (IAEA)."

3.6.7 Statistical analysis

All statistics were performed using Stata/IC v.13.1 (StataCorp, 2013). Descriptive statistics (mean, standard deviation) were calculated for all samples and demographic subgroups. Descriptive statistics of the sites and 'Atele mounds do not exclude subadults. The significance level of all inferential statistics is set at 0.05. All tests are two-tailed unless otherwise noted. Shapiro-Wilk tests were used to assess normality. Levene's test is used to assess equality of variances between groups in order to verify the assumption of homogeneity of variance for certain statistical tests. Pearson's correlations were tested between $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$.

When variances were equal I used the following statistical tests. Student's t-tests were used when analysing one interval dependent variable and one two-level independent variable. One-way analyses of variance (ANOVAs) were used when the independent variable had more than two levels. When two independent variables were tested with one interval dependent variable, factorial ANOVAs were used. If Wilk's λ were significant, multivariate regression was used to find were the differences lie. If variances were not equal or the data were not normally distributed, non-parametric tests were used. Wilcoxon rank-sum tests and Kruskal–Wallis one-way analyses of variance were used in place of Student's t-tests and ANOVAs, respectively.

3.7 Results

All isotopic data for paleodietary analysis is presented in δ notation, standardised to the international references relevant to the isotope. All $\delta^{13}C$ and $\delta^{15}N$ samples were analysed in duplicate. $\delta^{34}S$ analysis was conducted in duplicate if there was sufficient sample weight. If both duplicates were within acceptable preservation parameters, the

Table 3.6. *Samples excluded from analysis due to evidence of collagen preservation or contamination issues. Note that if one of the duplicate analyses was within acceptable parameters the sample is not listed here.*

Assemblage	Burial designation	Tissue	Integrity issue
'Atele	To-At-2/1e(2)	Dentine	%S, C:S, N:S
Bourewa	17	Bone	C:N
Bourewa	19	Bone	%C

mean of the two analyses were used. The data acquired from isotope analysis of human remains are listed in Appendix B. The dietary baseline stable isotopes data are listed in Appendix C.

Although some of the 'Atele samples showed signs of contamination or poor collagen preservation regarding carbon, nitrogen, and sulphur quality assessments, the duplicates of each of these excluded samples were within acceptable parameters and were included. One sample was an exception, listed in Table 3.6. The dentine collagen of To-At-2/1e(2) was within acceptable parameters when examining carbon and nitrogen quality assessments, but displayed %S, N:S, and C:S ranges outside of acceptable values. In this instance the $\delta^{34}S$ value was not included in inferential analyses but the $\delta^{13}C$ and $\delta^{15}N$ values were still included, given that collagen preservation assessments for sulphur are relatively newer and untested compared to those created for carbon and nitrogen. Note that the total samples in the results tables will differ from the tabular information in the sampling demographic information in the methodology section due to sample exclusion.

The analytical error of the instrument for all analysis runs conducted at Max Planck was 0.074 for $\delta^{13}C$ and 0.067 for $\delta^{15}N$. The analytical error of the instrument for the $\delta^{34}S$ standards was 0.4‰. For the 'Atele assemblage, the mean absolute difference for $\delta^{13}C$ value was 0.11±0.14‰. The mean absolute difference for $\delta^{15}N$ value was 0.11±0.10‰. The mean absolute difference for $\delta^{34}S$ values was 1.57±1.29‰.

Of the 46 duplicates from the Bourewa bone collagen samples, 17 were outside acceptable %C, %N, or C:N ranges. Two samples had to be excluded as both duplicates were outside acceptable ranges. For the Bourewa assemblage, the mean absolute difference for $\delta^{13}C_{bone}$ was 0.14±0.15‰. The mean absolute difference for $\delta^{15}N_{bone}$ was 0.11±0.13‰.

For the 16 tooth samples sent to Iso-Analytical Ltd., all displayed acceptable %C, %N, or C:N ranges. The mean absolute difference for $\delta^{13}C_{dentine}$ was 0.05±0.04‰.

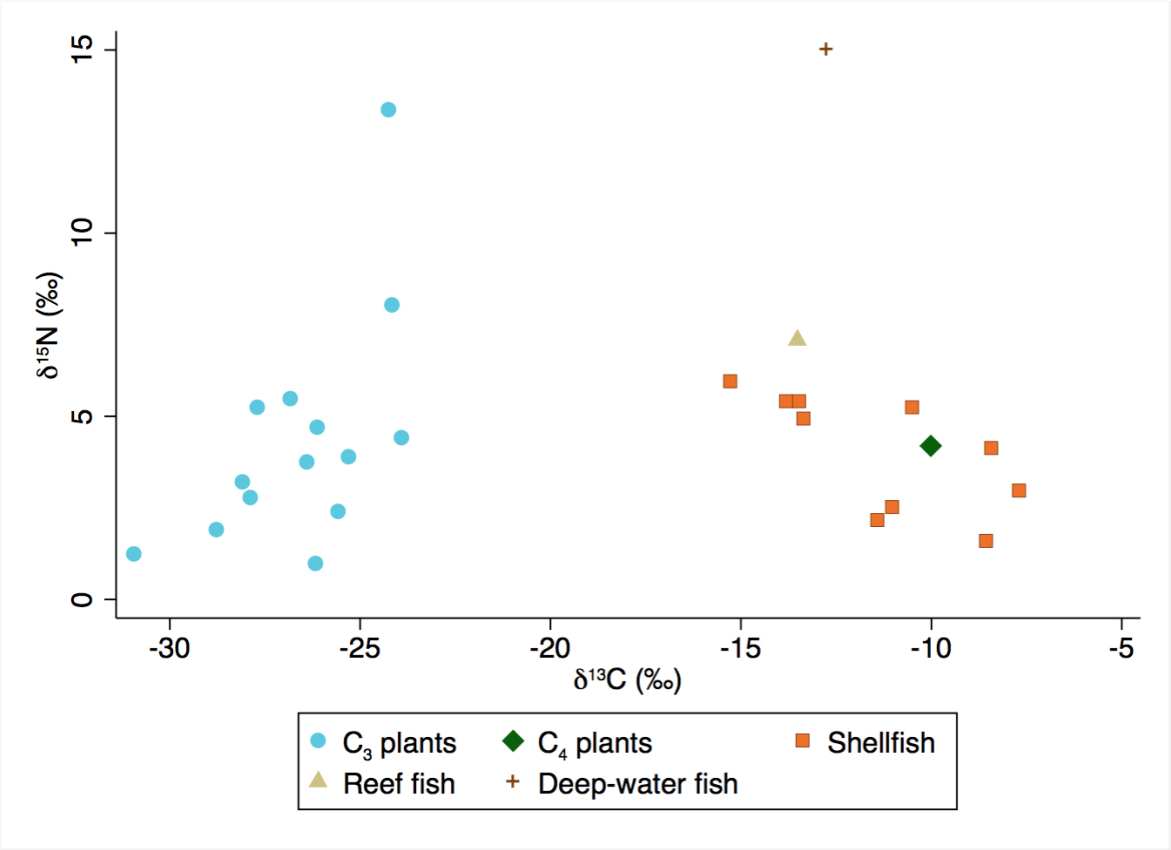


Figure 3.4. *$\delta^{13}C$ and $\delta^{15}N$ results from the baseline collection conducted in the Cook Islands.*

The mean absolute difference for $\delta^{15}N_{dentine}$ was 0.05±0.04‰. Analytical precision, determined using all reference materials analysed alongside the samples, was reported by Iso-Analytical to be less than 0.1‰ for all measurements of δ^{13}C and δ^{15}N values.

The mean absolute differences of δ^{13}C and δ^{15}N values are comparable to some studies (Katzenberg et al., 1993; Dupras and Tocheri, 2007). With the exception of the Bourewa tooth samples, the mean absolute differences are larger than found in previous isotope studies conducted in the University of Otago Bioanthropology Laboratory; Kinaston (2010) found duplicate mean absolute differences between 0.03–0.05‰ for her δ^{13}C and δ^{15}N values, and 0.4±0.3‰ for δ^{34}S.

3.7.1 Dietary baseline

The results of the dietary baseline created from the Cook Islands samples are displayed on Figure 3.4. In this graph, the bone values were not altered using bone-to-flesh corrections. All Cook Islands samples were corrected for the Suess effect, 1.5‰ δ^{13}C for terrestrial organisms and 0.86‰ δ^{13}C for marine organisms (Tieszen, 1991; Beavan Athfield et al.,

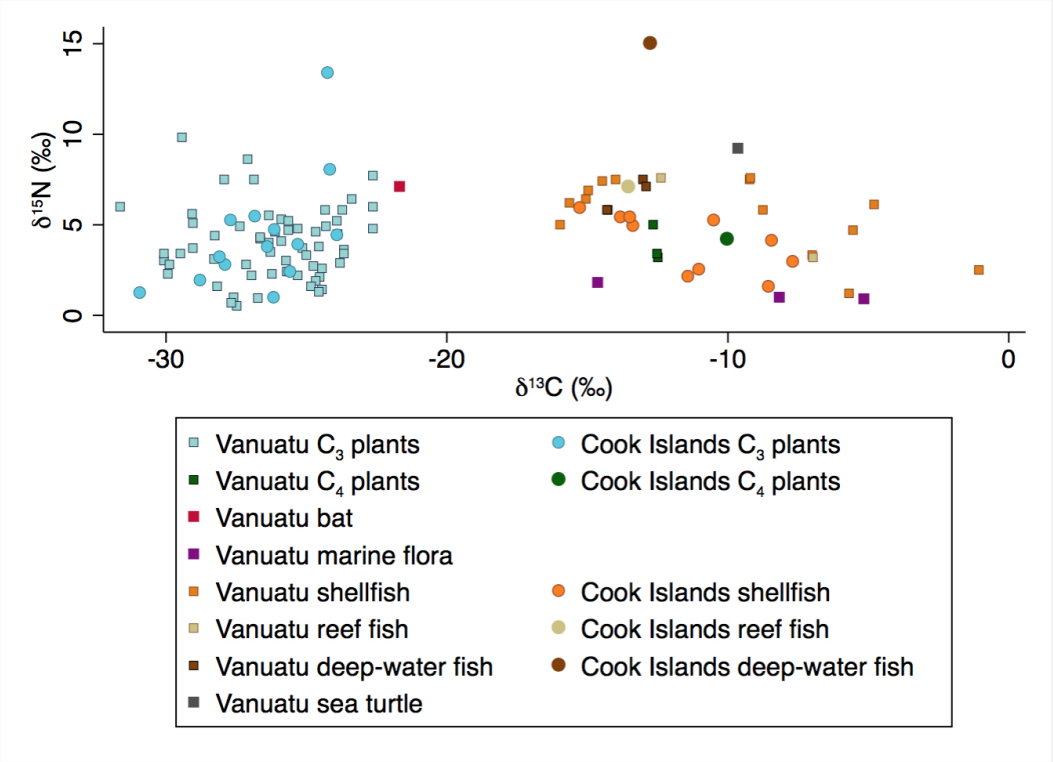


Figure 3.5. *$\delta^{13}C$ and $\delta^{15}N$ results from the baseline collections conducted in Vanuatu and the Cook Islands. Vanuatu data from Kinaston et al. (2014b) and Kinaston et al. (2014a). Data corrected for Suess effect. Other than shellfish, all animal data are from bone collagen.*

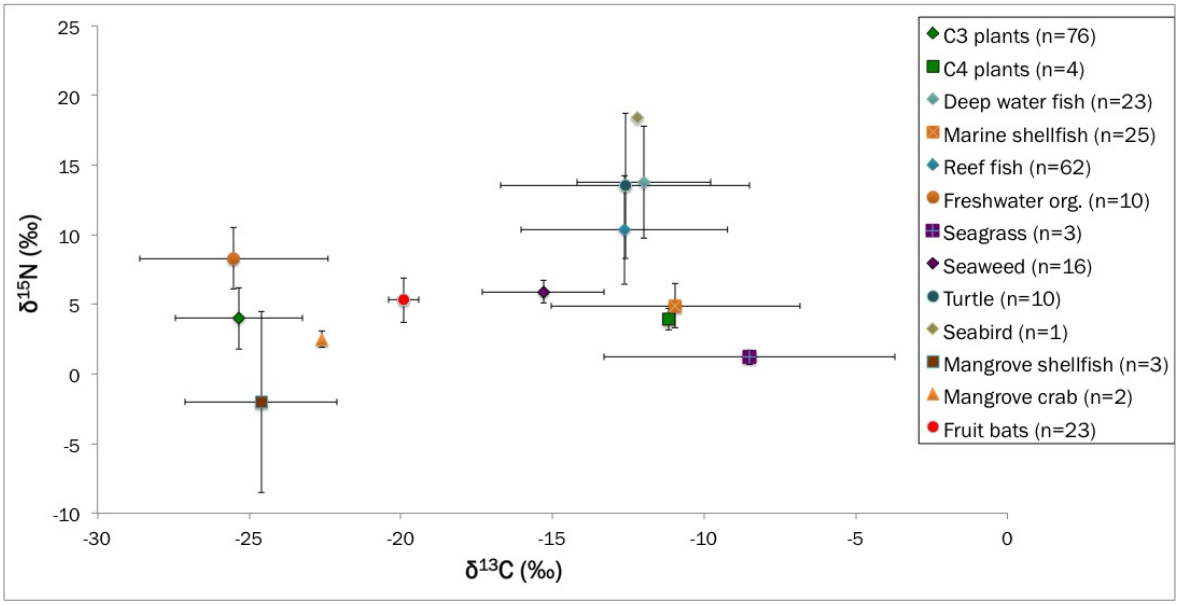


Figure 3.6. *$\delta^{13}C$ and $\delta^{15}N$ mean and 1SD for aggregated tropical Pacific island dietary baseline. All modern samples corrected for Suess effect. Other than shellfish, all animal data are from bone collagen.*

Table 3.7. *Bone collagen stable isotope results, by site and burial mound.*

Site	$\delta^{13}C_{bone}$			$\delta^{15}N_{bone}$			$\delta^{34}S_{bone}$		
	$\bar{x}$	SD	*n*	$\bar{x}$	SD	*n*	$\bar{x}$	SD	*n*
Bourewa	-15.1	1.0	21	8.6	0.8	21	–	–	–
‘Atele	-17.7	0.7	93	9.5	1.1	93	14.7	1.7	68
To-At-1	-17.6	0.6	38	9.7	1.2	38	14.7	1.6	27
To-At-2	-17.9	0.7	47	9.5	1.0	47	14.7	1.9	35

2008). The C_3 plant with the especially high $\delta^{15}N$ value is *Syzygium malaccensis*, a.k.a. a Malay apple. It is unknown why that sample is displaying such a $\delta^{15}N$ value relative to the other terrestrial plants, but is not excluded. Figure 3.5 displays the $\delta^{13}C$ and $\delta^{15}N$ baseline using both the Cook Islands data and the Vanuatu data from Kinaston et al. (2014b). C_3 plants and shellfish were the largest collections from both data sets and represent the marine and terrestrial environments; as such, comparisons between sources are made using these collections.

There were no significant differences in C_3 plants between sources regarding $\delta^{13}C$ or $\delta^{15}N$ values, $W(75) = 539$, $Z = 0.583$, $p = 0.56$ and $W(75) = 540$, $Z = -0.013$, $p = 0.989$, respectively. In shellfish there were no significant differences regarding $\delta^{13}C$ values, $W(23) = 108$, $Z = 0.995$, $p = 0.320$, but there were significant differences regarding $\delta^{15}N$ values, $W(23) = 88.5$, $Z = 2.138$, $p = 0.033$, with the Cook Islands shellfish displaying lower $\delta^{15}N$ values on average.

In order to place the ‘Atele and Bourewa individuals within a tropical Pacific island dietary baseline, data from this study, Kinaston et al. (2014b), and other tropical Pacific dietary studies (Leach et al., 2003; Ambrose et al., 1997; Allen and Craig, 2009; Field et al., 2009; Richards et al., 2009; Casu et al., 2009; Yoshinaga et al., 1991) are aggregated and displayed on Figure 3.6.

3.7.2 $\delta^{13}C_{bone}$, $\delta^{15}N_{bone}$, and $\delta^{34}S_{bone}$

Figure 3.7 displays $\delta^{13}C$ and $\delta^{15}N$ bone collagen results by sex and burial site. Figure 3.8 displays the site means ($\pm$1SD). Overall $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ results for bone collagen are shown on Table 3.7. Table 3.8 displays $\delta^{13}C_{bone}$, $\delta^{15}N_{bone}$, and $\delta^{34}S_{bone}$ by site, sex, and burial mound for the ‘Atele assemblage. Descriptive statistics for the sites, as divided into adults/subadults, are displayed on Table 3.9 and the descriptive statistics for the adult age categories (Young, Middle, and Old) are on Table 3.10.

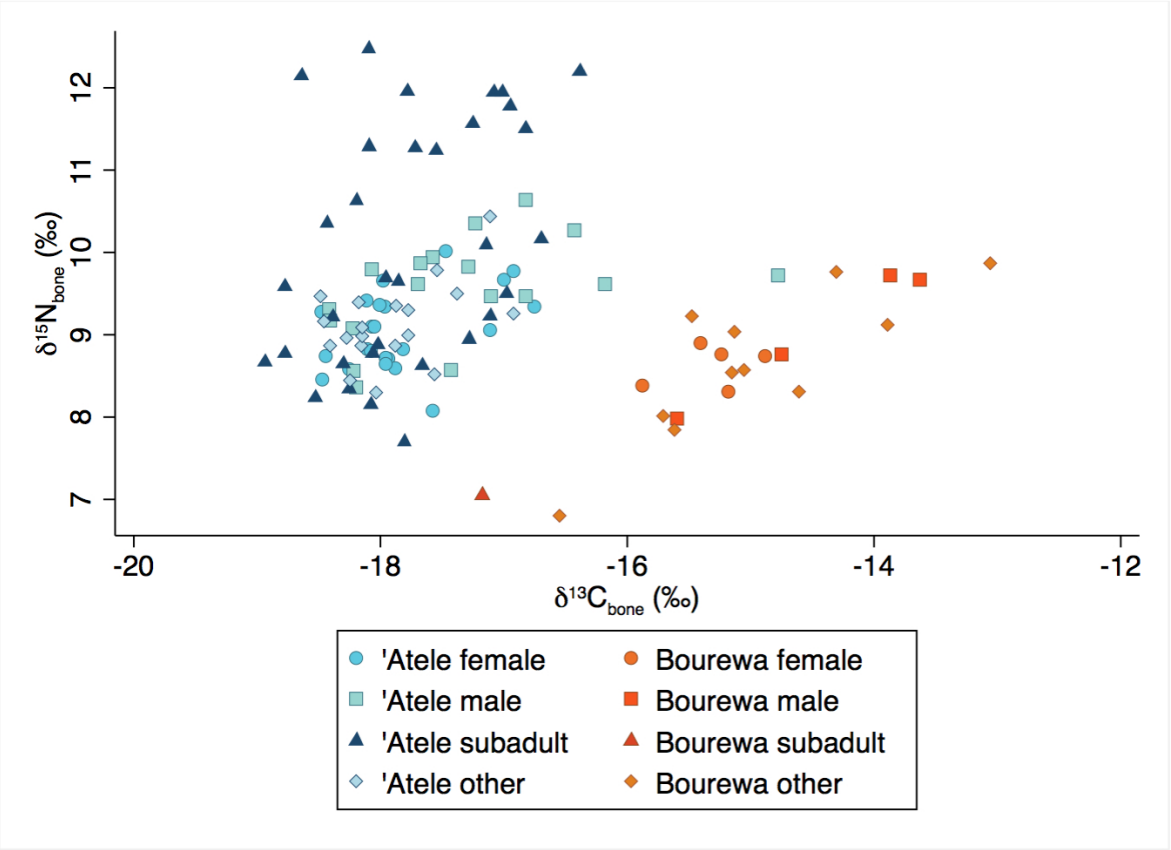


Figure 3.7. *$\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ results by site and sex. Note that subadults are not excluded. "Other" category included adults of indeterminate sex and individuals of indeterminate age.*

Table 3.8. *Bone collagen stable isotope results by sex, site, and burial mound.*

	$\delta^{13}C_{bone}$			$\delta^{15}N_{bone}$			$\delta^{34}S_{bone}$		
Site	$\bar{x}$	**SD**	***n***	$\bar{x}$	**SD**	*n*	$\bar{x}$	**SD**	***n***
Bourewa									
Females	-15.3	0.4	5	8.6	0.3	5	—	—	—
Males	-14.5	0.9	4	9.0	0.8	4	—	—	—
ʻAtele									
Females	-17.8	0.5	23	9.0	0.5	23	14.7	1.5	21
To-At-1	-17.5	0.6	9	9.1	0.6	9	14.9	1.6	8
To-At-2	-18.1	0.2	14	9.0	0.4	14	14.6	1.5	13
Males	-17.4	0.9	18	9.5	0.6	18	14.3	1.9	15
To-At-1	-17.1	0.7	7	9.5	0.6	7	14.4	1.5	5
To-At-2	-17.5	1.1	11	9.5	0.7	11	14.3	2.1	10

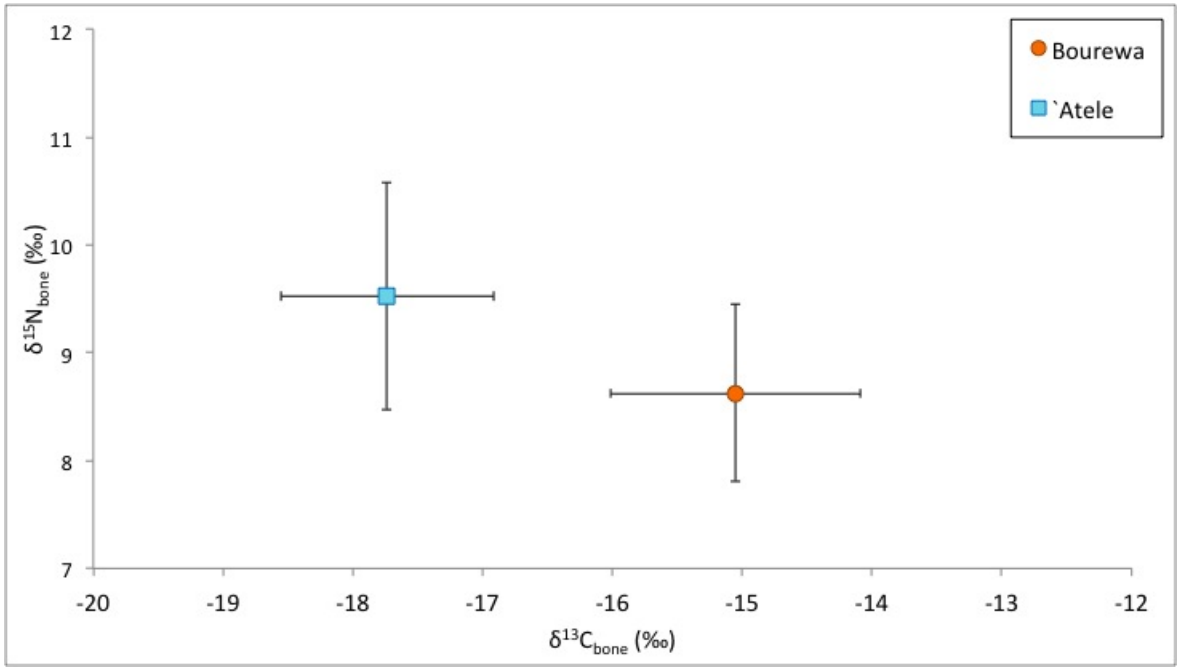


Figure 3.8. *Mean ± 1SD $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ results by site.*

Table 3.9. *Bone collagen stable isotope results by site and age (adult/subadult).*

	$\delta^{13}C_{bone}$			$\delta^{15}N_{bone}$			$\delta^{34}S_{bone}$		
Site	$\bar{x}$	**SD**	***n***	$\bar{x}$	**SD**	***n***	$\bar{x}$	**SD**	***n***
Bourewa									
Adult	-15.1	0.7	16	8.6	0.7	16	—	—	—
Subadult	-17.2	—	1	8.6	0.7	1	—	—	—
‘Atele									
Adult	-17.7	0.7	49	9.2	0.6	49	14.7	1.7	41
To-At-1	-17.4	0.7	17	9.3	0.6	17	14.7	1.5	13
To-At-2	-17.9	0.7	32	9.2	0.6	32	14.7	1.7	28
Subadult	-17.8	0.7	33	10.1	1.5	33	14.9	1.9	19
To-At-1	-17.7	0.6	20	10.0	1.5	20	15.0	1.6	13
To-At-2	-17.9	0.8	13	10.2	1.5	13	14.7	2.8	6

Table 3.10. *Bone collagen stable isotope results by site and adult age categories (Young, Middle, and Old).*

	$\delta^{13}C_{bone}$			$\delta^{15}N_{bone}$			$\delta^{34}S_{bone}$		
Site	$\bar{x}$	**SD**	***n***	$\bar{x}$	**SD**	***n***	$\bar{x}$	**SD**	***n***
Bourewa									
Young	-14.9	0.3	2	8.6	0.2	2	—	—	—
Middle	-15.7	0.2	2	8.2	0.3	2	—	—	—
Old	-14.4	0.8	3	9.2	0.8	3	—	—	—
‘Atele									
Young	-17.6	1.0	15	9.0	0.5	15	15.1	1.6	12
To-At-1	-17.4	0.6	8	9.0	0.5	8	14.7	1.5	13
To-At-2	-17.7	1.3	7	9.1	0.5	7	15.8	1.6	6
Middle	-17.7	0.6	10	9.3	0.7	10	14.5	2.2	8
To-At-1	-17.6	0.7	5	9.5	0.7	5	15.2	1.7	5
To-At-2	-17.8	0.5	5	9.0	0.5	5	13.8	2.7	4
Old	-17.8	0.3	7	9.6	0.6	7	13.5	1.1	7
To-At-1	—	—	0	—	—	0	—	—	0
To-At-2	-17.8	0.3	7	9.6	0.6	7	13.5	1.1	7

Bourewa $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$

In the Bourewa assemblage, 21 individuals provided bone collagen values. The $\delta^{13}C_{bone}$ values ranged between -17.2 and -13.1‰ (mean = -15.1 ± 1.0). $\delta^{15}N_{bone}$ values ranged between 6.8 and 9.9‰ (mean = 8.6 ± 0.8). In the Bourewa population, $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ were strongly correlated, $r(20) = 0.868$, $p < 0.001$. $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ were normally distributed in the Bourewa population. Levene's test indicated equality of variance in $\delta^{15}N$ and $\delta^{13}C$ in Bourewa, $p = 0.162$ and $p = 0.189$, respectively.

With only nine individuals of estimated sex with bone collagen (five females and four males), even simple statistics should be interpreted with caution. There were no statistically significant differences between the sexes regarding $\delta^{13}C_{bone}$ values when using a Wilcoxon rank-sum test, ($W(7) = 16.67, z = -1.47, p = 0.142$) or $\delta^{15}N_{bone}$ values ($W(7) = 16.67, z = -0.74, p = 0.462$).

With only one subadult in the Bourewa assemblage, no comparisons were made between adults and subadults. There were no significant differences between adult age categories regarding $\delta^{13}C_{bone}$, $F(2,6) = 3.38$, $p = 0.138$ or $\delta^{15}N_{bone}$, $F(2,6) = 1.98$, $p = 0.253$.

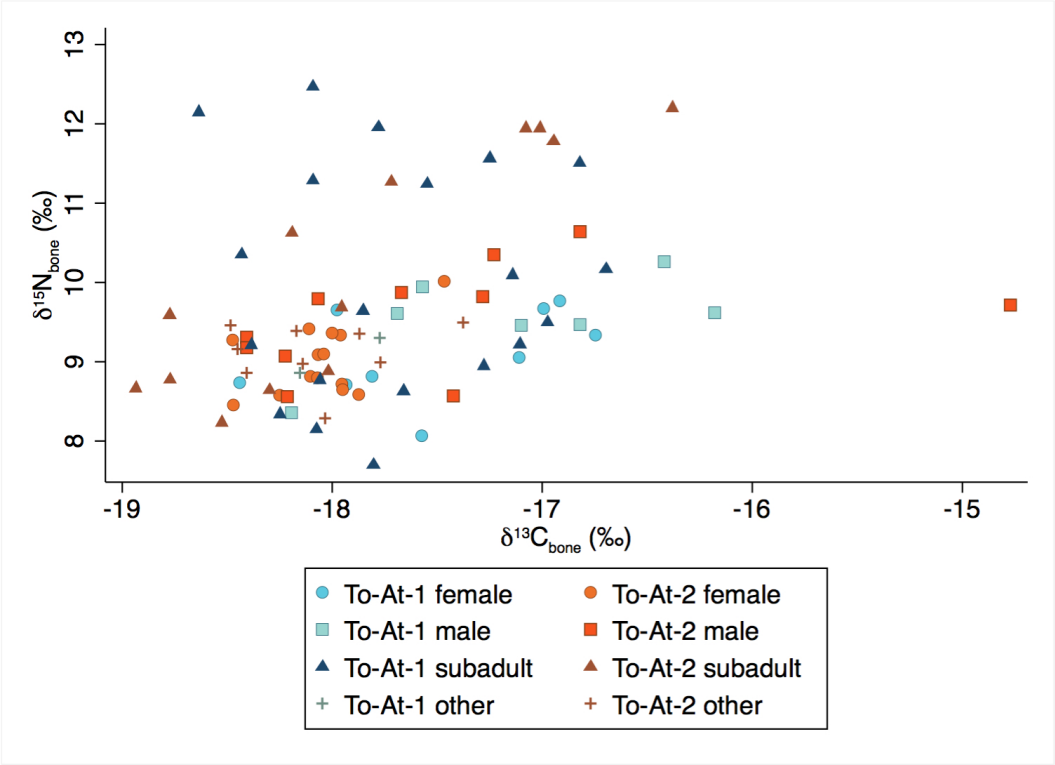


Figure 3.9. *$\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ results for 'Atele.*

'Atele $\delta^{13}C_{bone}$, $\delta^{15}N_{bone}$, and $\delta^{34}S_{bone}$

There were 93 individuals from the 'Atele burial mounds analysed for $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$. Of these 93, 68 individuals had sufficient collagen for $\delta^{34}S_{bone}$ analysis. Figure 3.9 displays the 'Atele $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ results by burial mound. Figure 3.10 displays the means (±1SD) by burial mound and sex. Figure 3.11 displays the 'Atele $\delta^{13}C_{bone}$ and $\delta^{34}S_{bone}$ results by burial mound and sex. There was one outlier (2SD) regarding $\delta^{13}C_{bone}$, To-At-2/33. He was still included in statistical analyses. The $\delta^{13}C_{bone}$ values ranged between -18.9 and -14.8‰ (mean = -17.7 ± 0.7). $\delta^{15}N_{bone}$ values ranged between 7.7 and 12.5‰ (mean = 9.5 ± 1.1). $\delta^{34}S_{bone}$ values ranged between 9.5 and 18.0‰ (mean = 14.7 ± 1.7).

In the 'Atele population, $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ were strongly correlated, $r(93) = 0.355$, $p = 0.005$. When subadults were excluded, the correlation was even stronger, $r(59) = 0.50$, $p < 0.001$. $\delta^{34}S_{bone}$ was not significantly correlated to either $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$: $r(48) = -0.08$, $p = 0.543$ and $r(48) = 0.27$, $p = 0.824$, respectively. $\delta^{34}S_{bone}$ was correlated to % sulphur by weight, $r(48) = 0.27$, $p = 0.0278$ (Figure 3.12). For $\delta^{13}C_{bone}$, Levene's test indicated unequal variances ($F = 3.73$, $p = 0.020$) and so non-parametric tests were used.

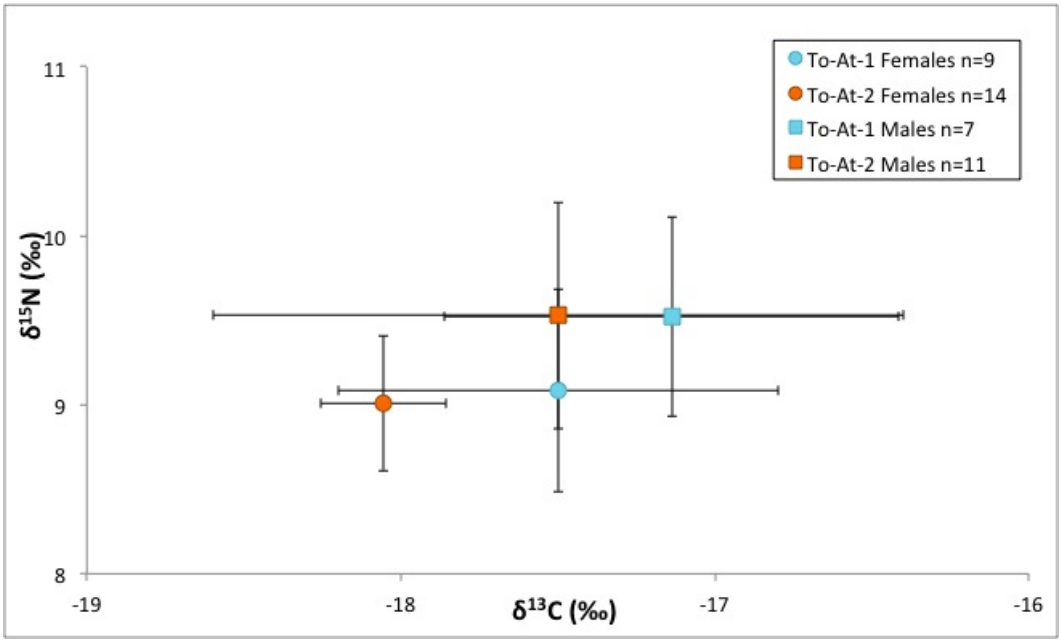


Figure 3.10. *Mean ± 1SD $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ results for sex and burial mound.*

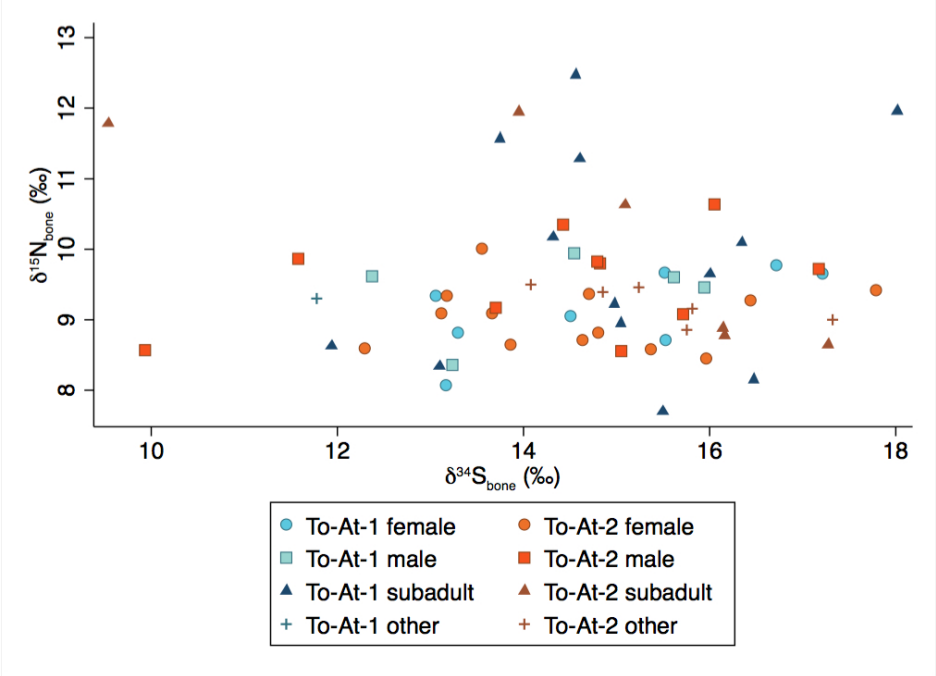


Figure 3.11. *$\delta^{15}N_{bone}$ and $\delta^{34}S_{bone}$ results by burial mound. "Other" category included adults of indeterminate sex or age and individuals of indeterminate age.*

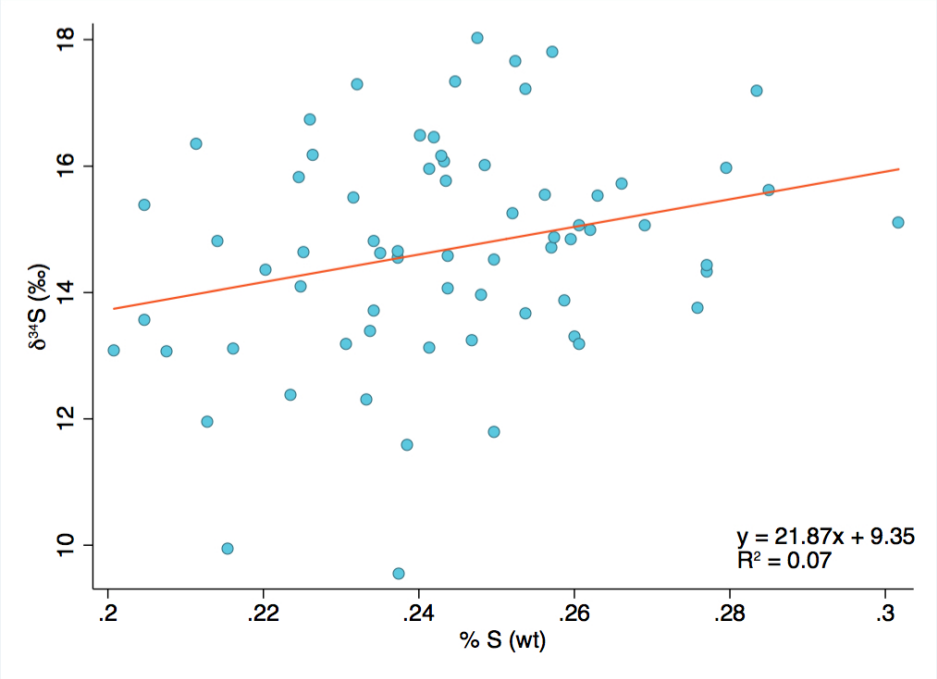


Figure 3.12. *Scatter plot of $\delta^{34}S$ and percent sulphur by weight. Linear regression plot of values overlaid.*

A Wilcoxon rank-sum test indicated no differences between males and females regarding $\delta^{13}C_{bone}$ ($W(41) = 1449.0, z = -1.58, p = 0.115$). There were significant differences between adults by burial mound regarding $\delta^{13}C_{bone}$ values, $W(85) = 2703, z = 2.9, p = 0.004$. To-At-1 individuals displayed higher $\delta^{13}C_{bone}$ values on average, 0.5‰ less negative. Males display a wider range of $\delta^{13}C_{bone}$(-18.4 to -14.8 ‰) compared to females (-18.5 to -16.8 ‰) as well as a slightly wider range of $\delta^{15}N_{bone}$(8.4 to 10.6‰) compared to females (8.1 to 10.0‰).

As normally distributed data, the $\delta^{15}N_{bone}$ values were subjected to a factorial ANOVA with sex and burial mound as the independent variables. There were significant differences in $\delta^{15}N_{bone}$ values between sexes, $F(1,40) = 2.22$, $p = 0.011$, with males displaying a higher mean. The $\delta^{15}N_{bone}$ means between burial mounds were not significant, $F(1,40) = 0.01$, $p = 0.841$. The interaction effect was non-significant, $F(1,40) = 0.02$, $p = 0.827$.

As normally distributed data, $\delta^{34}S_{bone}$ results were subjected to a factorial ANOVA with sex and burial mounds as predictor variables. There were no significant main effects for sex, $F(1,34) = 0.35$, $p = 0.558$, or burial mound, $F(1,34) = 0.10$, $p = 0.750$.

When comparing 'Atele adult and subadult bone collagen stable isotope values, infants and young children were excluded to avoid weaning effects. The differences were not significant for $\delta^{13}C_{bone}$, $W(59) = 3038, z = 0.962, p = 0.336$. Adults displayed

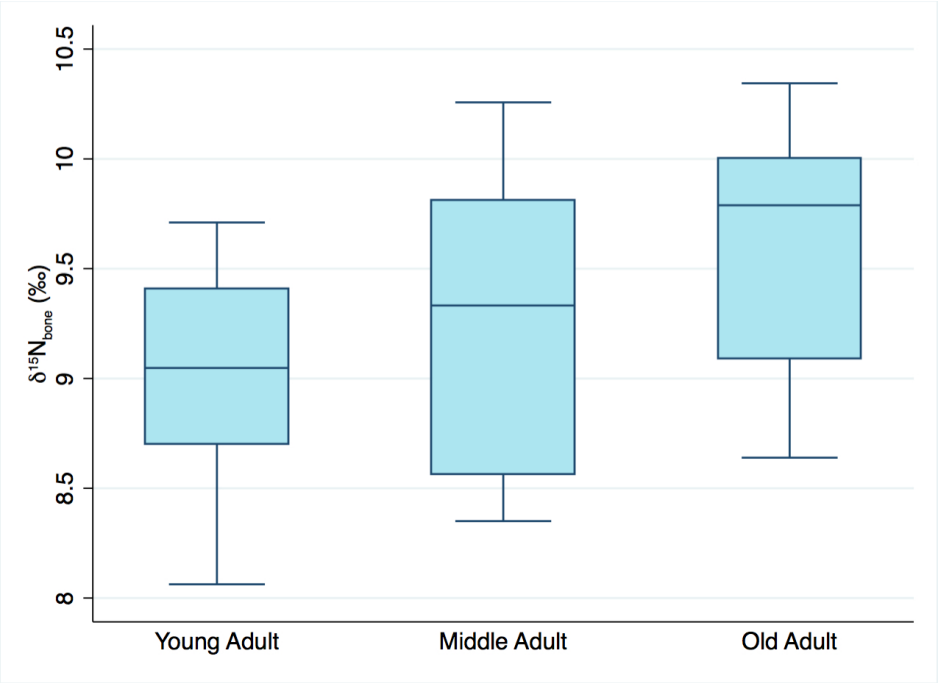


Figure 3.13. *Box plot of $\delta^{15}N_{bone}$values for 'Atele individuals by adult age category.*

significantly higher $\delta^{15}N_{bone}$ values than subadults, 0.6‰ higher on average, $t(59) = 3.10, p = 0.003$. There were no significant effects for age regarding $\delta^{34}S_{bone}$, $(48) = -0.393, p = 0.696$.

There were no significant differences between the three adult age cohorts (young, middle, and old) regarding $\delta^{13}C_{bone}$ using a Kruskal-Wallis test ($\chi^2 = 0.93, p = 0.926$). An ANOVA showed no significant differences between the age cohorts regarding $\delta^{15}N_{bone}$ $F(2, 31) = 2.66, p = 0.087$. Despite not being statistically significant, some trend towards higher $\delta^{15}N$ values in older adults was observed (Figure 3.13). This trend became less clear when the sexes were separated (Figure 3.14). A one-way ANOVA showed no significant difference regarding adult age categories and $\delta^{34}S_{bone}$, $F(2,26) = 1.84, p = 0.180$.

Inter-site comparison $\delta^{13}C_{bone}$, $\delta^{15}N_{bone}$, and $\delta^{34}S_{bone}$

Comparing only adults, there was a significant main effect for burial site when comparing $\delta^{13}C_{bone}$, $W(64) = 904$, $z = 5.77$, $p < 0.001$; the 'Atele individuals displayed a lower mean $\delta^{13}C_{bone}$. When comparing $\delta^{15}N_{bone}$ there was also a significant difference between the groups, $W(64) = 342$, $z = -2.83$, $p = 0.004$ with the 'Atele individuals displaying a higher mean (0.5‰ higher).

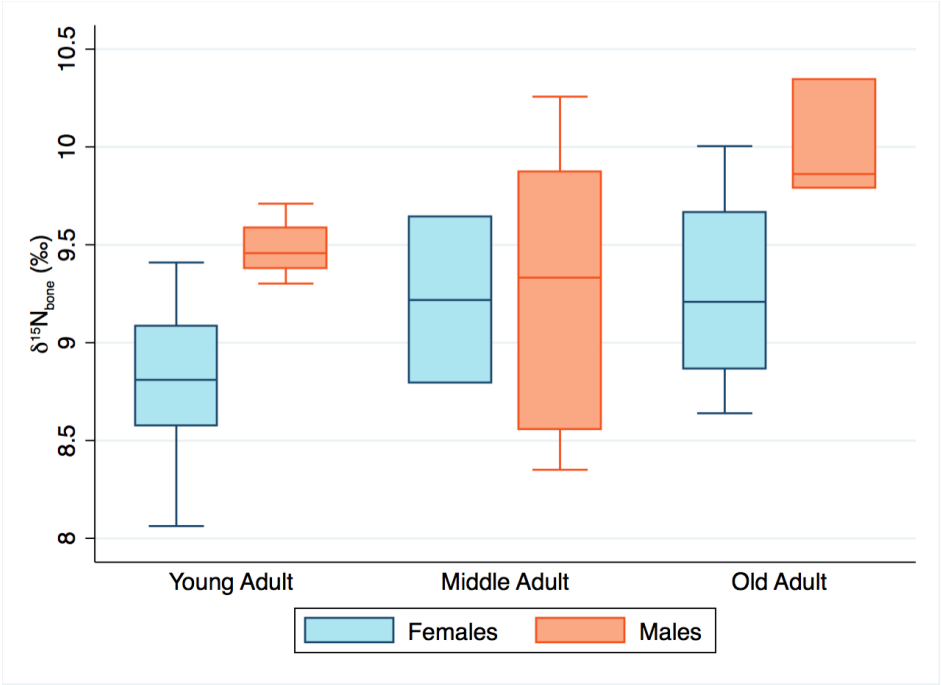


Figure 3.14. *Box plot of $\delta^{15}N_{bone}$ values for 'Atele individuals by adult age category and sex.*

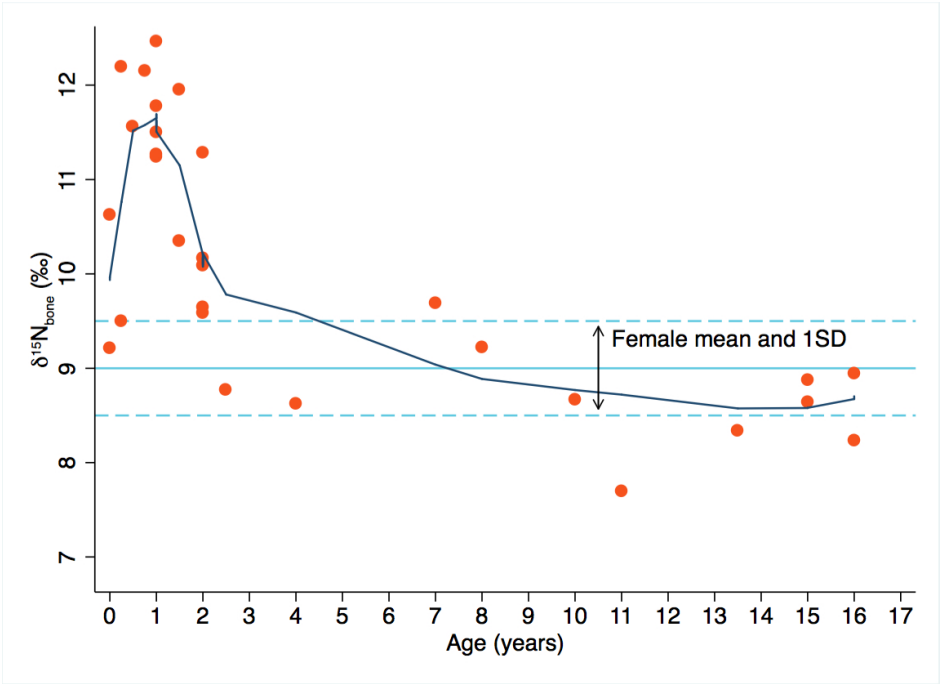


Figure 3.15. *$\delta^{15}N_{bone}$ values of subadults in the 'Atele assemblage with lowess curve prediction plot. Female mean and SD delineated.*

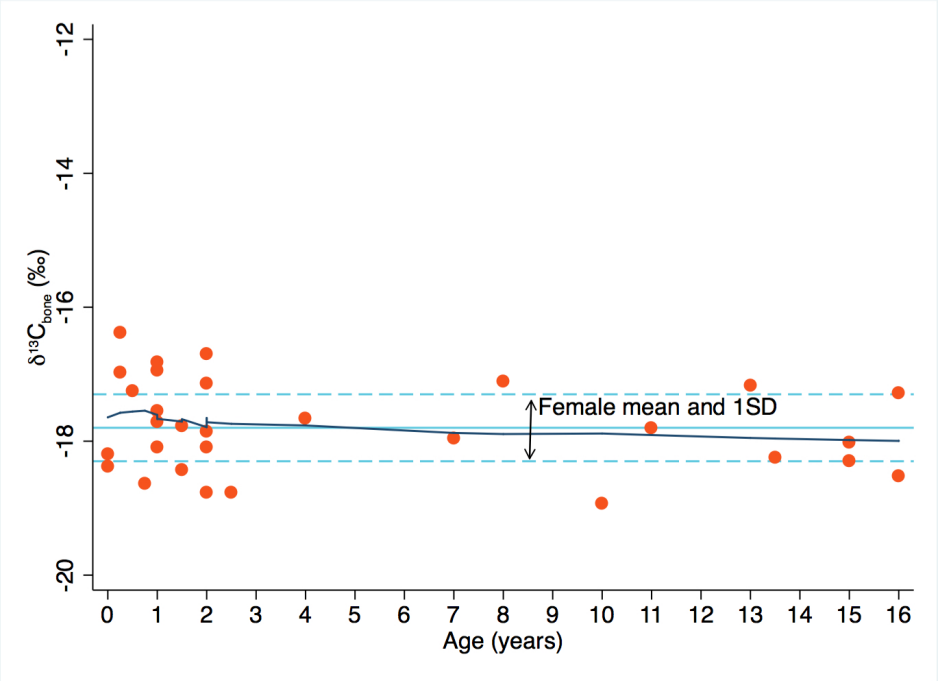


Figure 3.16. *$\delta^{13}C_{bone}$ values of subadults in the 'Atele assemblage with lowess curve prediction plot. Female mean and SD delineated.*

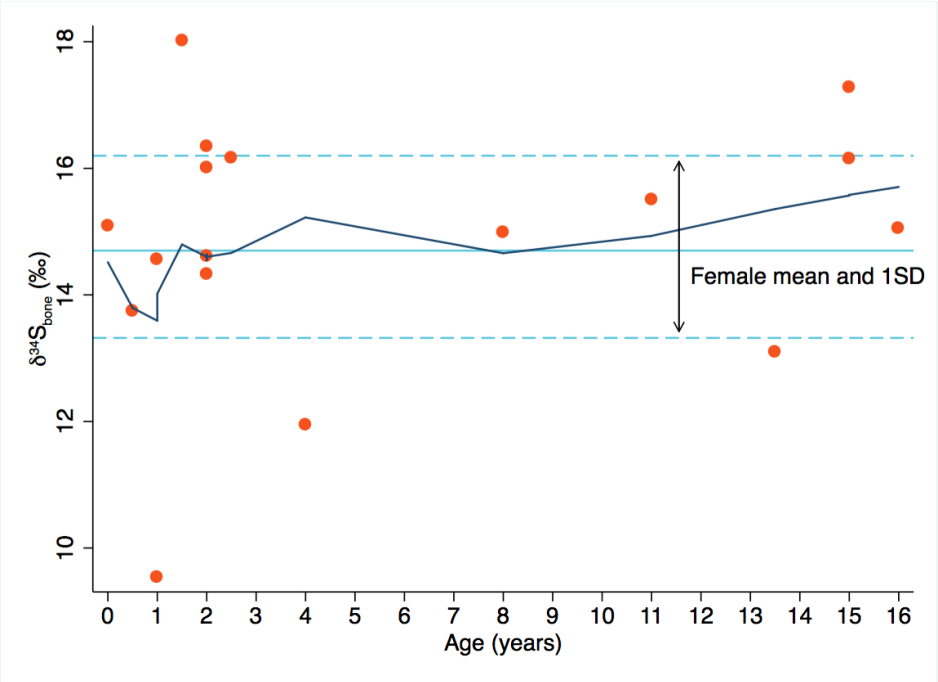


Figure 3.17. *$\delta^{34}S_{bone}$ values of subadults in the 'Atele assemblage with lowess curve prediction plot. Female mean and SD delineated.*

Table 3.11. *Dentine collagen stable isotope results, by site and burial mound.*

	$\delta^{13}C_{dentine}$			$\delta^{15}N_{dentine}$			$\delta^{34}S_{dentine}$		
Site	$\bar{x}$	**SD**	***n***	$\bar{x}$	**SD**	***n***	$\bar{x}$	**SD**	***n***
Bourewa	-16.2	1.1	16	9.1	0.8	16	–	–	–
‘Atele	-17.6	1.0	43	9.7	1.4	43	14.5	1.9	28
To-At-1	-17.3	1.1	21	10.0	1.9	21	14.2	1.9	13
To-At-2	-17.8	0.8	22	9.4	0.6	22	14.8	1.9	15

Weaning

To explore weaning practices in the ‘Atele assemblage, no statistical tests were necessary. When plotting the $\delta^{15}N_{bone}$ values by age (Figure 3.15), a predicted curve similar to Schurr’s 1997 expected plot is evident. There is a noted outlier well below the female mean: the eleven-year-old, To-At-1/13. The lowess curves for the subadult δ^{13}C and δ^{34}S values (Figures 3.16 and 3.17) largely fall near the adult female mean, though there is a wide variation in $\delta^{34}S_{bone}$ values. These results will be examined in more detail in the following discussion.

3.7.3 $\delta^{13}C_{dentine}$, $\delta^{15}N_{dentine}$, and $\delta^{34}S_{dentine}$

Table 3.11 contains the summary data for the dentine collagen results. Figure 3.18 displays δ^{13}C and δ^{15}N dentine collagen results by sex and burial site. To-At-1/13 in the upper-right corner of Figure 3.18 displayed $\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$ values outside 3SD. This outlier was excluded from statistical analyses even though all assessments of collagen preservation were within acceptable parameters.

The $\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$ values were correlated within both sites: $r(15) = 0.836$, $p < 0.001$ for the Bourewa assemblage and $r(42) = 0.753$, $p < 0.001$ for the ‘Atele assemblage.

Bourewa $\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$

As with the bone collagen, there were few individuals of estimated sex for $\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$ comparison: six females and three males. While females displayed $\delta^{13}C_{dentine}$ values 0.9‰ lower than males on average, there were no significant differences between the sexes $W(7) = 15, z = -1.03, p = 0.302$. Females displayed $\delta^{15}N_{dentine}$ values 0.4‰ lower than males on average, not to a significant degree, $W(7) = 15, z = -1.56, p = 0.120$.

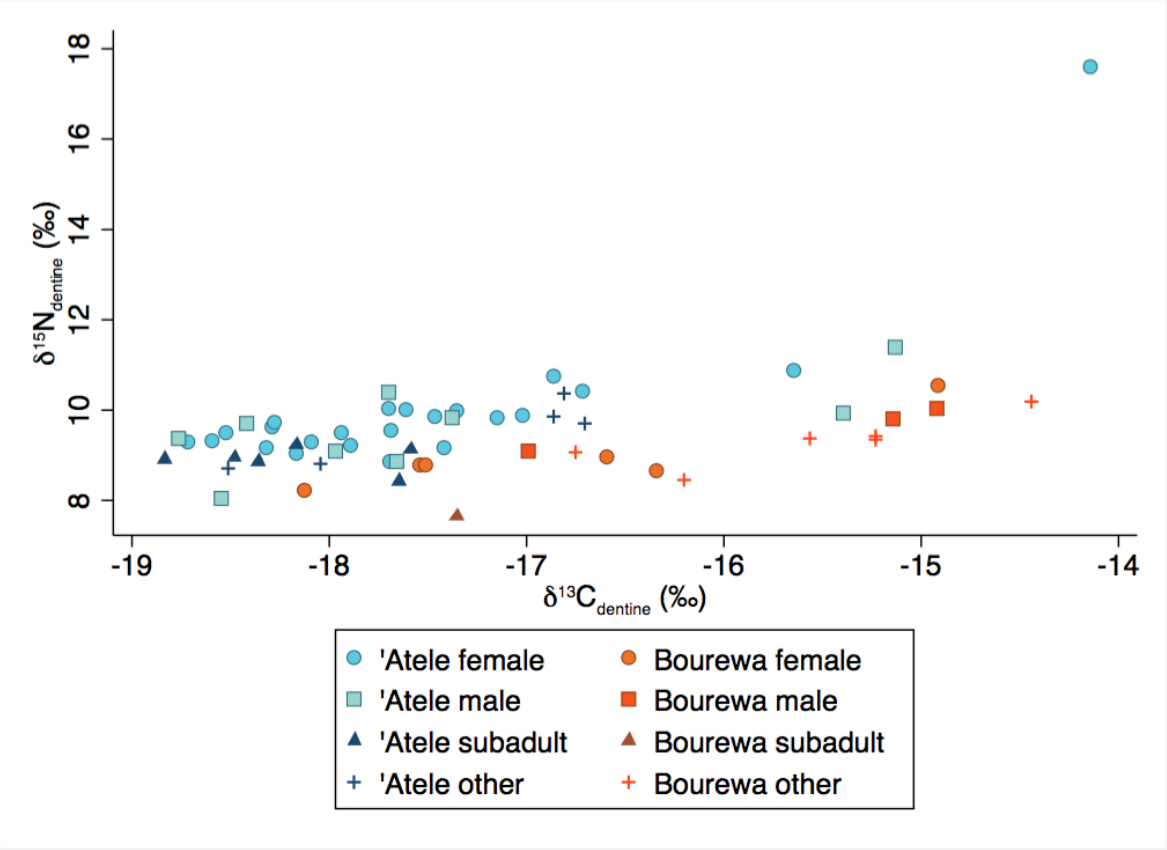


Figure 3.18. *$\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$ results by site and sex. "Other" category included adults of indeterminate sex or age and individuals of indeterminate age.*

Table 3.12. *Dentine collagen stable isotope results for males and females.*

	$\delta^{13}C_{dentine}$			$\delta^{15}N_{dentine}$			$\delta^{34}S_{dentine}$		
Site	$\bar{x}$	**SD**	***n***	$\bar{x}$	**SD**	***n***	$\bar{x}$	**SD**	***n***
Bourewa									
Females	-16.8	1.2	6	9.0	0.8	6	—	—	—
Males	-15.7	1.1	3	9.6	0.5	3	—	—	—
ʻAtele									
Females	-17.5	1.0	23	10.0	1.7	23	14.2	2.3	13
To-At-1	-17.0	1.3	10	10.6	2.5	10	14.5	2.7	5
To-At-2	-17.9	0.5	13	9.6	0.5	13	14.0	2.2	8
Males	-17.4	1.3	9	9.6	1.0	9	15.1	1.7	8
To-At-1	-17.2	1.2	5	9.9	1.0	5	14.3	1.7	5
To-At-2	-17.8	1.6	4	9.3	0.9	4	16.4	0.8	3

Table 3.13. *Dentine collagen stable isotope results by adult age categories (Young, Middle, and Old).*

	$\delta^{13}C_{dentine}$			$\delta^{15}N_{dentine}$			$\delta^{34}S_{dentine}$		
Site	$\bar{x}$	**SD**	***n***	$\bar{x}$	**SD**	***n***	$\bar{x}$	**SD**	***n***
Bourewa									
Young	-15.6	0.9	2	9.2	1.1	2	—	—	—
Middle	-17.3	0.4	2	8.9	0.2	2	—	—	—
Old	-16.6	—	1	9.0	0	1	—	—	—
‘Atele									
Young	-17.0	1.4	14	9.4	0.7	8	15.0	2.0	9
To-At-1	-16.6	0.6	8	10.1	2.8	8	14.5	2.4	5
To-At-2	-17.6	1.3	6	9.7	0.6	6	15.6	1.6	4
Middle	-18.0	0.6	8	9.4	0.7	8	14.7	1.7	6
To-At-1	-17.9	0.6	4	9.6	0.6	4	15.0	1.3	4
To-At-2	-18.2	0.6	4	9.2	0.8	4	16.0	0.7	2
Old	-18.2	0.3	4	9.5	0.2	4	16.0	0.7	2
To-At-1	—	—	0	—	—	0	—	—	0
To-At-2	-18.2	0.3	4	9.5	0.2	4	16.0	0.7	2

Statistical comparison between adult age categories in the Bourewa assemblage is impossible as the sample sizes are too small for meaningful comparison (two individuals in young and middle age categories, one old adult). From a qualitative assessment, there appear to be no patterns in stable isotope values from dentine collagen between the adult age categories.

‘Atele $\delta^{13}C_{dentine}$, $\delta^{15}N_{dentine}$, and $\delta^{34}S_{dentine}$

For the ‘Atele mounds, $\delta^{34}S_{bone}$ was not significantly correlated to either $\delta^{13}C_{dentine}$ or $\delta^{15}N_{dentine}$, $r(27) = -0.140$, $p = 0.479$ and $r(27) = 0.031$, $p = 0.877$, respectively. Figure 3.19 displays $\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$ by burial mound and sex. Figure 3.20 displays $\delta^{15}N_{dentine}$ and $\delta^{34}S_{dentine}$ by burial mound and sex.

There were no significant differences between males and females regarding $\delta^{13}C_{dentine}$, $W(30) = 569.25, z = 0.31, p = 0.753$ or $\delta^{15}N_{dentine}$, $W(30) = 569.25, z = 0.40, p = 0.691$. There were also no significant differences between the sexes regarding $\delta^{34}S_{dentine}$, $t(19) = -0.97$, $p = 0.345$. Between the burial mounds, there were no significant differences regarding $\delta^{13}C_{dentine}$ ($t[40] = 0.98$, $p = 0.333$), $\delta^{15}N_{dentine}$ ($t[40] = 1.33$, $p = 0.190$), or $\delta^{34}S_{dentine}$ ($t[40] = -0.82$, $p = 0.419$).

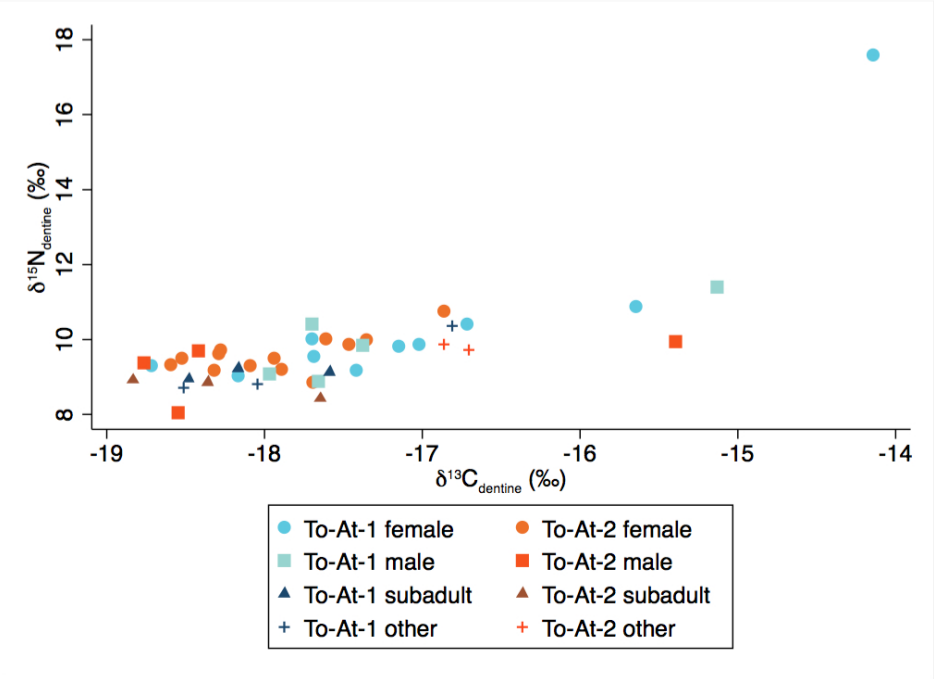


Figure 3.19. *$\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$ for the 'Atele assemblage by sex and burial mound.*

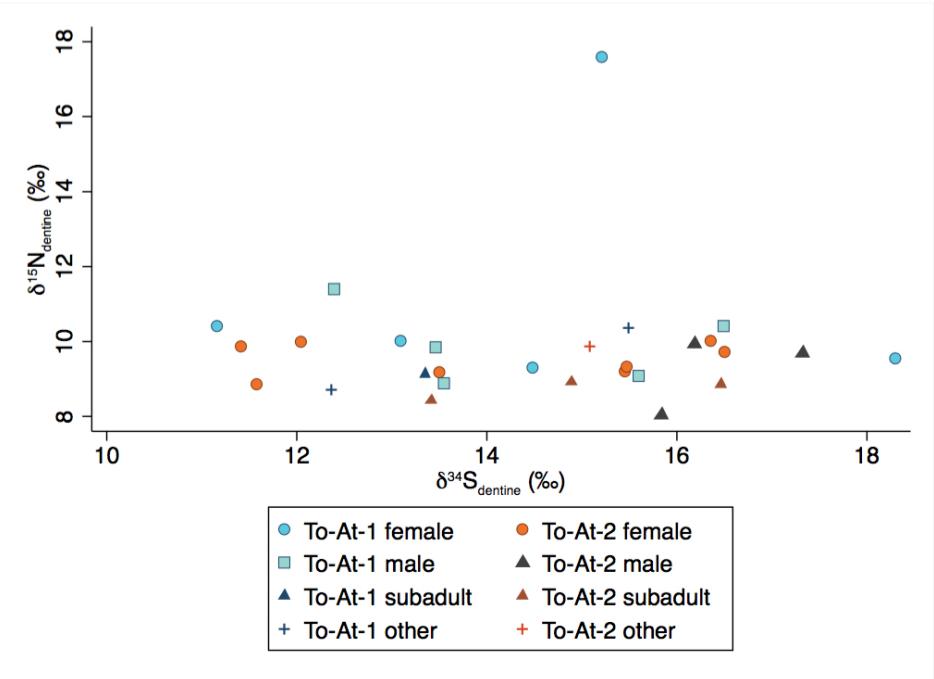


Figure 3.20. *$\delta^{15}N_{dentine}$ and $\delta^{34}S_{dentine}$ for the 'Atele assemblage by sex and burial mound.*

Inter-site comparisons $\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$

The mean difference between Bourewa and 'Atele $\delta^{13}C_{dentine}$ values was -1.5‰ with To-At-1/13 excluded. 'Atele individuals displayed lower $\delta^{13}C_{dentine}$ values to a significant degree, $t(56) = 5.33$, $p < 0.001$. The difference between mean $\delta^{15}N_{dentine}$ values were relatively smaller at 0.4‰ and non-significant, $t(56) = -1.91$, $p = 0.062$.

3.7.4 Comparing bone and dentine collagen stable isotope values

Bourewa

The adult and childhood diets of those who survived childhood were compared using bone and dentine isotope analyses. Figure 3.21 displays the bone and dentine isotopic results for the Bourewa assemblage. Burial 15, the adolescent, was excluded from these comparisons the first molar (sampled for Burial 15) and bone values of an individual approximately 13 years of age could capture roughly the same time period due to possible bone turnover (Hedges et al., 2007). The isotopic compositions of the two tissues (bone and dentine) were compared using Wilcoxon rank-sum tests. There were significant differences between bone and dentine δ^{13}C values ($W(33) = 900, z = 2.6, p = 0.009$); on average $\delta^{13}C_{dentine}$ values were 1.2‰ lower compared with $\delta^{13}C_{bone}$ values. The $\delta^{15}N_{dentine}$ values were 0.5‰ higher on average compared with the $\delta^{15}N_{bone}$ values, and these differences were also significant, $W(33) = 900, z = -2.07, p = 0.039$.

'Atele

In 'Atele, the dentine outlier outside 3SD of the $\delta^{15}N_{dentine}$ mean (To-At-1/13) was excluded from all tests and is also not displayed in the figures. In the 'Atele assemblage only adults were included when comparing bone and dentine isotopic values (Figure 3.22).

There were significant differences between $\delta^{15}N_{dentine}$ and $\delta^{15}N_{bone}$ values, $t(82) = -2.97$, $p = 0.004$. Dentine δ^{15}N values were 0.4‰ higher than bone, on average. There were no significant differences regarding stable carbon isotope values: $t(82) = -0.802$, $p = 0.425$. On average, adult dentine displayed δ^{13}C values 0.1‰ higher than adult bone.

In order to compare the childhood diet of survivors of childhood to the non-survivors of childhood, the dentine of adults was compared to the bone isotope compositions of subadults (Figure 3.23. Infants and young children were not included to prevent altered isotope values from breastfeeding or *in utero* effects (Tsutaya and Yoneda, 2015). The difference between adult $\delta^{13}C_{dentine}$ and subadult $\delta^{13}C_{bone}$ was small, with subadult bone

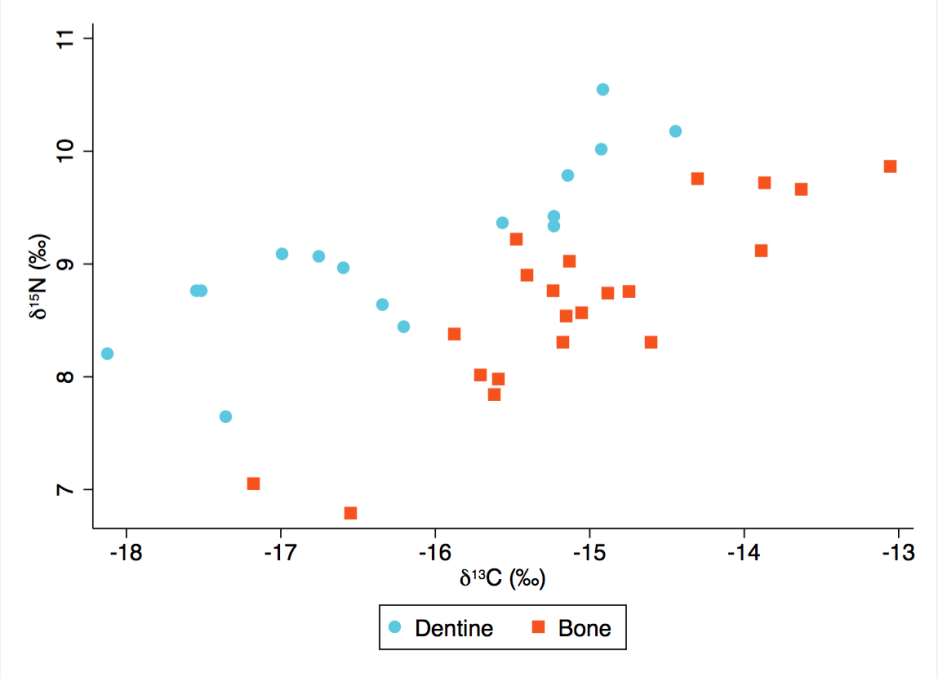


Figure 3.21. *Bone and dentine $\delta^{13}C$ and $\delta^{15}N$ values of Bourewa adults.*

displaying δ^{13}C values 0.3‰ higher, on average. These differences were nonsignificant, $t(57)$ = -1.33, $p = 0.1902$. There were significant differences between adult $\delta^{15}N_{dentine}$ and subadult $\delta^{15}N_{bone}$, with adult $\delta^{15}N_{dentine}$ displaying a mean 0.7‰ higher, $t(57) = 4.1$, $p = 0.0001$. A Student's t-test between $\delta^{34}S_{bone}$ and $\delta^{34}S_{dentine}$ showed no significant differences, $t(94) = 0.402$, $p = 0.689$.

Five subadults (1/14, 1/22, 1/30, 2/24a(2), and 2/9) had both bone and tooth collagen isotopic values. There were no differences between tissue types regarding δ^{13}C values, $W(8) = 22.92, z = 0.73, p = 0.465$, or δ^{15}N values, $W(8) = 22.92, z = -1.78, p = 0.076$. Only two of the dentine samples from subadults had enough collagen to also analyse sulphur stable isotope value, and so δ^{34}S cannot be statistically compared between subadult tissues.

3.8 Discussion

The aims relevant to this chapter were:

- To characterise the diet of prehistoric Tongans and Fijians as diet is intricately tied with all aspects of the social landscape in Remote Oceania
- To compare inter- and intra-populational differences between and within the two sites to gain a more nuanced understanding of differences between late prehistoric

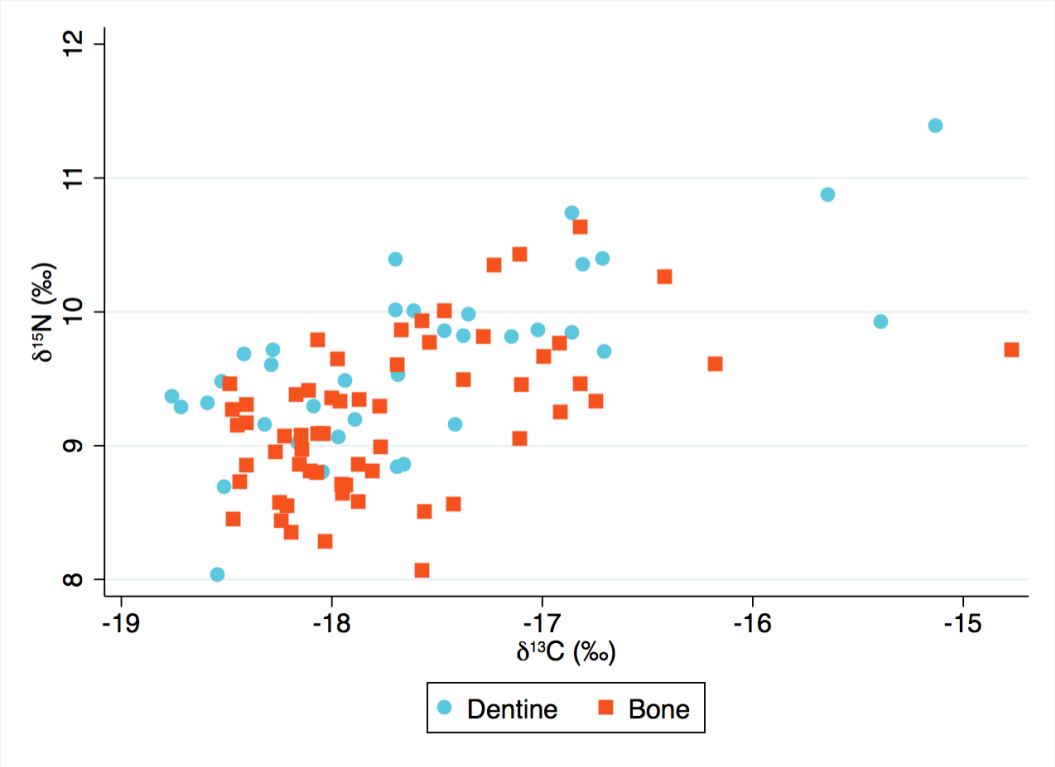


Figure 3.22. *Bone and dentine $\delta^{13}C$ and $\delta^{15}N$ values of 'Atele adults.*

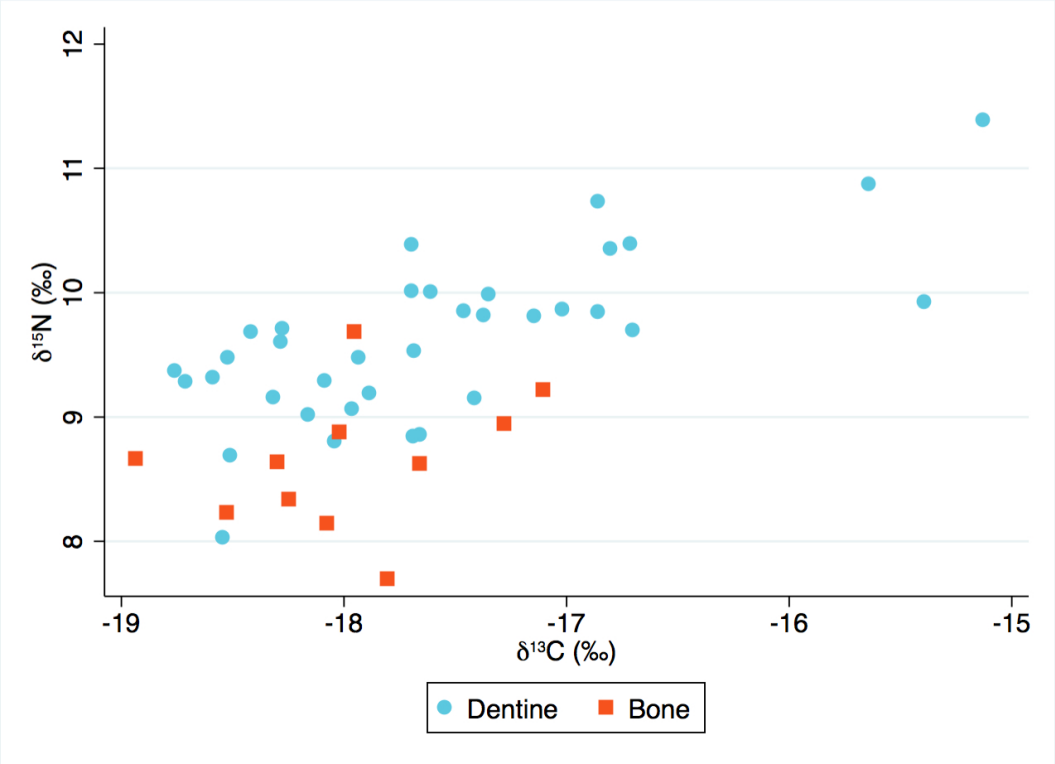


Figure 3.23. *Adult dentine and child and adolescent bone $\delta^{13}C$ and $\delta^{15}N$ values from the 'Atele assemblage.*

Tonga and Fiji and certain groups within these sites such as those of different age categories, sexes, or social status

- To understand age-at-weaning and weaning food practices in prehistoric Tongans, which is especially important for considering subadult health and the long-term effects of childhood diet in a person's life

The hypotheses relevant to this chapter were:

- **H_5:** Due to Viti Levu's larger island size, the Bourewan individuals will have a larger terrestrial component in their diet compared to the 'Atele individuals as evidenced by isotope analysis and oral indicators of diet
- **H_6:** With no previous studies finding differences between the two burial mounds at 'Atele, there will be no differences regarding diet or movement discerned in this study
- **H_7:** Adults will consume more animal protein than subadults (i.e. be on a higher trophic level)
- **H_8:** The childhood diet of adults, as inferred through isotope analysis of tooth collagen, will be on a lower trophic level compared to adults within the last few years of their lives as inferred through bone collagen
- **H_9:** The childhood diet of adults, as inferred through isotope analysis of tooth collagen, will be on a higher trophic level compared to the childhood diet of subadults as inferred through the analysis of bone collagen. In other words, the survivors of childhood (adults) will have consumed more animal protein than non-survivors (subadults)
- **H_{10}:** Using isotope analysis and oral indicators of diet, males and females will display similar diets due to the practice of communal meals in these islands as evidenced in ethnographic studies (Pollock, 1992; Jones, 2009)
- **H_{11}:** The age of complete weaning for Tongans, as interpreted through trophic level shifts in isotope analysis, will occur within the natural weaning age between 2.5 and 6.0 years (Dettwyler, 1995b)

A summary of the findings from paleodietary isotope analyses is presented on Table 3.14.

Table 3.14. *Summary of questions addressed and findings from paleodietary isotope analyses.*

Question	**Significant?**	**If significant, how?**	**Hypothesis addressed**
Dietary baselines different?	Yes	Cook Islands shellfish have higher $\delta^{15}N$ than Vanuatu shellfish	
Differences between the two sites?	Yes	'Atele have lower $\delta^{13}C_{bone}$ and higher $\delta^{15}N_{bone}$	H_5
Childhood diet differences between sites?	Yes	'Atele have lower $\delta^{13}C_{bone}$ and higher $\delta^{15}N_{bone}$	H_5
Sex differences in Bourewa?	No		H_{10}
Adult age differences in Bourewa?	No		
Childhood dietary differences b/n sexes in Bourewa?	No		
Childhood dietary differences b/n Bourewa adult age categories?	No		
Childhood diet vs. adult diet of survivors at Bourewa?	Yes	Childhood diet lower $\delta^{13}C$, higher $\delta^{15}N$ compared to adult diet	H_8
Burial mound differences in 'Atele?	Yes	To-At-1 have higher $\delta^{13}C$	H_6
Sex differences in 'Atele?	Yes	Males have higher $\delta^{15}N_{bone}$	H_{10}
Differences between adult and subadult bone collagen?	Yes	Adults 0.6‰ higher $\delta^{15}N_{bone}$	H_7
Adult age differences in 'Atele?	No		
Childhood diet differences b/n sexes in 'Atele?	No		
Childhood diet differences b/n burial mounds in 'Atele?	No		
Childhood diet vs. adult diet of survivors at 'Atele?	Yes	Childhood diet higher $\delta^{15}N$ compared to adult diet	H_8
Childhood diet of survivors of childhood vs. childhood diet of non-survivors	Yes	Higher $\delta^{15}N$ in survivors	H_9
Weaning occur within 2.5 to 6 years at 'Atele?	No	$\delta^{15}N$ values decrease earlier, around 2 years of age	H_{11}

3.8.1 $\delta^{34}S$ values

Contrary to the carbon and nitrogen results, the $\delta^{34}S$ values showed no significant differences between the burial mounds or sexes. There is one individual outside two standard deviations, To-At-2/27a, a middle-aged male. His carbon and nitrogen isotopic values are within the population averages. As $\delta^{13}C$ and $\delta^{15}N$ are correlated (in both bone and dentine) but the $\delta^{34}S_{bone}$ values are not correlated to the $\delta^{13}C_{bone}$ or $\delta^{15}N$ values, the sulphur results might not be related to marine/terrestrial consumption. All samples with sufficient collagen for sulphur analysis displayed acceptable ranges of %S, C:S, and N:S. However, sulphur analysis is still a relatively unexplored avenue for paleodietary research compared to carbon and nitrogen analyses. From the statistically significant positive correlation between the $\delta^{34}S$ values and %S, it is possible the effect of sea spray or underlying geological formations rich in ^{34}S may have affected the $\delta^{34}S$ isotopic compositions of the bones (Richards et al., 2001; Leach et al., 2003).

The relationship between $\delta^{34}S$ and %S has only been explored in one other isotope study in Taumako, Solomon Islands (Kinaston et al., 2013b). The statistically significant negative correlation between $\delta^{34}S$ and %S found in the Taumako population was interpreted as possibly resulting from diagenetic alteration in conjunction with a soil rich in sulphur from volcanism. Like Taumako, the topsoil of Tongatapu is largely volcanic ash although Tongatapu itself is not volcanic: the volcanic islands to the west contribute topsoil (Taylor and Bloom, 1977). However, in the Taumako study, the correlation between $\delta^{34}S$ and %S was negative; in this study, the correlation is positive. Given the small size of Tongatapu and large lagoon nearly bisecting the island sea spray is a possible contributor, although sea spray also does not satisfactorily explain the positive correlation. The combined effects of sea spray and the local soil environment seem to leave $\delta^{34}S$ analysis an inadequate tool for paleodietary reconstruction in many areas of the Pacific, although some success has been found examining populations from larger islands with more variable geology and no nearby volcanoes (Kinaston and Buckley, 2013).

3.8.2 Are the dietary baselines useful?

Creating a baseline is difficult; variable diet-tissue fractionation within and between species have been observed in fish independent of dietary changes but dependent on temperature and chronological age (Overman and Parrish, 2001; Power et al., 2003). Natural and anthropogenic sources of carbon and nitrogen can also alter the isotopic values within an ecosystem (Jardine et al., 2006). The lack of differences between

terrestrial C_3 plants supports the use of both data sets as a dietary baseline.

Statistical testing showed significant differences between the Vanuatu and Cook Islands shellfish $\delta^{15}N$ values. However, this does not dismiss the utility of an aggregated baseline. The differences most likely lie in the fact that different species were collected. As a "catch-all" term for any exoskeleton-bearing aquatic invertebrate, shellfish fill many ecological niches and occupy a variety of trophic positions in marine environments. For example, many mollusc species are herbivorous grazers or filter-feeders (Steneck and Watling, 1982) but some are active predators. Five of the fourteen shellfish collected by Kinaston et al. (2014b) were from two predatory species of gastropod, *Cypraea tigris* and *Conus litteratus*.

Comparison of the two baselines collected provided an excellent example of how different climatic conditions, variable food webs, and what species were collected can potentially affect these types of data sets. With no dietary baselines for Viti Levu or Tongatapu, combining the Vanuatu and Cook Islands data sets, along with the aquatic baseline data from other sources (Leach et al., 2003; Ambrose et al., 1997; Allen and Craig, 2009; Field et al., 2009; Richards et al., 2009; Casu et al., 2009; Yoshinaga et al., 1991) is the best method of interpreting paleodiet in this study.

3.8.3 Dietary interpretation

The strong positive correlation between carbon and nitrogen stable isotope ratios for each site (for both dentine and bone collagen) suggests that the differences in diet between individuals is a result of the different proportions of marine and terrestrial foods eaten (Richards and Hedges, 1999). There would be a lack of positive correlation if the population relied mainly on terrestrial and marine foods of the same trophic level or a single protein source (Richards and Hedges, 1999; Kinaston et al., 2013b). Instead, the dietary trend suggests that each population generally relied on marine animals and terrestrial plants. A positive correlation has been observed in other prehistoric Pacific sites (Ambrose et al., 1997; Kinaston et al., 2013b) and fits with ethnohistoric accounts of Fijian/Polynesian diet, where starchy root vegetables such as taro and yams and fruit trees such as bananas and Tahitian chestnuts were central to subsistence along with marine foods from the nearby reef and lagoon.

Figure 3.24 shows the Bourewa and 'Atele individuals plotted with the dietary baseline. In this graph, the mean and standard deviation of the different food types are presented as boxes and the human data are scattered on top of these. The open ellipses on the figure show the bone data adjusted for trophic level in a conservative manner, -1‰ for $\delta^{13}C$ and -3‰ for $\delta^{15}N$. As the edible portions, the plant material and

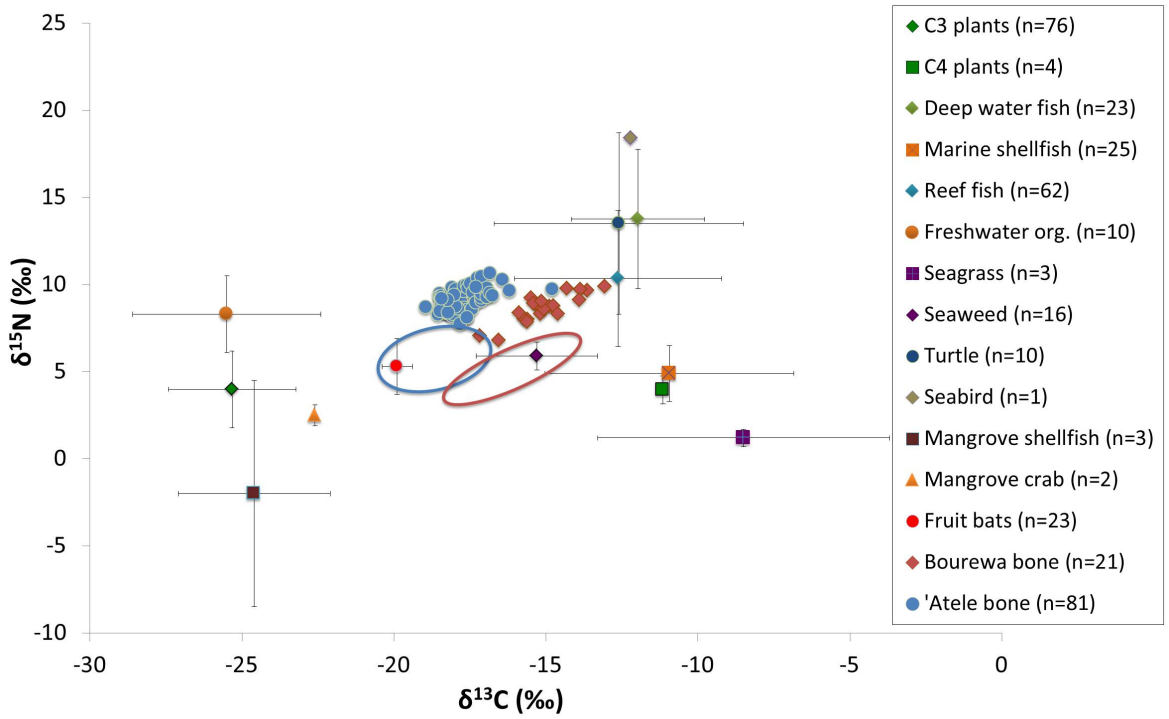


Figure 3.24. *$\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values for the 'Atele and Bourewa assemblages (infants and young children excluded) plotted with the dietary baseline ranges. Human values adjusted for trophic shifts of -1‰ for $\delta^{13}C$, -3‰ for $\delta^{15}N$and represented as empty circles. Dietary baseline samples adjusted for Suess effect but are otherwise unaltered. Fruit bat bone sample unadjusted to serve as an example of an entirely terrestrial diet.*

shellfish flesh are not altered. The fruit bat bone samples from Kinaston et al. (2014b) are unaltered to demonstrate the expected bone collagen values of a mammal eating an entirely terrestrial diet.

Examining Figure 3.24, it becomes clear that marine foods constituted a large portion of dietary protein for all individuals in both assemblages. This fits with the environment of the areas, as the Fanga'uta Lagoon near 'Atele and the broad fringing reef off the Rove Peninsula would have both provided seaweeds, seagrasses, and marine animals for consumption. If the two dietary endpoints are indeed terrestrial plants and marine animals, the higher protein content of fish and shellfish relative to low-protein terrestrial flora may be causing the marine contributors to appear "over-represented" when examining the isotopic composition of human collagen (Hedges, 2004). This may leave the 'Atele and Bourewa individuals possibly consuming more terrestrial plants than the isotopic results would suggest.

There are a few 'Atele individuals whose bone collagen values overlap with those of

the fruit bat bones. These individuals may have consumed up to 100% terrestrial or mangrove foods. For the Bourewa individuals, the northern part of the Rove Peninsula the site is located on contains a large mangrove system (Nunn et al., 2004a; Nunn, 2009). Molluscs and crabs from this habitat may have been a large portion of the Bourewa diet, especially if soil was as poor in the past as it is today on the peninsula (Nunn, 2009). The lower $\delta^{15}N$ values of mangrove foods might also explain the slightly lower $\delta^{15}N_{bone}$ of the Bourewa individuals compared to 'Atele, though that interpretation is not in line with the higher $\delta^{13}C$ values of the Bourewa individuals. The northern part of Tongatapu does contain some mangrove systems and so it is also possible the 'Atele individuals were consuming mangrove shellfish, though the richer soil of Tongatapu lends itself more to garden foods than the Rove Peninsula and the 'Atele burial grounds are on the southern part of the island (Taylor and Bloom, 1977; Nunn, 1998). It is more difficult to separate terrestrial garden crops and animals from mangrove foods using stable isotope analyses compared to separating marine and terrestrial resources.

Comparison to previous studies

The examination of dietary isotopes from collagen largely only yields information about the protein portion of an individual's diet (Ambrose and Norr, 1993; Fernandes et al., 2012). Low protein foods (such as terrestrial plants) could be overshadowed by higher-protein sources such as marine animals (Hedges, 2004). As other prehistoric tropical Pacific cultures largely consumed the same types of foods (Kirch, 2000), the comparison of the isotope results to previous prehistoric Pacific paleodietary studies aids in understanding the relative proportion of marine foods compared to terrestrial foods in Bourewa individuals.

Table 3.15 displays the mean $\delta^{13}C_{bone}$, $\delta^{15}N_{bone}$, and $\delta^{34}S_{bone}$ values for 'Atele, Bourewa, and other isotope studies that have been conducted in Remote Oceania. When comparing the Bourewa and 'Atele stable isotope results to other paleodietary studies from Fiji, Tonga, and the nearby archipelagos of Samoa and Vanuatu (Figure 3.25), it becomes clear that there was considerable diversity in the dietary range of these Pacific Island groups. For example, the assemblages analysed by Field et al. (2009) and Phaff (2012), though both are from the Sigatoka Valley on Viti Levu, display very different carbon stable isotope values from Bourewa. Despite being within the same geographic area, environmental differences between the two Sigatoka sites may be the underlying cause for the dietary differences given that the individuals sampled by Phaff (2012) come from the Sigatoka Sand Dunes near the mouth of the river and Field et al.'s (2009) individuals were excavated from inland settlements further upriver.

Table 3.15. *$\delta^{13}C_{bone}$, $\delta^{15}N_{bone}$ and $\delta^{34}S_{bone}$ summary data of 'Atele, Bourewa, and other Remote Oceanic sites. *Only late prehistoric/historic individuals from Uripiv (Kinaston et al., 2014a) included as a roughly contemporaneous group to Bourewa and 'Atele.*

Group	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	Reference	*n*
Cikobia, Fiji	-17.2	9.5		Valentin et al. (2006)	9
Sigatoka, Viti Levu, Fiji	-19.3	9.0	—	Field et al. (2009)	3
Waya Island, Fiji	-15.5	9.9	—	Field et al. (2009)	15
Lau Islands Group	-16.3	9.4	—	Jones (2009)	9
Tuitilia, Samoa	-18.1	10.8		Valentin et al. (2011)	12
Taumako, Solomon Islands	-16.4	11.5	14.5	Kinaston et al. (2013b)	99
Uripiv, Vanuatu*	-18.9	7.7	10.4	Kinaston et al. (2014a)	4
Teouma, Vanuatu	-15.7	12.1	11.3	Kinaston et al. (2014b)	40
J28, Tongatapu, Tonga	-18.1	9.5	—	Fenner et al. (2015)	13
To-At-36, Tongatapu, Tonga	-17.8	9.2	—	Fenner et al. (2015)	5
'Atele	-17.7	9.5	14.7	this study	81
Bourewa	-15.1	8.6		this study	21
Overall Mean	-17.0	9.5	12.4		

Temporal variation is also a likely cause for much of the dietary variation between the samples from different Pacific island sites. The Sigatoka Valley sites on Viti Levu both span several Fijian time periods and centuries. The individuals from Efate, Vanuatu (Kinaston et al., 2014b) the late prehistoric/historic individuals from Uripiv Island, Vanuatu (Kinaston et al., 2014a) provide a good example of the importance of considering temporal variation: though relatively close spatially the two sites are separated by almost 3000 years, and display vastly different carbon and nitrogen stable isotope means on Figure 3.25.

Compared to these other assemblages and the Pacific island dietary baseline, it can be suggested that the community at Bourewa relied heavily on marine foods from lower trophic levels, such as seaweeds, shellfish and reef fish. The only Fijian site with individuals displaying a higher carbon value is the Natunuku site on Viti Levu (c. 2000 BP), but it should be noted that there was only one individual available for analysis (Leach et al., 2003). Natunuku, like Bourewa and the Sigatoka Sand Dunes, is located on the coast. It is interesting that these coastal assemblages appear to be consuming a more marine diet compared to individuals from much smaller islands, like the assemblages from 'Atele, Cikobia Island (Valentin et al., 2006), and late prehistoric/historic individuals from Uripiv Island (Kinaston et al., 2014a), which are located on islands 259 km^2, 19 km^2, and < 1 km^2 in size, respectively. The small size of these islands could have

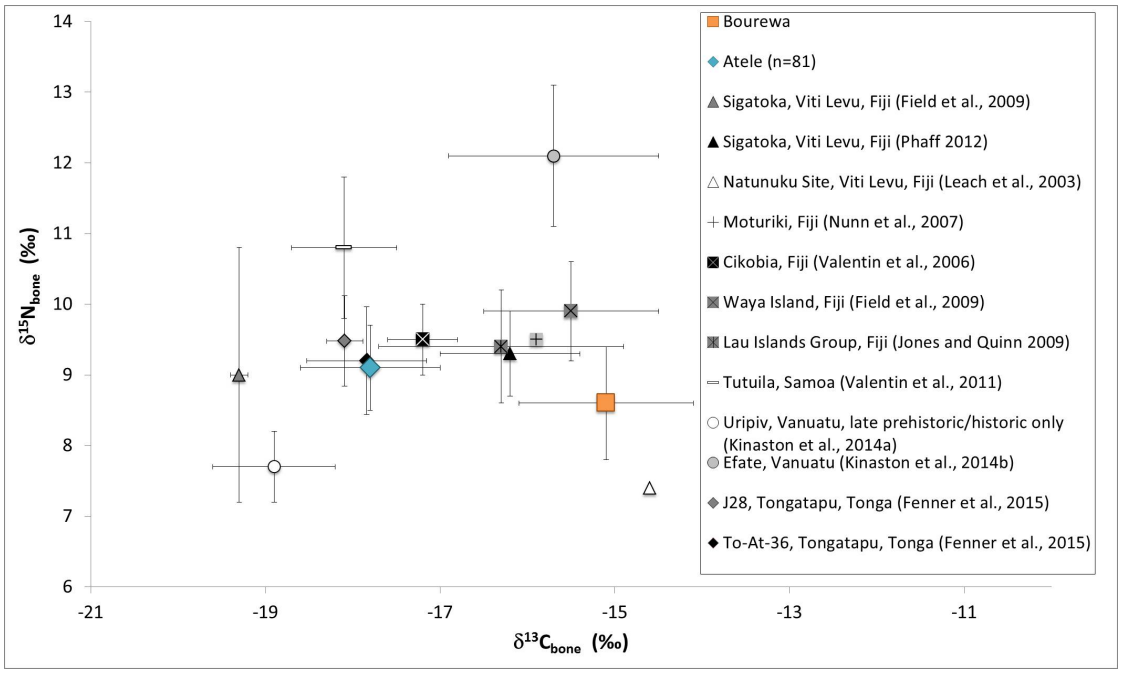


Figure 3.25. *$\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ mean and SD for the 'Atele and Bourewa assemblages compared to other Remote Oceania sites. Infants and young children excluded from 'Atele sample.*

presumably made horticultural subsistence less productive and necessitated a greater reliance on reef, deep water, and lagoon resources. Instead, these populations seem to have consumed proportionately more terrestrial resources. All of these small island cohorts are dated to the late prehistoric/historic periods (there are individuals dated to earlier time periods on Uripiv, but only late prehistoric/historic individuals are discussed here). Thus, these individuals were living hundreds, if not thousands, of years after initial colonisation of their respective archipelagos and roughly contemporaneous with Bourewa. That these late prehistoric/historic populations practised intensive horticultural pursuits fits with the current archaeological models of later communities becoming less reliant on marine resources as their gardens become established and the local marine resources become depleted due to overuse by the initial settlers (Kirch and Hunt, 1997; Burley et al., 2001; Kennett et al., 2006; Kinaston et al., 2014b).

Why then did the Bourewa community rely more heavily on marine resources despite also being from late prehistory? One reason may be that there was no ecological pressure to discontinue heavy reliance on coastal resources. The source community (somewhere near Bourewa) may have been small enough, and/or the large fringing reef and lagoon on the coast of the Rove Peninsula may have been productive enough, that only small gardens kept as complementary foods were necessary to support the needs

of the settlement.

The uncommon dryness and poor soils of the Rove Peninsula, on which Bourewa is located, may have also contributed to the emphasis on marine food consumption, a similar situation for subsistence communities in the area today (Nunn, 2009). Climatic fluctuations during the Vuda Phase may have exacerbated the poor conditions for maintaining gardens. Trade with other, more inland communities may have been restricted because of conflict and the increased competition for resources during this period (Field, 2004, 2005; Nunn, 2012).

The heavy reliance on marine foods with terrestrial garden yields as a complementary food supply flips the typical subsistence pattern in the tropical Pacific on its head, where normally the farinaceous root crops are the basis of subsistence and are supplemented by marine protein (Pollock, 1992; Jones, 2009; Kirch, 2000). Without individuals from earlier times in the Rove Peninsula to analyse, it is not possible to determine whether the higher proportion of marine foods in the Bourewa diet was an adaptation to the devastation of terrestrial resources during the Vuda Phase or an indication of a lack of ecological pressure to intensify horticultural subsistence. A thorough examination of skeletal indicators of nonspecific and nutritional stress in this assemblage, as has been conducted in ‘Atele (Buckley, 2000, 2001), will be useful to help further understand the biocultural pressures affecting this population.

The ‘Atele individuals were consuming a diet with $\delta^{13}C$ and $\delta^{15}N$ values not far removed from the aggregated mean. The other sites from Tongatapu (Fenner et al., 2015) cluster closest to ‘Atele. Examining the Tongatapu sites more closely (Figure 3.26), there is overlap in the $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values of all four burial mounds. To-At-36 is too small of a cohort for meaningful statistical comparison, but when the three burial mounds with larger sample sizes (J28, To-At-1, and To-At-2) are compared using Kruskal-Wallis tests, there are significant differences in regards to $\delta^{13}C_{bone}$, $\chi^2(2) = 9.03, p = 0.011$, but no differences regarding $\delta^{15}N_{bone}$, $\chi^2(2) = 2.19, p = 0.334$. Post hoc comparisons using Wilcoxon rank-sum tests show significant differences between To-At-1 and To-At-2, $W(52) = 1378, z = 2.90, p = 0.004$. There were also significant differences between To-At-1 and J28, $W(30) = 465, z = 2.11, p = 0.034$. There were no significant differences between To-At-2 and J28, $W(46) = 1081, z = 0.275, p = 0.783$.

With J28 a stone-lined burial *langi* mound compared to the earthen mounds of ‘Atele and To-At-36, greater dietary differences may have been expected. Given that the small size of Tongatapu may have limited variance in subsistence strategies, it is perhaps not surprising that individuals from the Chiefdom period consumed largely the same proportions of foods regardless of potential status in comparison to populations

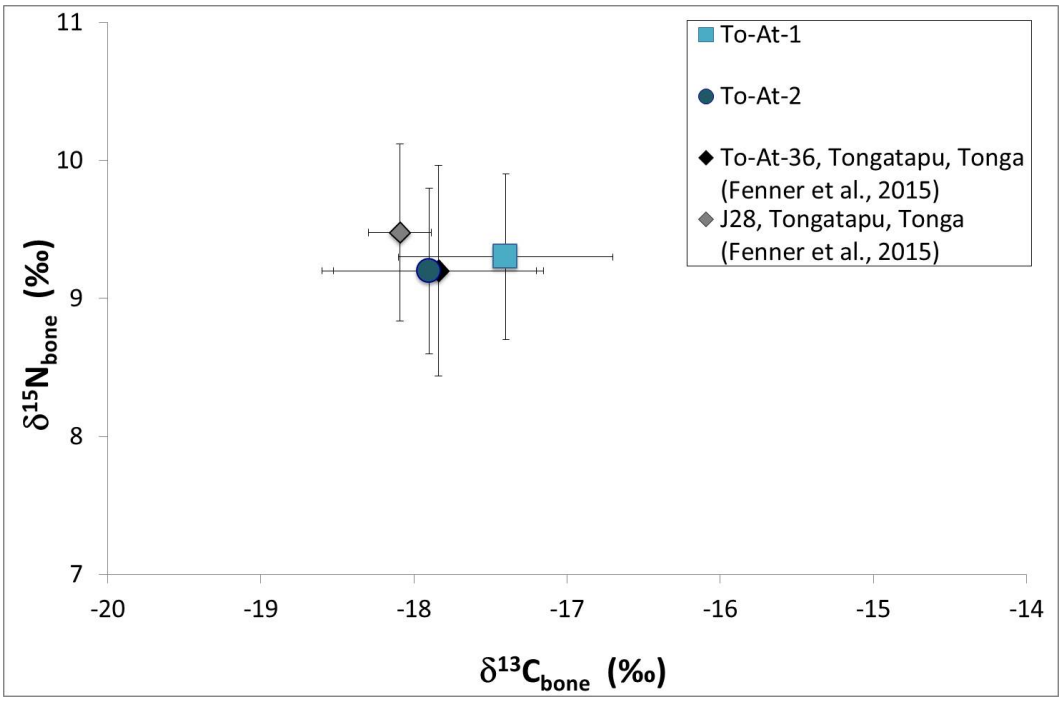


Figure 3.26. *$\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ mean and SD for the 'Atele burial mounds and other Tongatapu studies of human paleodiet (Fenner et al., 2015). Infants and young children excluded from 'Atele sample.*

from other islands. To-At-1 individuals display $\delta^{13}C_{bone}$ values lower on average than the other three burial mounds. The possible reasons for these differences between To-At-1 and To-At-2 will be discussed further below.

Placing this study's results against the backdrop of a dietary baseline and comparative studies has proven useful for contextualising the proportions of food types consumed. However, addressing the aims and hypotheses of this study does not entail interpreting diet in this manner. Instead, comparing intra- and inter-populational dietary differences within the two assemblages is the main focus of this discussion.

3.8.4 Inter-site comparisons

There are several potential interpretations for the differences between the sites observed from statistical analysis and the dietary interpretation from Figure 3.24. It becomes clear that the individuals from the Bourewa assemblage were consuming a higher proportion of marine foods compared to those from 'Atele. The lower $\delta^{13}C_{bone}$ and higher $\delta^{15}N_{bone}$ values of the 'Atele individuals imply that not only were they consuming a higher proportion of terrestrial foods, they were also consuming a larger proportion of foods from a higher trophic level.

The trophic level differences are not as disparate as the terrestrial versus marine divide between the sites, but they are interesting. If the Bourewa individuals were consuming more marine foods, it would have made sense for them to also fall on a higher trophic level given the longer food chains in marine environments. Instead, they are slightly lower. The ‘Atele individuals may have been consuming more terrestrial animal protein (whether from animal domesticates or wild fauna), or their marine constituent may have included more high trophic level fish.

The Bourewa diet, conversely, may have consisted of more marine flora or shellfish with smaller proportions of terrestrial plants or fish. Terrestrial C_3 plants and shellfish occupy approximately the same nitrogen isotopic range. Using isotope analysis, hypothesis 5 would be rejected; the Bourewa individuals display a higher proportion of marine foods in their diet compared to the ‘Atele individuals. This may seem counter-intuitive given that Viti Levu has a wider variety and more abundant plant resources due to its large size and varied landscape. The Bourewa individuals were buried on the coast, and may have lived close to the coast. Access to freshwater and arable soil was difficult in comparison to reef access Nunn (2007). While trade with inland populations was possible, the rise of fortifications implies resource control that may not have encouraged trade or sharing of resources (Field, 2004, 2005).

The differences between sites continue in childhood diet, with the ‘Atele individuals displaying higher $\delta^{15}N_{dentine}$ and lower $\delta^{13}C_{dentine}$than Bourewa. However, the differences (while still significant) are somewhat lessened; the mean difference between bone collagen $\delta^{13}C$ values are 2.6‰ and the mean difference between $\delta^{13}C_{dentine}$ values are 1.4‰.

With both sites combined, the clustering of dentine values becomes more obvious. There is a slight trend towards males having values in the >-16‰ group, with 4/12 (33%) of males in that group compared to 3/29 (10%) of females. There is also a slight trend towards young adults being found in the >-16 group (in fact *only* young adults have $\delta^{13}C_{dentine}$ values greater than 16‰). However, young adults are nonetheless spread fairly evenly though the clusters, with 5/16 (31%) in the higher $\delta^{13}C$ cluster. Ultimately, a cause behind this patterning cannot be posited with the contextual information available.

3.8.5 Comparing subgroups in Bourewa

There was little variation between subgroups in Bourewa. There were no significant differences between sexes or adult age groups regarding bone collagen isotope values, or childhood dietary differences between sexes or adult age groups when comparing dentine collagen isotope values.

Equality in regards to food access in adults rarely happens even in the most egalitarian societies (Jelliffe, 1967; Flanagan, 1989; Danforth, 1999). The lack of sex- and age-based differences in Bourewa could simply be a sampling issue, and the nine individuals of estimated sex with cortical bone for isotope analyses might not represent the living population from which they were derived (Wood et al., 1992; Waldron, 1994). With the assumption that this pattern is representative of the living population's diet, perhaps there were mitigating factors such as ecological pressures reducing the typical dietary differences between subgroups observed in other prehistoric Pacific samples.

If the Bourewa diet as observed through isotope analyses was an adaptation to the devastation of terrestrial resources during the Vuda Phase, as discussed in Chapter 2, it is possible that the resource pressures reduced individual choice, lifted food taboos (if present), or encouraged food-sharing. In direct conflict with this supposition, there is strong evidence in modern events of food insecurity that certain household members, most often males as the primary resource providers, are given priority for food (Wutich and Brewis, 2014). Nonetheless, Wutich and Brewis (2014) concede that there are few archaeological, ethnographic and historical pointers to this conclusion.

It should be noted that there were also no sex-based differences in diet found through isotope analyses on Cikobia, a smaller Fijian island northeast of Viti Levu (Valentin et al., 2006), leaving the possibility that it is not so unusual for equal access to certain types of food in Fiji. The Cikobia assemblage is protohistoric (c. 100 BP) and also suffers from a small comparative sample for sex comparisons (five males and two females). Phaff's (2012) Sigatoka Sand Dune assemblage, spanning c. 1750 – 150 BP, also found no dietary differences between the sexes. Bioarchaeological studies of health, nutrition, and metabolic stress in the Bourewa assemblage will be necessary in future research to further explore these possibilities.

Childhood diet

Re-examining Figure 3.18, there seems to be two clusters of $\delta^{13}C_{dentine}$ values for the Bourewa assemblage: one group clusters below -16‰ while the other clusters above -16‰ with slightly higher $\delta^{15}N$ values than the first group. With only five aged adults, the size is too small to determine if any trends are present regarding adult age category. Both sexes are dispersed across these clusters. In fact, there were no differences in childhood diet between the sexes or adult age groups.

The significantly lower $\delta^{13}C_{dentine}$ values compared to the $\delta^{13}C_{bone}$ values indicate that the individuals from Bourewa consumed proportionately more terrestrial foods compared with marine foods in childhood compared to the last few years of their

lives. Significant differences between $\delta^{15}N_{dentine}$ values compared to the $\delta^{15}N_{bone}$ values suggests that childhood diets contained proportionately more animal flesh, suggesting that differences between childhood and adult diets were also a difference of trophic level. A possible explanation is snacking outside mealtimes. Significantly higher $\delta^{15}N_{dentine}$ values compared to adults eliminate fruits, such as bananas and coconuts, as likely candidates for the isotopic differences. Nuts display higher $\delta^{15}N$ values than other terrestrial plants while still displaying $\delta^{13}C$ values within a terrestrial range (Kinaston et al., 2014a,b), and so can account for both the higher nitrogen value. Canarium nuts would have been available seasonally in Fiji and could be preserved through smoking (Smith, 1979; Elevitch et al., 2006). Modern Pacific children are also commonly seen snacking on lagoon and reef shellfish, but these foods would raise $\delta^{13}C_{dentine}$ rather than lower these values. This discrepancy may have been associated with inconclusive ethnographic accounts (Pollock, 1992; Jones, 2009). Regardless of the underlying dietery causes, H_8 is rejected for Bourewa.

If some sort of scenario involving food insecurity were in fact occurring on the Rove Peninsula during the Vuda Phase, why are adult and childhood diets not more similar? It is possible there were no severe dietary pressures, and sex- or age-based differences in the adult populations were not present or are unobservable via isotope analyses. It is also conceivable that, in the event of food insecurity, subadults were affected more severely than adults. Eating proportionately more protein-poor terrestrial flora, the Bourewa individuals may have experienced nutritional stress as subadults resulting in catabolisation, which also explains the lower $\delta^{13}C$ and higher $\delta^{15}N$ values in subadults (Hobson et al., 1993; Reitsema, 2013). Severe nutritional stress (e.g. starvation) is necessary for catabolisation to occur, and so isotope analyses of paleodiet may have raised more questions than they addressed for the Bourewa assemblage, but further exploration of health and nutrition in this understudied population will undoubtedly shed light on an interesting, though not well-understood, time period in Fijian prehistory.

3.8.6 Comparing subgroups in ‘Atele

One individual (To-At-2/33) is an outlier (outside 2SD) regarding $\delta^{13}C_{bone}$ values. With isotopic values placing him more comfortably in the Bourewa assemblage, the possibility of To-At-2/33 eating a vastly different diet because he spent his life in a location other than Tongatapu is suggested. Vastly different dietary isotopic compositions have been discussed as evidence of movement in a study of prehistoric New Zealand (Kinaston et al., 2013c) as well as in Europe (Richards et al., 2001; Müldner and Richards, 2007).

Whether $^{87}Sr/^{86}Sr$ analysis supports this possibility will be discussed in later chapters.

‘Atele mound differences

There were significant dietary differences between adults in the two burial mounds at ‘Atele as evidenced by isotope analyses. These findings are contrary to previous bioarchaeological studies which found no indication of differences between the mounds as evidenced by health or activity (Buckley, 2001; Foster, 2011) and would reject the sixth hypothesis proposed in this study (there would be no differences between the mounds). To-At-1 individuals displayed significantly higher $\delta^{13}C_{bone}$ values than individuals excavated from To-At-2, suggesting that To-At-1 individuals consumed proportionally more marine foods. The lack of trophic level difference as inferred by the similar $\delta^{15}N_{bone}$ values could be a result of terrestrial C_3 plants and shellfish occupying roughly the same $\delta^{15}N$ range.

It is possible the dietary differences between mounds are due to the differences in proportions of adult age groups. Old-aged adults are only present in To-At-2 and if older individuals were consuming less terrestrial foods compared to younger adults then that could be the cause of the burial mound differences. However, there were no significant differences between the age groups regarding paleodietary isotopic values and so it would seem age differences cannot explain the mound dietary differences.

Another possibility is the temporal difference between mound use. To-At-1 appears to have been used for interment between 489–278 ±21 BP, while To-At-2 was used between 280–220 ±23 BP. Though there is some overlap, To-At-1 was used at an earlier segment of the Chiefdom Period. Food procurement strategies can never be assumed to be static and it is possible those interred in To-At-2 relied more on terrestrial plant foods not because they were accorded these foods due to higher status, but had access to better-established gardens with higher, more consistent yields. While temporal differences remain a possibility, the political environment of the period encompasses both mounds’ ranges of use.

It is also possible that the dietary differences between mounds are related to the different level of prestige accorded to certain foods in the tropical Pacific. While no Polynesian meal is truly a meal without starchy root vegetables, the consumption of large proportions of horticultural plants (especially when fermented or prepared into pudding) is associated with high prestige (Pollock, 1992). As such, starchy root vegetables played a key role in tribute to the Tu‘i Tonga and other nobility during ceremonies (Mariner and Martin, 1827). Despite the low visibility of these low-protein foods in isotope analyses obscuring the true contribution of these plants to diet (Ambrose

and Norr, 1993), the individuals of To-At-2 seem to have consumed more starchy root vegetables than the individuals of To-At-1. Initially, these results may be counter-intuitive given the status associated with certain types of animal foods. Greasy/fatty foods are arguably accorded an even higher status than labour-intensive puddings and fermentations, especially pork (Oliver, 1989). While pigs may have had increased status associated with their ownership or consumption, the relative abundance of lower-status animal protein, relative scarcity of high-status animal protein, and a culture of pork redistribution may suggest that Tongan nobility would not necessarily eat significantly more animal protein despite the status associated with certain animals.

The arguably small differences between mounds are likely reduced because many foods in the Pacific, regardless of associated status, are isotopically similar (Kinaston et al., 2013b, 2014b). For example, a meal of roasted taro and raw coconut would display the same isotopic composition as the higher-status taro pudding with grated coconut cream as an emollient. Another confounding factor may be the cultural practice of burying servants with the chiefs in chiefly burial mounds although these servants were not necessarily eating the same foods as their chiefs (McKern, 1929). It must be noted that social status in Tonga is a continuum rather than discrete units. It has been said no one in Tonga is the same rank as another (Bott, 1981), and the complex system regarding authority and ceremonial rank amongst individuals based on factors such as lineage, age, gender, and birth order complicates understanding status in the context of the discrete archaeological units used in this study: the two burial mounds. The burial mound classification created by McKern (1929) defined three types of mounds, but this classification system does not take into consideration the complex heterarchy present in Chiefdom Period Tonga. It is entirely possible that both mounds are "commoner" mounds as Davidson concluded with no archaeological evidence suggesting status differences (Davidson, 1969). Instead, the individuals interred in To-At-2 may be generally of higher status such as skilled workers or retainers to a chief, offering these individuals access to different foods from unskilled workers of the lowest status. This may also explain why the differences are small (though still significant).

Sex-based differences

Females displayed significantly lower $\delta^{15}N_{bone}$ values compared with males within the entire assemblage. The isotope evidence supports the hypothesis (H_{10}) that males and females were consuming different diets. This is not necessarily surprising as even the most egalitarian societies tend to show age- and sex-based differences regarding wealth, power, and access to foods (Flanagan, 1989; Danforth, 1999). However, it is important

to consider the extent and type of differences in regards to diet, as sex-based dietary differences have not been thoroughly addressed in Polynesian ethnohistoric literature outside of island-specific taboos.

The $\delta^{15}N_{bone}$ differences between the sexes imply that females tended to eat foods from a lower trophic level compared with males, regardless of burial mound. Similar differences have been observed in Taumako, a Polynesian outlier and were interpreted as an indication of males having greater access to high status foods (Kinaston et al., 2013b). In Tonga, these differences could be attributed to sociocultural patterns of food allocation and consumption related to sex. Sisters are granted higher social status than their brothers in Tonga (Kaeppler, 1971; Bott, 1981). While this rarely translated to increased power or agency outside of ritual honours regarding births, weddings, and funerals (Rogers, 1977), deference may have been given to women during mealtimes. Animal protein has been noted as restricted or controlled for women and may have repercussions on overall health (Jelliffe, 1967). In many parts of Polynesia, women were forbidden from eating certain animal foods (Oliver, 1989) although evidence for this practice could not be found in Tongan ethnographic or historical literature.

Although both females and To-At-2 individuals display lower $\delta^{13}C_{bone}$ values than their comparative groups (though the difference between the sexes was not significant), the dietary discrepancies between the sexes may have less to do with social status (as the differences between the burial mounds might indicate) and more with how readily available foods are to certain individuals where varying forms of cultural pressures may result in near-identical archaeological patterns in the classic problem of equifinality (Torrence, 1986; Torrence et al., 1992). Modern ethnographic studies have shown Polynesian men are generally the fishers (Kirch and Dye, 1979; Pollock, 1992), and snacking between meals is a possible scenario that would cause males to display isotopic compositions reflective of higher trophic level and increased marine proportion (Pollock, 1986). Many fish and shellfish can be eaten raw on the beach or in the ocean (Jones, 2009). However, it is often the task of women and children to gather lagoon and reef organisms in the Pacific, and so it is just as likely they were snacking (Jones, 2009).

In modern Oceania, while maritime exploitation past shores and reefs is almost always within the male sphere, land-based food production can be a male-dominated or a female-dominated domain of labour (Ohtsuka, 1985; Levy, 1988; Hezel, 2001; Jones, 2009). In early historic Tonga, women were reportedly freed from "heavy" work and the female domain of labour was restricted to household duties (raising children, cleaning) and the production of wealth objects such as mats and barkcloth (Helu, 1995). Ethnohistoric accounts support the concept that "boys go and girls stay" near or in

the home (Morton, 1996). Mariner, an English ship's clerk who was stranded in Tonga between 1806 and 1810 wrote about the division of labour:

> "It seems to be a peculiar trait in the character of the Tonga people... that they do not consign the heaviest cares and burdens of life to the charge of the weaker sex; but, from the most generous motives, take upon themselves all those laborious or disagreeable tasks which they think inconsistent with the weakness and delicacy of the softer sex. Thus the women of Tonga, knowing how little their own sex in other islands are respected...seldom associate with foreigners." (Mariner and Martin, 1827, 211)

William Anderson, the surgeon's mate on Captain Cook's second voyage, also commented on the relative ease of Tongan women:

> "The employment of the women is of the easy kind and for the most part such as may be done in the house. The province allotted to the men is as might be expected far more laborious and extensive than that of the women. Agriculture, Architecture, Boat building, Fishing and other things that relate to Navigation are the objects of their care." (Anderson, 1967, 932–3)

Furthermore, it has been argued that a united Tongan chiefdom gave men some degree of freedom from preparing for intertribal conflicts (Helu, 1995), thus increasing the amount of time they could spend in food procurement and "freeing" women from that burden. However, internecine conflict over control and distribution of goods, land, and prestige still influenced Tongan life during the Chiefdom Period (Campbell, 1992; Burley, 1998). Thus, the theory of prehistoric Polynesian women not contributing to horticultural production or tending of the earth ovens is suspect. The women observed by Mariner and Anderson may have been of high status and thus not normally involved in manual labour anyway (Campbell, 1992).

Adult diet: comparing young, middle, and old-aged adults

There were no observable differences between the adult age categories regarding bone collagen values (as in Bourewa), and the problems of small sample categories and accuracy in age estimation are again an issue. Unlike Bourewa, a trend (though non-significant) could be observed in $\delta^{15}N_{bone}$ with values increasing in direct proportion with age when the sexes are not pooled. With burial mounds and sexes pooled, older adults appear to be consuming a slightly higher proportion of animal protein, marine

foods, or both. As all of these foods are associated with luxury and prestige, status or power could explain the trend found in adults. The Tongan hierarchy is age and birth order, with older individuals afforded deference from young siblings and community members (Bott, 1981).

However, when the sexes were separated and nitrogen values were again compared between adult age categories, the trend became less clear. Females displayed a slight trend towards higher $\delta^{15}N$ values with increasing age, but middle-aged males displayed a wide range of $\delta^{15}N$ values, encompassing the entire range displayed by young adult males and most of the value range for older males. As with Bourewa, age-based differences in adult diet, if present, could not be observed using isotope analyses. As with social status and burial mounds, the deferences afforded to those of older ages are not translated to dietary differences or are not observable in isotope analyses of diet.

3.8.7 Childhood diet in ‘Atele

There were statistically significant differences between adult and subadult diet at ‘Atele as inferred through bone collagen analyses, with adults displaying higher $\delta^{15}N_{bone}$ values than subadults. Hypothesis 7 (adults will consume more animal protein than subadults) is supported by the isotopic data.

Examining dentine collagen, the childhood diet of adult survivors form two distinct clusters as it did in Bourewa: one below -16‰ $\delta^{13}C$ and one above -16‰ $\delta^{13}C$ with slightly higher $\delta^{15}N$ values (Figure 3.18). For dentine collagen, there appear to be no trends regarding age, sex, or burial mound for these groups, and tests reveal no significant differences.

There were no differences in the childhood diet of adults (inferred via dentine collagen) between the sexes or between burial mounds. The outlier for dentine samples, To-At-1/13, is identified as a young adult female. Her unusually high $\delta^{15}N$ values could have been caused by a physiological response during childhood to extreme protein insufficiency. Buckley (2001) reports no evidence of disease in To-At-1/13, but as she survived childhood any osteological evidence of disease or stress, if it were ever present, could have been erased with time. Unfortunately, her enamel could not be processed for $^{87}Sr/^{86}Sr$ preventing further understanding of her childhood life.

There were differences between the childhood diet of adults and diet of adults within the past 10–15 years of their lives, where dentine $\delta^{15}N$ values were significantly higher compared to bone collagen. Thus, these adults were eating more foods from a higher trophic level in childhood than within the last few years of their lives. The trend continued when comparing the diet of subadults to the childhood diet of adults, where

dentine $\delta^{15}N$ values of adults were higher compared to the bone collagen of subadults. Those who survived childhood ate more higher trophic level foods during their childhood than those who died as subadults.

As with the Bourewa assemblage, the higher $\delta^{15}N$ values in the dentine of adults could arise from consuming more animal protein or could have arisen as a consequence of dietary stress. It seems unlikely almost every individual who survived childhood underwent dietary stress between 5–10 years of age. However, when considering the osteological paradox (Wood et al., 1992), perhaps they survived *because* their bodies successfuly responded to dietary stress (Temple and Goodman, 2014), while the lower $\delta^{15}N$ values of the non-survivors implies a lesser ability to adapt and survive. Adults may have been subjected to the same childhood diseases the subadults displayed evidence of, but re-modelled any evidence. Conversely, perhaps the reason they survived childhood was because they did not undergo dietary stress and were instead given preferential access to animal protein during a critical point in their life. Determining whether the $\delta^{15}N$ differences are due to nutrition or successful stress responses is difficult and there can be no definitive answer within this study.

Comparing the bone and tooth collagen of subadults aged 10–16 years, it is no surprise that there are no significant differences in isotopic values between tissue types. Even with a faster turnover rate for collagen in subadults, much of the life history captured in their bone collagen will coincide with that captured in their dentine. One individual, aged 11 years, displayed the lowest $\delta^{15}N_{bone}$ value in the entire assemblage. This individual (To-At-1/30) was identified by Buckley (2001) as a possible case of scurvy with "porosity at the temporalis muscle attachment site and new woven bone of the alveolar processes of the maxillae" (p. 501). Nuritional stress from severe malnutrition may have affected To-At-1/30's $\delta^{15}N$ values.

3.8.8 Weaning and complete weaning times in 'Atele

Examining Figure 3.15, infants before one year of age fall within the adult mean and standard deviation or slightly above it, and infants around one and two years of age tend to have elevated $\delta^{15}N$ values indicative of breastfeeding. While many infants display nitrogen isotope values consistent with a higher trophic level due to breastfeeding, some individuals have noticeably low values. Two infants, aged 0 and 0.25 years old, display $\delta^{15}N$ values between 12 and 13‰, well within the mean of adult females. Given their young age, it is possible that they died before bones metabolised the ^{15}N enriched breast milk (Katzenberg et al., 1993; Kinaston et al., 2009).

The $\delta^{13}C_{bone}$ values of infants are much closer to the adult mean than their $\delta^{15}N$

values. Breast milk and complementary foods appear to be similar in carbon isotopic composition to those of the adult diet. This is consistent with ethnographic accounts of complementary foods, which were often mashed root vegetables with fish or shellfish integrated in the paste (Jansen, 1982).

No subadults older than two years of age display the elevated $\delta^{15}N$ values expected from breastfeeding. Accounting for faster collagen turnover rates in infants and young children, this suggests that infants were generally completely weaned a few months before the age of two years. This implies that the general Tongan age of weaning occurs before the "natural" weaning age proposed by Dettwyler (1995b), between 2.5 and 6.0 years. The weaning time *is* close to the weaning age described by ethnohistoric accounts of Polynesian breastfeeding practices, which found complete weaning occurring around 2–3 years of age (Handy and Pukui, 1952; Gill, 1979; Jansen, 1982). As this is the only means of examining weaning age in this study, hypothesis 11 (the weaning age of Tongans will occur within the natural weaning age) is rejected. Consideration must be given that these infants who did not survive infancy may have experienced different breastfeeding practices to those who did survive. The examination of collagen from sections of dentine formed during infancy and childhood in adults would allow the examination of breastfeeding and weaning patterns in those who survived childhood (Reynard and Tuross, 2015; Beaumont et al., 2015).

Infancy is a difficult period in childhood life history, and early weaning greatly affects pathogen resistance, nutrition status, and other health factors (Katzenberg et al., 1996; Lewis, 2007; WHO, 2009). The relatively early weaning period is viably a major contributor to infant malnutrition and morbidity and corroborates with the high rate of infant mortality and disease in 'Atele (Buckley, 2000, 2001).

In another light, the relatively short period of breastfeeding might also imply increased fertility. Shorter periods of lactation contribute to smaller birth spacing and increase fertility in a population Bongaarts and Potter (2013); Riordan and Wambach (2010). Although the relatively short period of breastfeeding in 'Atele may have increased mortality and morbidity risk in infants, the increased fertility could be interpreted as an increase in the relative health of the overall population. Tsutaya and Yoneda (2015) found a similarly early point of complete weaning in a Japanese hunter-gatherer-fisher population, around 1.8 years of age and conjectured that better nutrition promoted populational increase.

Malnourished women in modern industrialised societies have been found to breastfeed and experience lactational amenorrhoea longer, decreasing fertility (Potter, 1975), while a study on modern foragers found that male contributions to female diet increased

fertility significantly (Marlowe, 2001). When Buckley examined the ‘Atele assemblage, the old radiocarbon dates by Davidson (1969) were still assumed to be correct, placing the mounds within the Formative Period of Tongan settlement history. Now that recent AMS dates have placed ‘Atele within the Chiefdom period (Kirch, 1984a; Burley, 2007), perhaps a re-evaluation of the implications of childhood health in ‘Atele are necessary. While the Formative Period was when the Tongan population was increasing as gardens become established and rise of the Tu’i Tonga’s influence was beginning to ensure surpluses, the Chiefdom Period is assumed to have been the point when Tongatapu was populated to its capacity limit (Kirch, 1984a; Burley, 1998). The rising population density from increased fertility could be the link between short breastfeeding period (as observed by isotope analyses in this study) and increased exposure to infectious disease in nonadults (as observed by Buckley, 2000, 2001). The isotope study on the Japanese population with a similar age of weaning Tsutaya and Yoneda (2015) is unfortunately not supplemented with any paleopathological studies of childhood health like the ‘Atele population, and thus whether or not that population followed a similar pattern of disease prevalence cannot be determined.

3.9 Summary

The dietary findings from this research will be compared to the oral indicators of diet in Chapter 6. Individual movement as interpreted by $^{87}Sr/^{86}Sr$ analysis will be considered in conjunction with the dietary findings in the final discussion and conclusion. Until then, it is too early to reject or fail to reject the initial hypotheses, other than those which were examined using solely paleodietary isotope analyses (H_7, H_8, H_9, H_{11}).

Chapter 4

Oral Indicators of Diet

Every tooth in a man's head is more valuable than a diamond.
Miguel de Cervantes, *Don Quixote*

This chapter addresses the first aim of this thesis: the characterisation of diet in the prehistoric assemblages of Bourewa and 'Atele. While the previous chapter discussed the use of isotopes as a means of determining dietary patterns, here I examine the oral evidence of paleodiet. Extrapolating diet and oral health from macroscopic examination of teeth and the surrounding bony structures is a common approach in bioarchaeology, partially due to their high preservation potential (Lukacs, 2012; Masotti et al., 2013; Halcrow et al., 2013). Often, oral indicators of diet are used to investigate subsistence strategies such as hunter-gathering or agriculturalism (e.g. Turner, 1979; Smith, 1984; Lukacs, 1992; Temple and Larsen, 2007; Watson, 2008; Deter, 2009; Watson et al., 2013). As identified in Chapter 1, prehistoric Fijians and Western Polynesians do not fit neatly on this subsistence continuum with their reliance on marine gathering and horticultural gardening. Despite this, examining oral indicators of diet in the Tongan and Fijian assemblages can provide evidence of dietary differences between the sites and between subgroups such as the sexes and different age cohorts. Understanding dietary differences can yield insights about Fijian and Tongan cultural systems, how status and power affect access to food resources, and how groups may have adapted to certain environments.

The oral conditions recorded for this study are: caries, occlusal macrowear, calculus, occlusal edge chipping, periodontal disease, alveolar lesions, and ante-mortem tooth loss. Each oral condition to be studied will be introduced: its physical manifestation, underlying aetiology, and the risk factors specific to age and sex if present. Next, a review of the existing literature concerning oral indicators of diet in Oceania (prehistoric

and modern) will be presented. I make no pretence that these regions are not incredibly diverse in terms of both culture and ecology, but the scant amount of research available concerning oral conditions in both modern and prehistoric Remote Oceania requires an examination of ecologically similar regions. Although each dental condition will be given separate consideration when the physical presentation and aetiology are discussed, the anthropological and clinical studies will be narrated in a comprehensive manner. Just as this study examines several dental conditions at once, so do most previous studies: it would be tortuous to present each dental condition separately rather than treat the growing understanding of dental health and diet as a holistic narrative. Any trends concerning sex or other population subgroups found in these studies will be highlighted. Then, the methods used in this study for recording dental markers of diet and subsequent statistical analyses will be explained. Finally, the results will be summarised and interpreted within the context of Fijian/Polynesian cultural food practices as inferred from the archaeological and ethnohistorical literature (detailed in Chapter 2).

As will be discussed below, some of the oral indicators of diet examined in this study are evidence of disease: caries, periodontal disease and periapical cavities. Others may be the results of disease, such as ante-mortem tooth loss (AMTL) or may potentially leave the oral cavity more susceptible to disease, such as advanced occlusal wear, calculus, or large dental chips. Other conditions explored are not necessarily associated with disease at all: mild calculus, small dental chipping and moderate occlusal wear are not pathological in nature. Thus, while some treatises relate these conditions as "oral health indicators" or "oral pathologies," these terms are not completely correct. Though arguably laborious, I try to group these conditions as "oral conditions" or "oral indicators of diet" with the understanding that diet is not the only factor affecting their expression.

Substantial portions of the methods, results, and discussion of this chapter are based on the published book chapter, "Diet and subsistence in Remote Oceania: an analysis using oral indicators of diet." (Stantis et al., 2015c, in press).

4.1 Caries

Dental caries is the most studied dental disease in both modern clinical literature and bioarchaeology (Lukacs, 2012), likely due to its complex aetiology and interactions with other dental diseases (Fejerskov, 2004). As such, dental caries is the first and most comprehensively described condition presented in this chapter. How diet relates to the

cause of dental caries is a major focus of this section, as this provides the aetiological framework for many of the other oral conditions examined.

Dental caries is a bacterial infection of the tooth leading to demineralisation of the inorganic portion and destruction of the organic portion (Featherstone, 2000). The most often blamed microflora for caries are *Streptococcus*, especially *S. mutans, Lactobacillus, Enterococci*, and *Actinomyces* species (Tanzer et al., 2001). These microflora live on the surface of the tooth, forming a dental biofilm (a.k.a. dental plaque). As the bacteria metabolise fermentable carbohydrates, they produce acid which diffuses into the porous tooth material, demineralising the inorganic portion of tooth tissue (calcium, phosphate, and carbonate). Dental caries typically begin on the enamel, although the cementum can develop carious lesions if the tooth root has been exposed to the oral environment and dentine or pulp can also be the primary infectious area if exposed to the biofilm through tooth fracture or wear (Selwitz et al., 2007).

While dental cavities are the stereotypical presentation of carious lesions, a cavity does not form until the final stages of carious lesion progression; more subtle signs are present as a result of infection before a cavity forms (Featherstone, 2004). During the initial stage of infection, only microscopic examination can pinpoint demineralisation. Later, a pinpoint white spot lesion becomes visible although the tooth surface is still smooth and glossy (Featherstone, 1999). The lesion will turn brown as bacteria and food stain the surface (Hillson, 1996). Remineralisation of the tooth surface is possible in the early stages of dental caries, but as the lesion develops the tooth surface finally breaks down from demineralisation, appearing matte rather than glossy and becoming soft enough that the lesion "catches" when scraped with a dental probe. Finally, a cavity forms in the enamel. As demineralization progresses the underlying tooth layers are exposed, allowing cariogenic bacterial access to these layers (Hillson, 1996). Carious lesions in dentine and pulp progress even faster than lesions on enamel, due to the lesser proportion of inorganic components in these tissues (Selwitz et al., 2007).

4.1.1 Aetiology of dental caries

Other than newborns not yet exposed to oral pathogens, all human mouths host cariogenic microflora (van Palenstein Helderman et al., 1996). Thus, the prevalence of dental caries is not determined simply by the presence or absence of cariogenic microflora. Other factors, whether intrinsic parts of a person's biological makeup or external influences such as diet, affect caries prevalence.

The morphology of the teeth plays a vital role in host resistance. The degree of morphological crown complexity (number or depth of naturally occurring pits, fissures,

and grooves) contributes directly to the likelihood of dental caries. Deep pits, fissures, and grooves provide easy surfaces for microflora to adhere to and safe havens from most dental cleaning (König, 1963; Juhl, 1983). Tooth size also contributes to caries resistance, and fossil, archaeological, and clinical studies present a positive correlation between greater tooth size and higher caries rates, possibly relating to the complex relationship between shrinking tooth size and simplification of tooth morphology (Greene, 1970, 1972; Anderson and Popovich, 1977).

Although not seen as often in modern individuals, dental wear also plays an important role in caries incidence. The loss of enamel through dental attrition exposes the more susceptible dentine and the pulp chamber to cariogenic bacteria, and chipping or fracturing of the tooth as a result of wear can create fissures for the microflora to accumulate (Hillson, 2001). Long-term occlusal attrition also causes continuous tooth eruption which exposes the roots of the affected teeth to carious infection (Beck, 1993).

It has been suggested that, since the smoothing of the occlusal surface can remove the pits, fissures, and grooves where biofilm can reside, wear might help prevent carious lesions rather than contribute to them (Thylstrup et al., 1989; Manji et al., 1991). In addition, some types of tooth wear have been suggested not to directly cause dental caries, but to share the same aetiology; heavy anterior wear in a Brazilian population, along with the relatively high rates of caries in the population, was attributed to eating starchy tubers by pulling the edible portions across the anterior teeth (Turner and Machado, 1983). As with many dental markers, the observance of dental wear and dental caries rates needs to be conducted while avoiding the common scientific trap of confusing correlation with causation.

The composition of saliva is important in caries prevention. When in equilibrium, saliva buffers the acidic effects of oral bacteria and initiates remineralisation of the tooth surface as inorganic salivary constituents are absorbed onto the tooth surface (Jenkins, 1979). However, when saliva is at or below critical pH (5.5), demineralisation occurs as saliva ceases to be saturated with calcium and phosphate (Stookey, 2008). Furthermore, the microflora that cause dental caries tend to flourish in the low pH environments they create (Marsh, 2006). In addition to the chemical properties of saliva, the physical properties of saliva (viscosity and amount) also play an important role in caries rates. Saliva clears away food debris and acid from the tooth, and individuals with lower than normal levels of saliva or highly viscous saliva tend to experience significantly higher rates of carious lesions (Fure and Zickert, 1990; Pierce, 1991; Powell et al., 1991; Gopinath and Arzreanne, 2006).

Diet is perhaps the most important contributor to rates of dental caries within

past populations (Mobley, 2003). It is also one of the most complicated factors when exploring cariogenesis. When considering diet as a contributor to caries prevalence, one must consider food composition, preparation methods, and eating habits. Food composition refers to the ratio of macronutrients (carbohydrates, fat, and protein) in foods eaten. Fermentable carbohydrates are the most direct cause of dental caries; without them, oral bacteria cannot metabolise and produce the acid which causes a carious lesion (Selwitz et al., 2007).

Sugar has been positively linked with dental caries since the 1940s, when the infamous Vipeholm experiment was conducted (Gustafsson et al., 1953). Monosaccharides and disaccharides are easily processed by bacteria, producing acid and lowering the pH of the mouth (Luoma et al., 1970). In vitro and pH test experiments suggest that sucrose, glucose, and maltose are fermented the fastest, at approximately the same rates while fructose is processed slightly slower. Lactose is metabolised approximately 40–60% less efficiently than sucrose (Edgar and Higham, 1991). More complex carbohydrates are not as readily metabolised, but can still cause acid production by microflora. Although starches are not easily fermented and cannot readily become part of the biofilm matrix, the breakdown of starches by salivary enzymes can enable starch fermentation (Bird et al., 2000).

The effect of fats and proteins on dental caries prevalence is not as well studied. Fat might reduce the pH-lowering effects of carbohydrates (Frostell, 1969), the coating of the tooth surface in oils may inhibit microbial growth on the surface (Volker, 1957). Protein might also have a protective effect on the tooth surface. Nizel (1970) points out that initial demineralisation of the tooth occurs at the layers of enamel just below the surface and suggests that phenomenon may be because protein can interact with the tooth surface and protect it during the initial stages of caries progression. The relationship between dietary fats and carious lesions were largely ignored for forty years, but renewed investigation corroborate with past research that certain fatty acids reduce enamel demineralistion from *S. mutans* biofilm (Giacaman et al., 2014). While the number of studies investigating the caries-preventing effects of fats and proteins are limited, it appears that fats and proteins do not seem to contribute to dental caries.

The alteration of food can also affect its cariogenicity (Lingstrom et al., 2000). Complex carbohydrates are easier to diffuse into biofilm if made softer and less dense, such as when a root vegetable is boiled and turned into paste (Edmondson, 1990). The chemical and physical processes involved in cooking can also break more complex carbohydrates into simpler sugars. Food preparation can also affect how much saliva is produced during consumption, and thus increase or reduce the cariogenic factor of that

food (Mundorff-Shrestha et al., 1994).

The eating habits of an individual will also affect caries susceptibility. Constant snacking throughout the day causes more frequent fluctuation of salivary pH, creating a more cariogenic environment than eating a few larger meals (Marshall et al., 2005). The order of food eaten has also been shown to have an effect; eating a less cariogenic substance before or after a sugary food reduces the cariogenic effect, while eating two cariogenic substances can compound the pH reaction (Geddes, 1994; Marshall et al., 2005). Unfortunately, understanding ancient eating habits can be difficult, especially when individual agency is considered.

Trace elements in food and water can also contribute to caries rates. Vitamins A, C and D are necessary for proper mineral deposition (Dreizen, 1970). Insufficient levels of calcium, phosphate, and other minerals that are inorganic constituents of the tooth will inhibit remineralisation (Dreizen, 1970; Nanci, 2013). However, these trace elements are typically present within the body and do not factor as strongly in dental caries susceptibility as another mineral: fluoride. Fluoride availability and intake is a major oral environmental factor to consider when examining dental caries development (Griffin et al., 2007). Fluoride is a catalyst for the diffusion of calcium, carbonate, and phosphate onto the tooth surface, reversing damage from the early stages of carious disease progression (Levy, 2003). In addition, if the remineralised crystalline contains fluoridated hydroxyapatite and fluorapatite it will be more resistant to later bacterial infection (Clarkson and McLoughlin, 2000).

The intentional fluoridation of drinking water by government organisations for the purposes of dental health is now common practice (Fawell et al., 2006). Although not intentionally ingested by ancient populations, fluoridated water could have been ingested by past populations depending on their geographical location. Some drinking water sources naturally have a higher fluoride concentration, such as water sources in the East African Rift System (Fawell et al., 2006). Environmental fluoride levels are difficult to ascertain. While volcanic activity contributes to heightened environmental fluoride levels (D'Alessandro, 2006), calcium in limestone, such as the coralline limestone that constitutes many raised coral reef islands, can bind to fluorine and defluoridate water negating any carioprotective advantage (Reardon and Wang, 2000). To my knowledge, no fluoride studies have been conducted on Tonga or Fiji, so I cannot comment on whether this will influence the caries profile of these assemblages.

Although drinking water is the greatest contributor to fluoride levels in humans, food and other beverages have some influence as well. Tea (*Camellia sinensis*), rice (*Oryza sativa*), and barley (*Hordeum vulgare*) have high concentrations of fluoride (Cao et al.,

1996; USDA, 2004), and high-protein and/or high-calcium diets can aid in fluoride retention (Narasinga Rao et al., 1968; Reddy and Narasinga Rao, 1971). Perhaps most important when considering Pacific island diets, relatively high concentrations of fluoride have also been observed in fish, taro, and yams (Barnaud, 1975; Murray, 1986).

Dental hygiene is also important for the prevention of dental caries. Indeed, modern research suggests that oral hygiene is more influential regarding caries prevalence than any other aspect, including sugar consumption (van Loveren and Duggal, 2004; Zero, 2004). Some paleontological and archaeological samples have displayed interproximal grooves that could be attributed to toothpicking or fibre flossing (Formicola, 1988; Brown, 1991; Bermudez de Castro et al., 1997).

Sex-based differences must also be considered. Dental research since the 1930s repeatedly finds, with little exception, that females experience a higher rate of caries than males regardless of location in the world or time period (Munblatt, 1933; Lukacs and Largaespada, 2006; Lukacs and Thompson, 2006; Lukacs, 2008; Patir et al., 2008; Demirci et al., 2010; Ferraro and Vieira, 2010). Caries rates in preadolescent children show no significant difference between males and females and it is not until pubescence that caries prevalence becomes higher in females (Stoughton and Meaker, 1932).

The reasons for sex-based differences are multifaceted and still not well understood. Hormonal influences (Lukacs and Largaespada, 2006) and sex-linked heritability to carious susceptibility (Patir et al., 2008; Vieira et al., 2008) have been investigated as possible reasons for these observed differences between the sexes. Genes might affect deciduous and permanent teeth differently (Wang et al., 2010), which undoubtedly complicates matters but may help explain the lack of differences in preadolescent males and females. Regardless, cultural factors could still result in different food consumption patterns between men and women (Danforth, 1999), which could influence caries susceptibility. Whether culturally- or hormonally-influenced, some studies have shown gender-based differences in food preferences (Wansink et al., 2003; Wardle et al., 2004). It quickly becomes obvious that sex-based differences in cariogenesis are a complex interaction between genetics, hormonal influences, and even cultural expectations of food choice. Regardless of the underlying cause, it is expected that females will experience more caries than men.

Age is also an important factor that affects all oral indicators of diet; older individuals would be expected to display higher frequencies of all dento-alveolar features used in this study, simply because of the increased time of exposure and the fact that teeth do not remodel. However, older adults are also at greater risk for new caries formation, likely because tooth wear and gum recession exposes softer, more susceptible dentine

(Beck, 1993; Griffin et al., 2004, 2005). As such, differences between age categories (i.e. adult/subadult, young-, middle-, and old-aged adults) are an important point of consideration.

4.2 Dental macrowear

Dental wear is the loss of tooth material through attrition, abrasion, erosion, or abfraction. Attrition is the loss of the tooth surface due to tooth-on-tooth contact, most often on occluding surfaces (Hillson, 2000). Abrasion is tooth surface wear caused by foreign substances such as food and dental picks (Hillson, 1979, 1996). The combined effects of attrition and abrasion on the occlusal surface of the tooth, also known as occlusal wear, are most often studied in bioarchaeology (Hillson, 2008).

Erosion is the wear of teeth through non-bacterial chemical processes such as gastrointestinal acids and acidic foods or beverages (Cheng et al., 2009). Erosion is underrepresented in archaeological research, although some studies have commented on its presence in skeletal samples (Cox, 2000; Kieser et al., 2001). Abfraction is the loss of tooth surface at the cervico-enamel junction and is sometimes included as a type of dental wear (e.g. d'Incau et al., 2012). The underlying aetiology is not well understood in the clinical literature, though the leading theory is that abfractions are not a type of dental wear at all, but a result of non-axial tooth loading causing stress at the cervical region (Michael et al., 2009). Curiously, while abfraction has been observed in a clinical setting it has never been found in archaeological samples, and the causes behind abfraction may be uniquely modern (Aubry et al., 2003).

The first archaeological studies of occlusal wear were published in the 1910s, when heavy dental wear was noted in Nubian and Egyptian populations and attributed to tough, gritty foods (Smith and Jones, 1910; Thoma, 1917). Anthropological studies have now used dental wear not only to examine diet in past human populations (Molnar, 1971; Turner and Machado, 1983) but also ancient hominids (Ungar et al., 2001, 2008) and modern primates (Teaford and Walker, 1984; Galbany and Perez-Perez, 2004). Anthropologists have also examined teeth as tools or a "third hand" as evidenced by unique wear patterns (Blakely and Beck, 1984; Turner and Anderson, 2003). As dental wear is a continuous, unidirectional process, it is progressive with age and is frequently used as a marker of biological age-at-death (Miles, 1962, 1963; Lovejoy, 1985; Brothwell, 1989).

The analysis of microscopic patterns of dental wear can be used by bioanthropologists for dietary reconstruction (Ma and Teaford, 2010; Scott et al., 2012). High-resolution

casts of all teeth destroyed for isotope analyses were collected in case of future microwear research (as described in the methods section of Chapter 3). However, microwear analysis is outside the scope of this thesis. Only macrowear was examined for paleodietary analysis in this study.

Dental wear can be an indicator of the coarseness of the food eaten by an individual. Populations that regularly include sand or grit in their food, whether on purpose or unintentionally, experience relatively high rates of dental abrasion (Puech et al., 1983). High levels of tooth wear are commonly associated with hunter-gatherers rather than agriculturalists (Lukacs, 1989), although this line of reasoning needs to be tempered with consideration of culture-specific diets. It has also been suggested that hunter-gatherers display more pronounced wear on their anterior teeth compared to agriculturalists (Molnar, 1971; Hinton, 1981; Smith, 1984; Kaifu, 1999; Deter, 2009). Other, non-dietary contributors to dental wear must also be considered when examining dental wear as a marker of diet, such as bruxism (tooth grinding), the use of teeth as tools, dental modification, and accidental damage to the teeth (Milner and Larsen, 1991).

Generally, mild wear (wear of the enamel only) is asymptomatic in living individuals (Nanci, 2013). Extreme dental wear (resulting in exposure of the pulp chamber) can leave the tooth unable to deposit secondary dentine as a protective measure, leaving the tooth more susceptible to carious lesions, periodontal disease, alveolar lesions, and tooth loss (Lukacs, 1989; Hillson, 1996). Thinning of the enamel from extreme dental wear also increases the likelihood of chipping of the enamel (Lukacs, 1989; Scott and Winn, 2011).

4.3 Calculus

Just as plaque is a causative factor in destruction (dental caries), so too is plaque involved in an accumulative process: calculus. Calculus is mineralised plaque adhered to the surfaces of teeth (Hillson, 1996). Unlike many of the oral conditions explored in this study, the accumulation of mineralised plaque can be reversed with mechanical removal from the tooth surface. The chemical composition and pH of oral fluids is understood to be a contributor: while high acidity demineralises the tooth surface, resulting in dental erosion (see below) and leaving the tooth surface vulnerable to dental caries, a highly alkaline oral environment causes the accumulation of minerals which can ultimately lead to dental calculus (Gurney and Huschart, 1950). Of course, diet must also be considered; a high-protein diet contributes to a more alkaline oral environment which has been associated with calculogenesis (Hillson, 1979). However, sugar consumption is

also positively correlated with the plaque formation necessary for calculus deposition (Fry and Grenby, 1972). Ultimately, the aetiology is multicausal and not well defined (Lieverse, 1999).

Dental calculus can be divided into two categories: supragingival and subgingival calculus. Supragingival calculus, also known as coronal calculus, forms around the crown of a tooth. Supragingival calculus tends to be more prevalent in teeth near the ducts of the major salivary glands: the lingual surface of mandibular anterior teeth (near the sublingual gland) and the buccal surfaces of the molars (near the parotid and mandibular glands) (Alexander, 1971; Lieverse, 1999). Supragingival calculus can also form over the occlusal or incisal surfaces of the teeth if they are not used frequently and subjected to wear.

Subgingival calculus forms within the thin gingival sulcus and is attached to the tooth root. Differences in mineral composition (mostly owing to the different oral fluid contributors of supra- and subgingival calculus, saliva and gingival crevice fluid, respectively) cause a difference in macro- and microscopic appearance between the two types. Supragingival calculus tends to be a creamy yellow-brown colour and have a softer texture due to its lesser degree of mineralisation compared to subgingival calculus, which tends to be harder and darker in appearance (Hillson, 1996). Unlike supragingival calculus, subgingival calculus follows no pattern of distribution within the oral cavity (Alexander, 1971; Corbett and Dawes, 1998).

The relationships between calculus and other dental diseases are not well established (Lieverse, 1999). Given that calculus is the accumulation of minerals on the tooth surface, and carious lesions are the demineralisation of the tooth surface, common sense would hold that the two diseases are negatively correlated. However, the non-mineralised areas of supragingival calculus could harbour harmful bacteria, causing increased rates of dental disease (Tan et al., 2004). Conversely, some modern research has found no significant relationship between dental calculus and dental caries (Pattanaporn and Navia, 1998). Subgingival calculus is positively correlated with periodontal disease: as the gingival sulcus expands and the periodontal pocket deepens due to periodontitis, calculus adheres to the exposed root (Albandar et al., 1998). Although the subgingival calculus is not the initial cause of periodontitis, it has been suggested that the bacteria adhered to the subgingival calculus can cause further progression of periodontal disease (Mandel and Gaffar, 1986).

4.4 Dental chipping

Enamel, although hard, is very brittle (Chai et al., 2009). While other tissues might respond with some level of elasticity or plasticity when subjected to a higher force than they can withstand, enamel instead fractures (Lee et al., 2011). Traumatic tooth fractures from personal injury, such as falling or interpersonal violence, often occur at the alveolar margin and may result in the loss of the entire tooth crown (Lukacs, 2007). Chipping caused by tough food particles, on the other hand, tend to be smaller in size and originate on the occlusal surface (Scott and Winn, 2011). In addition to diet, the use of teeth as a third hand or extensive occlusal wear can leave the occlusal surface vulnerable to chipping (Turner, 1969; Scott and Winn, 2011). Differentially diagnosing between diet-related occlusal chipping and the use of teeth as tools has not been undertaken in the literature and may be more difficult than differentiating between dietary and trauma-related dental chipping. Post-mortem chipping can be differentiated from ante-mortem chipping by the lack of wear on the chipped facet, and the exposure of lighter-coloured enamel and dentine that was not exposed to the oral environment in life (Scott and Winn, 2011).

Although chipping has been studied in cultures that practice intentional tooth modification (Ikehara-Quebral and Douglas, 1997; Arcini, 2005), little research has been conducted on dental chipping as a marker of diet. A few studies (Bonfiglioli et al., 2004; Belcastro et al., 2007; Scott and Winn, 2011) have suggested that comparing the relative prevalence of chipping in anterior and posterior teeth can be used to examine subsistence patterns; hunter-gatherers will experience more chipping on their posterior teeth while agriculturalists will have more chipped anterior teeth. No researchers hypothesise the reason for this pattern. It is possible that individuals who regularly consume a tougher diet will route food particles to their molars in order to maximise the compressive forces on tough food particles. Individuals who expect their food to be soft (as is often the case in agricultural foods) will initiate food particle size reduction with their anterior teeth and will experience chipping of anterior teeth when a hard particle is unexpectedly in food.

4.5 Periodontal disease

Periodontal disease involves inflammation of the periodontium, the tissues surrounding the teeth. The initial stage of the disease (gingivitis) is not the destruction of the underlying bone, but inflammation of the soft tissue lining (Bascones-Martínes et al.,

2011). Gingivitis is present in the majority of modern adults, around 95% (Ogden, 2008). As gingivitis does not do significant damage to the gingiva, is reversible, and appears to be a normal reaction to the oral environment in most of the population, its categorisation as a disease is questionable.

The more severe form of periodontal disease, periodontitis, affects the periodontal ligament and alveolar bone (Darveau, 2010). Unlike gingivitis, periodontitis can be arrested or slowed but the damage is irreversible (Hillson, 1996). In the past, it was assumed that gingivitis would progress to periodontitis if unchecked with improved oral hygiene or host response, and that periodontitis was a chronic, gradual progression of destruction (Reddy et al., 2000). Instead, periodontitis may be more accurately viewed with the "burst" model, where the disease occurs in short bursts with longer periods of quiescence (Reddy et al., 2000). Over time, the resorptive processes associated with periodontitis cause extensive root exposure and teeth can become loose and eventually lost. Even if not lost, the exposed tooth root is unprotected to the oral pathogens in the mouth and becomes more susceptible to caries (Berry et al., 2004).

As periodontal reactions involve the loss of alveolar bone, it can be confused with other conditions that cause the tooth root to become exposed: compensatory and continuous eruption. Compensatory eruption is the movement of the tooth towards its antagonist tooth and away from the jaw in order to maintain occlusion (Danenberg et al., 1991). Compensatory eruption counterbalances occlusal wear, which would eventually result in the teeth not coming to occlusion and thereby reduce masticatory effectiveness. Irrespective of occlusal wear, the teeth move gradually away from the jaw towards its antagonist tooth throughout life in a process known as continuous eruption (Whittaker et al., 1990). Neither compensatory nor continuous eruption are diseases in themselves (although severe wear can lead to the teeth being pushed so far from the jaw that they are susceptible to loss), and can be differentiated from periodontal disease by examination of the alveolar margin (Clarke and Hirsch, 1991). Healthy alveolar margins will display a clean, sharp edge and be tight to the tooth root. Alveolar margins affected by periodontitis disease will be ragged, porous, and blunt. Periodontal pockets will form in the alveolar margins, creating space between the tooth and surrounding bone (Ogden, 2008).

Interpreting the underlying aetiology of periodontitis can be very complex, especially when trying to consider the influence of diet. Generally, infection by oral pathogens is the primary cause of periodontitis (Li et al., 2000). Oral hygiene is a major contributing factor in individual susceptibility to periodontitis (Löe et al., 1965). Diet has a significant effect on an individual's risk for periodontitis just like in risk for carious lesions (Al-

Zahrani et al., 2005). Regarding long-term nutrition, people with diabetes tend to have a significantly higher prevalence rate at an earlier age than non-diabetics though the underlying aetiology, infection, remains the same (Löe et al., 1992; Lalla et al., 2007). Hypovitamintosis C (scurvy), hypovitamintosis E, and hypervitamintosis A have all been linked to periodontal inflammation (De Menezes et al., 1984; Fain, 2005; Iwasaki et al., 2012). Certain nondietary activities have also been associated with periodontitis, such as betel nut (*Areca catechu*) and coca leaf (*Erythroxylaceae* spp.) chewing (Hung et al., 2000; Ling et al., 2001; Indriati and Buikstra, 2001).

Within modern populations, a general background level of periodontitis is expected to affect around 10% of individuals (Jenkins and Kinane, 1989). It has been proposed that populations experiencing greater than 10% prevalence may have these rates skewed from individuals with extreme periodontitis, or specific dietary patterns leaving the population more susceptible to periodontal disease (Skrepcinski and Niendorff, 2000; Hung et al., 2000; Indriati and Buikstra, 2001). Although most cases of periodontitis are likely a result of infection, there are some non-infectious causes of periodontitis; for example, trauma is the second-most likely cause of periodontitis in clinical cases (Armitage, 1999). In a paleopathological setting, examination of other dental features (e.g. caries prevalence) and their interaction with periodontal disease is important for considering the most likely causes of periodontal disease in past populations (Hillson, 2008).

4.6 Alveolar lesions

Alveolar lesions are cavities in the bony walls of the maxillae or mandible formed as a result of infection (Dias and Tayles, 1997). Periodontal disease can lead to alveolar lesions along the periodontal margin, though most alveolar lesions are periapical in origin like the example in Figure 4.1 (Dahlén, 2002). Periapical responses typically arise as a bony inflammatory response to pulpal infection. Most often the pulpal infection is chronic and the bone resorbs as granulation tissue accumulates (Dias and Tayles, 1997). Occasionally granulomas may develop into larger periodontal cysts as the granuloma tissue is replaced with fluid. Both periapical granulomas and periodontal cysts tend to be symptomless in life (Hillson, 2001). When the inflammatory response involves pus rather than granuloma tissue, abscesses are formed. The walls of an abscess cavity are rough rather than smooth like granulomas or periodontal cysts. Secondary acute abscesses may develop from granulomas and/or periodontal cysts (Dias and Tayles, 1997). Osteomyelitis may also form on alveolar bone, though this is easy to differentially

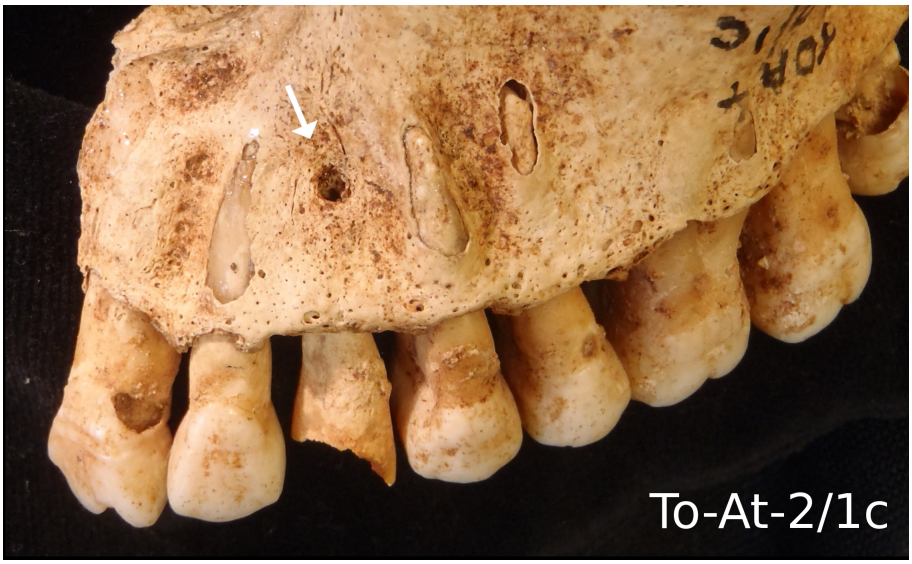


Figure 4.1. *Alveolar lesion adjacent to the maxillary canine, approximately 3 mm in diameter. Note the gross gross carious lesion that has destroyed much of the canine. Image by author.*

diagnose with the evidence of necrotic bone, sequestra, involucra, and multiple drainage sinuses (Ortner, 2003).

In many oral health reports, these alveolar cavities are all incorrectly categorised as "abscesses" with little descriptive information or differential diagnosis accompanying the report (Dias and Tayles, 1997). This leaves comparisons difficult. The terms *periapical cavity* (Dias and Tayles, 1997; Hillson, 2001) or *alveolar lesion* (Willis and Oxenham, 2013) have been used in bioarchaeological research as a general term for this category of conditions. Both terms will be used interchangeably in this study as both are acceptable in that they do not specify an underlying infection (unlike the term abscess), although these lesions do not always occur in the periapical region and so the term *alveolar lesion* might be more appropriate.

Unlike many of the other oral conditions examined in this study, alveolar lesions can remodel if the source of infection is removed (Dias and Tayles, 1997). The presence and severity of alveolar lesions are dependent on a number of factors, including host response, severe carious lesions, trauma, or severe dental wear leaving the pulp chamber exposed to infection (Littleton and Frohlich, 1993; Dias and Tayles, 1997). Interpretation of these cavities in relation to diet is dependent on differential diagnosis (Figure 4.2), though discerning between the types of alveolar lesions is perhaps less important than understanding that they all have a possible relationship with caries and ante-mortem tooth loss (Hillson, 2001).

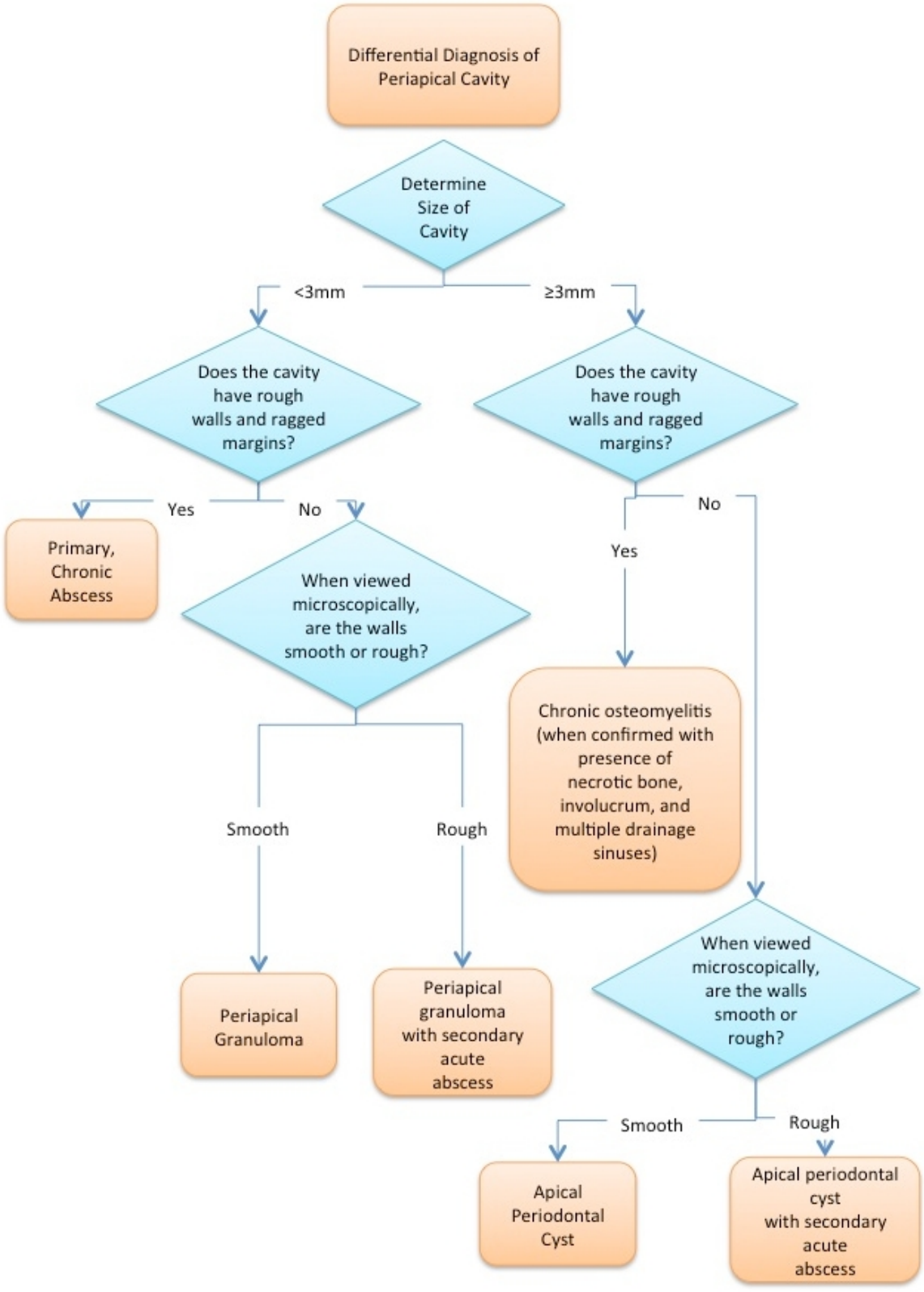


Figure 4.2. *Differential diagnosis flowchart for periapical cavities.*

4.7 Ante-mortem tooth loss

Ante-mortem tooth loss (AMTL) is the loss of a tooth before death. AMTL can be differentially diagnosed from post-mortem tooth loss by examination of the tooth socket. When a tooth is lost during life, the socket undergoes a remodelling of bone tissue; given enough time, the socket can be replaced with smooth lamellar bone that shows no sign a socket ever existed (Hillson, 1996). In the case of complete remodelling of the alveolar surface, AMTL can sometimes be confused with congenital absence of teeth or failure to erupt (Hillson, 2001). Radiography can help differentially diagnose between these conditions. When a tooth is lost post-mortem, the socket shows no sign of responsive remodelling. Teeth lost peri-mortem cannot be differentiated from post-mortem loss as the body never had time to begin the remodelling process.

AMTL has myriad aetiologies. Often, AMTL is secondary to some of the other dental diseases to be examined in this study: extensive macrowear, gross caries, and pronounced periodontitis can all cause tooth loss (Hillson, 2001). Trauma is another common cause of AMTL. Accidents, such as falling, could cause damage to any part of the dental arch. Trauma from interpersonal violence is thought to most often affect left anterior teeth with the assumption that interpersonal violence is typically conducted by right-handed attackers from the front (Lovell, 1997; Novak, 2000; Lukacs, 2007). Intentional tooth ablation (the removal of teeth, especially anterior teeth) for ritual purposes have been observed in Polynesia. William Anderson, a surgeon's mate on James Cook's second and third voyages, recorded the Tongan grieving custom of beating their teeth with stones (Cook, 1967b, 946). Intentional tooth ablation in living individuals as a means of honouring the deceased has been observed in Hawai‘i (Pietrusewsky and Douglas, 1993). These grieving practices could have caused dental trauma such as chipping and AMTL.

Given the number of aetiologies for AMTL, demographic trends are difficult to quantify. As a degenerative condition connected to periodontal disease and carious lesions, AMTL would be expected to be strongly correlated with age (Lukacs, 1989; Hillson, 1996). There are no global patterns of sex-based differences regarding AMTL, possibly because patterns of AMTL within the dental arch or by jaw are typically only studied when AMTL is derived from trauma (Lukacs, 2007) or aesthetic ablation (Temple et al., 2011) of anterior teeth.

4.8 Comparative dental studies

As one of the most prevalent chronic diseases in the world today (Selwitz et al., 2007), it is no surprise that the recording of dental caries prevalence is ubiquitous in biological anthropology. Examining caries in ancient dentitions has been of scientific interest since the 19th century, when some dental researchers were trying to determine the underlying causes of dental caries (Mummery, 1870; Richardson, 1881). Dental macrowear become a regular part of dental studies alongside dental caries beginning in the early 20th century (i.e. Smith and Jones, 1910; Thoma, 1917; Leigh, 1928). Although there is little doubt the earlier researchers knew of the correlation between dental disease and ante-mortem tooth loss, early studies did not typically note AMTL, Patrick (1895) being an exception. AMTL was not seriously studied until Hrdlička (1940) examined ritual ablation in prehistoric Inuit populations.

The study of dental calculus in an archaeological context is fairly recent compared to other dental aspects; although a recording method was established in Brothwell's *Digging up Bones* (1963), it was not until the 1970s that publications were produced examining dental calculus in an archaeological skeletal assemblage (Evans, 1973). In addition to the traditional method of recording the macroscopic presence of calculus, recent studies have begun to explore calculus as a proxy for paleodiet using advanced methods of research. Biochemical analysis of the composition of dental calculus as means of understanding ancient diets has been investigated (Hardy et al., 2009; Henry et al., 2011), as has isotope analysis of dental calculus (Scott and Poulson, 2012; Poulson et al., 2013; Salazar-García et al., 2014).

Lukacs (1989) was among the first to use multiple dental pathologies to reconstruct subsistence patterns in a material-scant archaeological setting. In doing so, he created dental pathology profiles (DDPs) for hunter-gatherers, agriculturalists, and a transitional subsistence pattern between the two. Unfortunately, these three patterns do not encompass the wide variety of subsistence practices found in human antiquity; for example, the horticultural subsistence system of the wider Pacific, which centres on starchy root vegetables with a heavy reliance on marine resources, does not fit within those patterns. Thus, the dental pathology frequencies of prehistoric Tongans and Fijians would likely not fit into any of those DPPs. A DPP from island and coastal communities from the Arabian Gulf (3000 B.C.E. to 1500 C.E.) has been created by Littleton and Frohlich (1993) for populations heavily reliant on fishing and agriculture, and a marine-dependent DPP had been created as part of a master's thesis from Pacific coastal and island populations (Selwood, 2010). Unfortunately, both of these DPPs

displayed different prevalences of dental pathologies. In addition, dietary differences between sex, age, and social class are rarely studied in Polynesian prehistory, most often because of poor preservation and small sample sizes in these collections from tropical locations. Creating a marine-dependent DPP is potentially useful in order to compare marine-dependent horticultural diets on a global scale, but the breadth of differences between tropical Pacific populations concerning oral conditions (below) makes generalising this vast region unlikely and will not be attempted in this study.

4.8.1 Oceanic bioarchaeological studies

Mummery (1870) is the first study of dental disease in non-living Pacific Island individuals. Mummery included in his global census prehistoric Pacific Island individuals (of unmentioned provenance and antiquity), and noted a comparatively low incidence of caries in the Pacific Island skulls he studied, with only 3.0% of individuals displaying carious teeth. Patrick (1895), in his comprehensive examination of crania from various United States museums (also of unmentioned antiquity), examined individuals from the Pacific. Patrick found a higher prevalence of caries in Pacific dentitions compared to Mummery's findings, 15.3% (417/2738 teeth). Patrick also noted AMTL, 299 remodelled sockets in 169 individuals, although he did not note how many unremodelled sockets he observed.

Pickerill provided the first in-depth analysis of prehistoric Polynesian dental health, examining macrowear, caries, and periapical abscesses (Pickerill, 1912a,b). Pickerill named the Maori as "the *most* immune race to caries" (Pickerill, 1912b, 12, original emphasis) and found only two skulls with carious lesions of the 260 examined, or 0.8% of individuals.

In his study of Maori and Moriori skulls, Taylor (1962) observed low prevalences of dental caries as appeared to be typical for Polynesian pre-Contact individuals, but noted a high rate of periapical abscesses as well as extensive macrowear in the populations. Taylor also presented the prevalence of AMTL in his sample, finding 29.2% (19/65) of maxillae had teeth missing pre-mortem, and 37.9% (11/29) of mandibles (Taylor did not display his findings in terms of individuals, only single bones). Taylor was the first to report dental calculus prevalence in a Polynesian population, but found very little.

Taylor was also the first to conduct an assessment of dental health on 52 individuals with 855 teeth from the 'Atele burial mounds (Taylor, 1971). Taylor's results could be compared to the findings of this study, but the assemblage as Taylor studied it in 1971 is not completely the same as it is at the time of this project. More individuals are examined in this study, 89 compared to Taylor's 52. Some of the crania examined

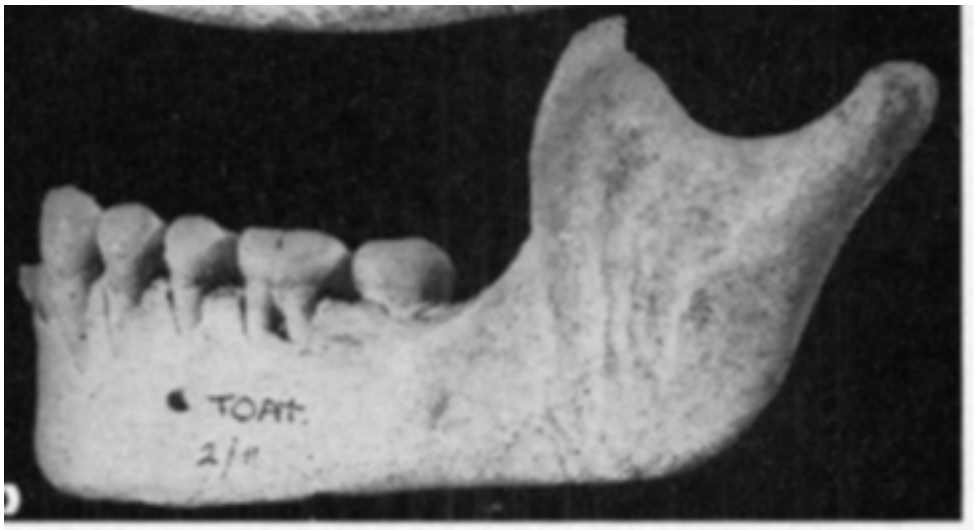


Figure 4.3. *Photo of the mandible of To-At-2/11, which is no longer in the 'Atele collection curated at the University of Otago for unknown reasons. Photo by R.M.S. Taylor, originally published in Taylor (1971).*

in this study are from individuals without burial designations, which Taylor did not examine. There also appear to be some skeletal elements Taylor was able to examine that, for whatever reason, are no longer part of the collection. For example, Figure 4 (p. 180) of Taylor's article is a photo of the mandible of To-At-2/11, and this mandible is no longer in the collection.

The only other remains from Tongatapu to be studied using a bioarchaeological approach are individuals excavated from site To. 1 (Poulson, 1987). These remains from To.1 (now designated To-Pe-1 using the modern system) were originally considered Lapita-associated, although radiocarbon dates suggest that they are post-Lapita (Petchey et al., 2011). Unfortunately, as only three individuals of varying preservation were found, there is little comparative data to be gleaned from this sample of 19 teeth (Spennemann, 1987).

Keene and Keene (1985) provide the only research on prehistoric Polynesians thus far to thoroughly record caries in subadults. A sample of 245 subadults (2854 teeth) from prehistoric Hawai'i (c. 1700–150 BP) were examined for carious lesions. Keene and Keene (1985) report 3.7% of deciduous teeth affected (63/1855) and no permanent teeth affected in mixed dentitions (0/999 teeth). Keene (1986) found higher caries rates than previously recorded in Polynesian adults, with 34.5% (462/1338) of prehistoric Hawaiian (c. 1700–150 BP) crania examined displaying carious teeth and 9.8% (1895/19425) of total teeth affected.

An unpublished PhD thesis focused on demography and macroscopic evidence of

health in the burials from the Sigatoka Sand Dune on Viti Levu, Fiji (Visser, 1994). Dental pathologies in sexed adults (15+ in his study) were examined. Periapical cavities were reported by individual, where 13 of 40 (33%) adults were affected. Twelve of the thirteen affected display two or more cavities. A higher proportion of females display alveolar lesions, 10/21 (48%), compared to 3/19 (16%) males. Visser tabulated AMTL by sex, but did not statistically compare the two groups. Using Visser's data (p. 108) and a Pearson's chi-square test, there appear to be no differences between the sexes in the Sigatoka assemblage, $\chi^2(1) = 1.03$, $p = 0.309$. Visser (1994) reported caries lesions prevalence by tooth between males and females, but did not compare them using inferential statistics. Again with his data, there were no significant differences between males and females (p. 110), $\chi^2(1) = 0.72$, $p = 0.397$.

Kieser et al. (2001) examined dental macrowear in pre-Contact Maori teeth. The 50 individuals examined displayed heavy rates of wear consistent with the late prehistoric Maori diet, which was largely composed of gritty shellfish and fern root. Scanning electron microscopy revealed that erosion played a large part in tooth wear in this population. Whether this erosion was caused by high-acid foods or gastro-intestinal acids could not be determined (Kieser et al., 2001).

The Latte Period (1000–1521 CE) site of Apurgan in the Marianas Islands, a Micronesian archipelago, 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. Pietrusewsky et al. (1997) presented an in-depth analysis of prehistoric (1000–1521 C.E.) health in the Mariana Islands using a collection from the Bernice P. Bishop Museum (Honolulu, Hawai'i). They found 9.9% (157/1591) of teeth affected by carious lesions, 30.3% (871/2876) had "moderate" wear (teeth with dentine exposure), and 5.8% (265/4532) of sockets showing remodelling associated with AMTL. A study focusing on carious lesions in the permanent dentition of prehistoric/protohistoric 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 examined sex-based differences in dental wear, but did not compare the sexes for any other dental diseases (Evans, 1987).

In 2006, nine individuals from Fiji (dated c. 1850 C.E.) were examined for dental markers of diet (Valentin et al., 2006). Only the eight adults were examined, and the 198 teeth present created a sample size too small for meaningful statistics. Nevertheless, the authors found a high rate of carious lesions (15.6% or 31/198) and low rates of

macrowear, calculus formation, periapical cavities, and alveolar recession. Valentin et al. concluded that these oral conditions (combined with isotope analyses) suggest a vegetable-rich diet with little shellfish consumption.

Kinaston's PhD thesis (2010) centres on dietary reconstruction in the Pacific Islands, using six prehistoric skeletal assemblages. Kinaston's investigation of oral pathology in the Namu burial ground from Taumako, a Polynesian outlier from the Solomon Islands (c. 750–300 BP) revealed low rates of wear, carious lesions, and periapical cavities, and high rates of calculus and periodontal disease. Kinaston found no sex-based differences in the severity of wear, or prevalence of caries, calculus, cavities, periodontal disease, and AMTL in the Taumako assemblage. 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. 3000 BP); 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. 800 - 300 BP), Kinaston (2010) observed that males had significantly higher rates of heavier wear compared with females. Kinaston (2010), following Littleton and Frohlich (1993), investigated the utility of a marine-dependent DPP in the six sites. There were significant differences between the six sites regarding oral indicators of diet prevalences and thus very different DPPs. This led Kinaston (2010) to conclude that the use of DPPs are not appropriate in the Pacific.

Kinaston's (2010) research included an examination of deciduous dentition. The Namu burial site was the only assemblage with enough subadults to examine subadult oral indicators of diet in-depth. Teeth from subadults aged 4–16 years of age displayed relatively high prevalences of caries, 11% (12/114) of permanent teeth and 24% (28/115) of deciduous teeth showing cavitated caries. The subadult caries prevalence in Taumako was much higher than adults, who display 4% (63/1679) caries prevalence per tooth. A high prevalence of non-specific indicators of childhood stress (linear enamel hypoplasia) in the Taumako adults, combined with the high rate of caries in subadult deciduous teeth was interpreted by Kinaston (2010) as two manifestations of prenatal and early postnatal environmental stress.

Buckley et al. (2010) provide a comprehensive examination of health in the skeletal remains from Wairau Bar, the oldest dated assemblage in New Zealand (c. 1288–1300 C.E.), examining patterns of infection, degenerative joint disease, stature, trauma, and non-specific indicators of stress in addition to oral indicators of diet. Buckley et al. (2010) examine wear, periodontal disease, alveolar lesions, AMTL, and caries in adults of estimated age and sex. No inferential statistics were reported, but some simple

Pearson's chi-square tests between the sexes in the young adult age group (the largest cohort) could be conducted with the information provided (Buckley et al., 2010, 15). There were no differences between young adult males and young adult females regarding periapical cavities, $\chi^2(1) = 0.89$, $p = 0.345$, or AMTL, $\chi^2(1) = 2.58$, $p = 0.108$. Young males from Wairau Bar display significantly higher rates of periodontitis, $\chi^2(1) = 12.50$, $p < 0.001$ and significantly higher rates of caries, $\chi^2(1) = 6.05$, $p = 0.014$.

The most recent bioarchaeological analysis of dental conditions is a PhD thesis on prehistoric (c. 500–150 BP) Maori and Moriori from New Zealand (George, 2013). George attempted to create a DPP specific to New Zealand subsistence using dental wear, calculus, caries, periodontal disease, alveolar lesions and AMTL. As with previous studies of New Zealand Maori, heavy occlusal wear (to the point of pulp exposure) was observed, most likely related to high prevalences of AMTL and periodontal disease. No differences between the sexes were observed in the prehistoric New Zealand assemblages.

4.8.2 Oceanic dental studies in living populations

Modern epidemiological studies can provide information of whether living Pacific Islanders have similar patterns of risk regarding oral condition. 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. There are a few 20$^{\text{th}}$ century medical studies of oral health in living populations, and from them 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% of teeth or 3528/9965) and periodontal disease (26.8% of individuals or 92/343) on Rarotonga, the main point of European contact in the Cook Islands, Eastern Polynesia. The island of Pukapuka in the Cook Islands was more isolated than Rarotonga when Davies visited to collect data on oral health. Regarding periodontal disease, 45% (225/497) of individuals were affected, a higher rate compared with those on Rarotonga. In contrast, the caries prevalence on Pukapuka was markedly lower (12.1%,1573/12981 teeth) compared with Rarotonga.

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, 1956). In the Pukapuka population there was no association between caries and hypoplasia or caries and dental wear (Davies, 1952, 1956).

A study of three Papua New Guinean villages relatively isolated from Western influence at the time of research (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 compared with females.

4.9 Methods

The dental recording methodology for this study was largely based on the Hillson (2001) method for recording dental caries, with some modifications and additions. All data were collected in the University of Otago Anthropology Laboratory under strong, oblique lighting. A magnifying lens (10×) was used as needed. Teeth were removed from their alveoli when possible for closer examination. Root exposure was measured using a graduated periodontal probe. All data were recorded to Filemaker Pro 11.0v3.

The general census of the dental material was recorded using Hillson's (2001) method. Hillson's census method records the number of teeth present for the study, but also ante- and post-mortem tooth loss, post-mortem damage, anomalous eruption, and what Hillson designates "gross gross carious lesions," wherein the carious destruction has progressed so that only the apical portion of the tooth root remains and it is impossible to determine where the lesion originated (Hillson, 2001, 258). Noting the presence of gross gross carious lesions and post-mortem damage provides a record of the tooth's presence, as well as an explanation for why the tooth could not be recorded for other conditions.

Several patterns are compared throughout this study. For each dental condition, the frequency of teeth affected to the number of total teeth observed was reported, as was the prevalence of individuals with any manifestation of the dental condition to the total number of individuals. Differences in the frequency of oral conditions between the different tooth types (incisors, canines, premolars, and molars) were compared. In order to examine spatial differences in the dental arch, all incisors and canines are considered 'anterior' and all premolars and molars are considered 'posterior.' Differences in the frequency of conditions between the jaws (maxilla and mandible) were also considered.

4.9.1 Regression modelling

For each dental condition, 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 dental conditions. The outcome variable for each of the models was whether or not each tooth displayed a given condition under examination (hence the need for a logistic model). While linear regression could be utilised with ordinal data (e.g. caries severity), collapsing all dental conditions into present/absent data types for logistic regression enables a quick comparison of outcomes between all dental conditions. 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).

Two 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.

The first class of model included both assemblages to compare ‘Atele and Bourewa. The following predictor variables were included in the first model: sex, position in the jaw, dental arch, and adult age categories (young, middle, and old adults). Age was included in the model to remove the effect of age when looking at the associations for the other characteristics. If age was not included, it would not be known if significant effects were related to other predictor variables or due to age as it is already known that increasing age has an impact on oral health (Demirci et al., 2010). Young adults were the reference category in the model, and then a linear combination of estimators were conducted between middle-aged and old adults.

Some individuals, as mentioned in Chapter 2, were categorised as indeterminate for sex or age. Subadults were not placed in any adult age category and could not be estimated for sex. Any of these individuals with missing demographic data were not included in the models. While there are techniques for replacing missing data with values (Howell, 2008; Baradli and Enders, 2010), these approaches can introduce error when the sample size is small or the data are not missing completely randomly. In this study, sample size could be an issue, and the non-random demographic trends in the

burial assemblages is always a possibility in bioarchaeology (Waldron, 1994; Pinhasi and Bourbou, 2008). Thus, listwise deletion of any cases with missing data were conducted rather than trying to replace the data.

In the second multi-level logistic model, each site was tested separately to understand site-specific age and sex differences. Position in the jaw and dental arch would have been included in the second models, but the Bourewa data alone are too limited to support these extra predictor variables: initial models including all four predictor variables often could not iterate. So, position in the jaw and dental arch were dropped in the second model. Burial mound was included as a predictor variable when examining the 'Atele mounds. As with the first model, young adults were the reference category in the model, and then a linear combination of estimators were conducted between middle-aged and old adults.

A second kind of regression model was used for oral conditions that were measured on an ordinal scale (i.e. by severity): an ordered logit model. Ordered logit regression was conducted to understand the relationships between the severity of oral conditions and other variables (e.g. position in the jaw, dental arch, tooth type). One assumption underlying ordered logit modelling is parallel regression: that the relationship between each pair of outcome groups is the same. For example, in the case of caries severity, parallel regression assumes that the relationship between the first category (caries absence) and the other three categories is to the same degree as the relationship between the first two categories and the last two categories is to the same degree as the relationship between the first three categories and the last. If this assumption is violated, ordered logit model was still conducted, but interpreted with caution. Another type of regression, multinomial modelling, could have been conducted and does not require parallel regression. Multinomial modelling, however, does not treat the oral condition severity as a ranked scale. Since it is the ordinal relationship regarding severity that is interesting, a multinomial model is not as appropriate as an ordered logit model even if the assumption of parallel regression is violated.

4.9.2 Caries recording and statistical analysis

The Hillson (2001) method of dental caries recording examines each surface of the tooth as separate areas. Root and crown surfaces of each aspect (buccal, lingual, mesial, distal) were recorded separately, totalling eight aspect surfaces. The occlusal surface (fissures, grooves, fossae) were recorded in molars and premolars. The buccal and lingual pits sometimes found in molars and incisors were recorded, if present. Although discolouration of tooth surfaces was recorded, only cavitated lesions are considered

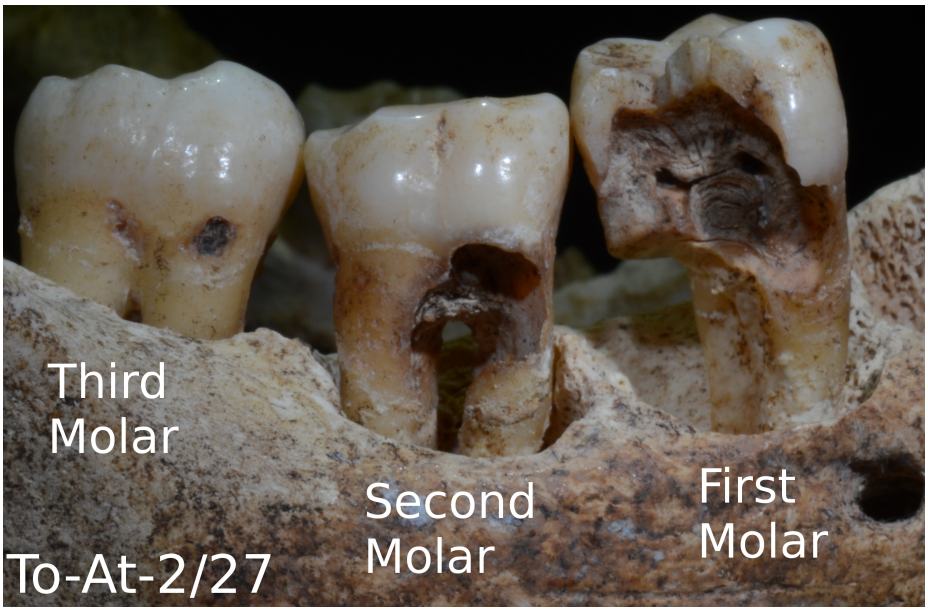


Figure 4.4. *Example of different progressions of carious lesions. The carious lesion on the third mandibular molar is shallow and penetrating the dentine, while the carious lesion on the second molar opens the root canals. Despite some post-mortem damage, it can be observed that the lesion on the first molar root has destroyed neighbouring areas and opened the pulp chamber. Image by author.*

carious for this study, as taphonomic staining can cause recording error in archaeological material. Thus, any mention of dental caries forthwith refers to cavitated carious lesions. Carious lesion severity was recorded as "absent," "penetrates enamel," "penetrates dentine or root surface," or "open pulp chamber or root canals." Gross gross carious cavities were recorded and were not included when examining surface patterns of carious lesions since their origin cannot be determined. The severity of gross gross caries (whether or not they penetrated the pulp chamber and/or root canal) was recorded.

In archaeologically-derived skeletons, some teeth will have been lost ante-mortem as a result of progressive destruction from caries. 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 (Waldron, 1994; Lukacs, 1995; Hillson, 2001). Some researchers have created equations to account for the teeth lost to caries before death by including the number of teeth lost antemortem 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 teeth were lost specifically to caries, many researchers are critical of these caries correction factors (Hillson, 2001; Oxenham and Matsumura, 2008; Wasterlain et al., 2009). For this reason, no caries correction factors were included in this study.

First, caries presentation were considered by surface type. The contact areas (mesial and distal crown), smooth surfaces (buccal and lingual crown), roots, pits/fissures (present on the buccal and/or lingual aspect of some teeth), occlusal surface, and occlusal attrition facets were compared. The percent prevalence (number of caries observed on a particular surface divided by number of a particular surface observed in total) was tabulated by site and sex. The caries prevalence by surface was also compared between adults in the ‘Atele burial mounds.

For further statistical tests, tooth surfaces data were collapsed to a single tooth; a tooth or surface with any number of carious lesions on its surface was considered carious. The frequency of teeth affected by carious lesions was reported, as was the prevalence of individuals with carious lesions. The severity of the carious lesions were also tabulated. Ordered logit regression was conducted to understand the relationships between the severity of carious lesions and other variables (e.g. position in the jaw, dental arch, tooth type). After further collapsing the data to a binary variable of presence/absence of carious lesions, multi-level logistic regression was conducted in the manner described above (section 4.9.1).

4.9.3 Occlusal wear recording and statistical analysis

There are several methods available to score dental wear. For this study, the Smith method (1984) was used for the anterior teeth and premolars. The Smith method involves assigning degree of wear on a tooth using the text (Smith, 1984, 45) and visual descriptions (Figure 4.5) provided. This method was chosen for its ease of use and compliance with Hillson’s (2001) recommendations for recording wear. However, unlike Hillson’s recording system, the Scott system of recording molar wear (Scott, 1979a), was used for molars. The Scott system uses textual and visual descriptions to assign degrees of wear, like Smith, but divides each molar into four quadrants to prevent the generalisation of wear patterns between quadrants that would prevent understanding directional wear (Figure 4.6). The Scott system provides a detailed, reliable method of scoring molars when revised for consistent orientation between teeth (Shykoluk and Lovell, 2010). By orienting the teeth in a consistent manner, directional wear patterns can be observed and wear angle can be extrapolated (Figure 4.7). An example of the Scott molar wear recording method using the Shykoluk orientation can be seen on Figure 4.8. For any recorded molar, each quadrant visible was assigned a score between 1–10, leaving each complete molar with a composite score between 4–40.

In complete dentitions, only one side (left or right) was scored per individual in regards to tooth wear, for maximum efficiency of time. In the case of missing teeth,

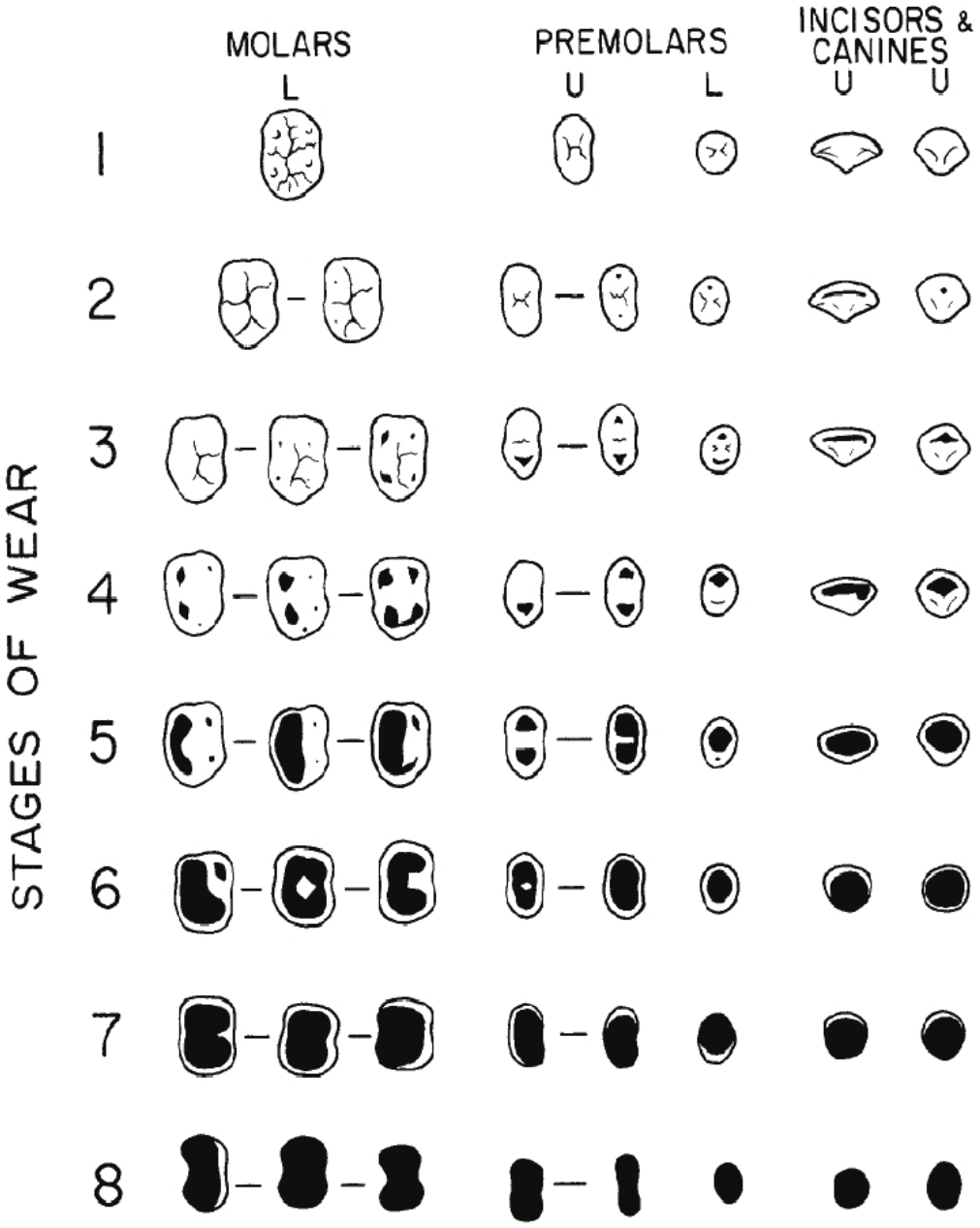


Figure 4.5. *Visual guide for the Smith wear method (Smith, 1984, 46).*

TABLE 1

Attrition scoring technique

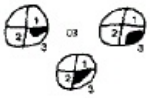
	Score	Description
	0	No information available (tooth not occluding, unerupted, antemortem or postmortem loss, etc.)
	1	Wear facets invisible or very small
	2	Wear facets large, but large cusps still present and surface features (crenulations, noncarious pits) very evident. It is possible to have pinprick size dentine exposures or "dots" which should be ignored. This is a quadrant with *much* enamel.
	3	Any cusp in the quadrant area is rounded rather than being clearly defined as in 2. The cusp is becoming obliterated but is not yet worn flat.
	4	Quadrant area is worn flat (horizontal) but there is no dentine exposure other than a possible pinprick sized "dot."
	5	Quadrant is flat, with dentine exposure one-fourth of quadrant or less. (Be careful not to confuse noncarious pits with dentine exposure.)
	6	Dentine exposure greater: more than one-fourth of quadrant area is involved, but there is still much enamel present. If the quadrant is visualized as having three "sides" (as in the diagram) the dentine patch is still surrounded on all three "sides" by a ring of enamel.
	7	Enamel is found on only two "sides" of the quadrant.
	8	Enamel on only one "side" (usually outer rim) but the enamel is thick to medium on this edge.
	9	Enamel on only one "side" as in 8, but the enamel is very thin—just a strip. Part of the "edge" may be worn through at one or more places.
	10	No enamel on any part of quadrant—dentine exposure complete. Wear is extended below the cervicoenamel junction into the root.

Figure 4.6. *Description of Scott molar wear method (Scott, 1979a, 214).*

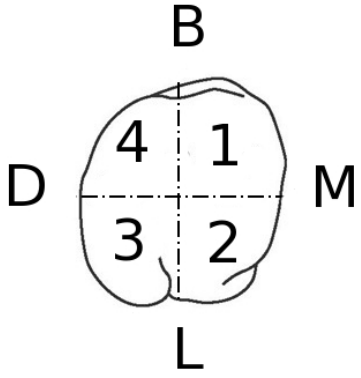


Figure 4.7. *Using the Shykoluk and Lovell (2010) modification of the Scott method (1979a) for recording occlusal wear, cusps are consistently oriented when recording to allow observation of directional wear patterns.*

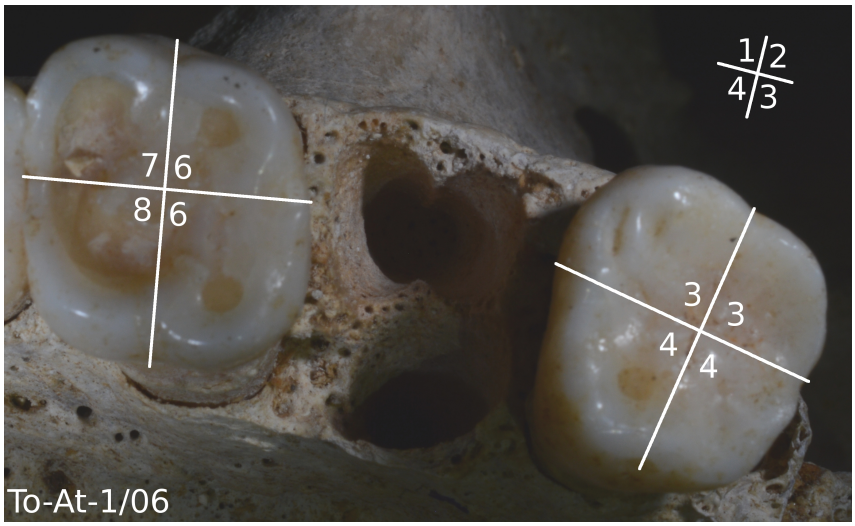


Figure 4.8. *Example of recording molars using the Scott molar wear method. Cusp orientation using the Shykoluk and Lovell (2010) method in the upper-right corner. Image by author.*

antimeres were recorded if present. A study of pigs demonstrates that, when consuming a soft diet, pigs do not significantly favour one side or the other (Dias et al., 2011). Thus far, no studies have followed Dias et al.'s work examining hard diet in pigs, or side-related trends in chewing in other mammals. If other mammals follow the dietary pattern found by Dias et al. (2011), recording dental wear in humans on only one side should not matter. The use of teeth as tools might also cause wear asymmetry. The comparison of right and left sides is not always evaluated when identifying tooth-tool use (e.g. Scott and Jolie, 2008; Waters-Rist et al., 2010). One study investigating wear in living Hazda people in Tanzania found the males displayed significantly different wear patterns in the left and right side of their dentitions which the authors attribute to tooth-tool use (Berbesque et al., 2012), although another study examining tooth-tool use in modern humans and Late Pleistocene hominins did not find any differences in wear between left and right teeth (Clement et al., 2012). In a subsample of individuals in this study, both right and left first molars will be recorded to test whether there significant side-based differences in wear within individuals.

Within any given population, there is an obvious correlation between age of an individual and the degree of macrowear: so much so that macrowear can be used as a method for determining age (Miles, 1962, 1963; Brothwell, 1989). As previously mentioned in Chapter 2, the adult age estimation of the Tongan individuals involved seriation of wear severity (Buckley, 2001, 95). Since young, middle, and older aged adults were partially assigned these age categories bases on degree of occlusal wear,

Table 4.1. *Conversion of Smith (1984) and Scott (1979) methods of wear to facilitate comparison.*

Descriptive	Smith (1984)	Scott (1979)
None	1	4
Mild	2–3	5–14
Moderate	4–5	15–24
Heavy	6–8	25–40

there will be an obvious association between age and degree of wear. The inclusion of adult age categories in inferential statistics is not so much because I am interested in the how age affects dental wear (the correlation between the two variables is expected), but to account for age when examining other predictor variables such as site or burial mound.

Descriptive statistics will include the number of teeth scored and the mean wear of each tooth type (molar quadrants will be totalled for a possible range of 4–40 for each molar). In order to compare anterior and posterior teeth, the two different ordinal recording methods used in this study were collapsed into even simpler ordinal values: none, mild, moderate, and heavy wear. The conversion of the Scott and Smith methods is described on Table 4.1. This simpler ordinal method also facilitates comparisons with other prehistoric Pacific dental studies. With a binary model of "no dentine exposure"/"dentine exposed" for each tooth, multi-level logistic regression was conducted. To do this, the cut-off point for dentine exposure using the Smith system was 3 and in the Scott system, molars with any cusp recorded as 5 or greater were considered to display dentine exposure. Although a "4" on the Scott system explicitly states that small pinpricks of dentine may be observed, these small amounts were not considered enough to warrant deeming the tooth 'worn'.

One way to determine the relative coarseness of foods in a given population is to determine the average rate of dental wear. The use of principal axis analysis, a type of exploratory analysis similar to principal component analysis, eliminates the problem of age affecting interpretation (Scott, 1979b; Watson, 2008). Principal axis analysis is typically conducted using interval data, but the use of ordinal data (such as occlusal wear recorded using the Scott method) produces similar results to interval methods of recording wear (Benfer and Edwards, 1991).

Due to the strong genetic controls on tooth eruption, the first and second molars will enter occlusion in strongly regulated times. The first molars, both mandibular and maxillary, erupt around six years of age, while the second molars erupt around twelve years of age (Hillson, 1996). Thus, no matter how old an individual is, their first molars

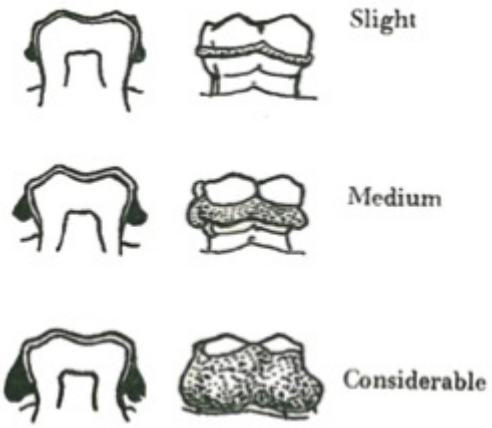


Figure 4.9. *Illustration from Brothwell,1963, 150, showing three degrees of severity of calculus accumulation.*

will have had six more years of exposure to attrition and abrasion than second molars. This principle allows bioarchaeologists using principal axis analysis to formulate rates of wear for groups of people. This rate of wear does not actually translate into an actual unit rate such as µm/year, but the slope of the principal axis equation can be compared to others created and avoids the problems of comparing assemblages with different age demographics. Comparing the amount of wear between the two teeth in multiple individuals can yield a general rate of wear for the population (Watson, 2008). Although principal axis analysis has not been used in the Pacific, a number of studies exist for comparison on a global level (Scott, 1979b; Richards, 1984; Chattah and Smith, 2006; Watson, 2008). Upper molar pairs were preferred, but lower molar pairs were included in case of upper molar absence. Molar pairs were never mixed (e.g. a mandibular first molar was never paired with a maxillary second molar). Principal axis analysis was conducted and compared by site, sex, and burial mound.

4.9.4 Calculus recording and statistical analysis

Supragingival calculus was recorded using Brothwell's ordinal scheme, as can be seen in Figure 4.9 (Brothwell, 1963). Subgingival calculus was only recorded as present/absent when the root could be examined (i.e. the tooth could be removed from the alveolus or the bony structure was not present). Supragingival and subgingival calculus were recorded separately. Descriptive statistics of calculus severity were tabulated. For multi-level logistic regression, any degree of supragingival calculus is considered 'present.'

Calculus build-up can be unintentionally removed post-mortem, especially when cleaning the archaeological remains. The unintentional removal is expected and will affect the study of calculus severity, but unfortunately cannot be accounted for.

Figure 4.10. *Examples of variation in size of occlusal edge chipping. The damage on the left tooth may have been caused by a relatively large particle such as a small rock, nut, or bone, while the smaller "nibbling" around the edges of the right tooth may be from smaller particles such as sand and grit (Scott and Winn, 2011). Note that in both cases the chips can be differentiated from post-mortem damage due to their slightly rounded edges and similar colour to the rest of the tooth. Image by author.*

4.9.5 Occlusal edge chipping recording and statistical analysis

Hillson's (2001) recording scheme for recording dental chipping, a simple presence/absence score, was used for this study. Only chipping on the occlusal surface in recorded. Ante- and post-mortem dental chipping are recorded separately. Examples of ante-mortem chipping can be observed in Figure 4.10. Post-mortem chipping will display sharp enamel edges and brighter enamel and dentine underneath compared to the surface. If a tooth is chipped ante-mortem the edges will become rounded with continued use of the tooth and the underlying enamel and dentine will become coloured similarly to the tooth surface (Hillson, 2001). While size, number, and/or location of the chipping have been recorded in other studies (Bonfiglioli et al., 2004; Belcastro et al., 2007), these attributes of chipping have been less studied in human dentitions and have little comparative data. As extreme tooth wear can remove all evidence of previous chipping and puts the thin enamel at higher risk of subsequent chipping, heavily worn teeth (ranked six and above on the Smith method, eight and above on the Scott method) were not scored for chipping.

Frequency of teeth affected and prevalence were reported. In order to compare these

findings with previous research (i.e. Scott and Winn, 2011), the percentages of affected tooth frequency were presented as ratios between males/females, mandibular/maxillary, and anterior/posterior. Chi-squared tests between the sexes, dental arch location, and jaws were conducted to create comparative results with Scott and Winn (2011). The data did not need to be transformed in any way for multi-level logistic regression. Ordered logit regression cannot be conducted as chipping was solely recorded as a binary (present/absent) variable.

4.9.6 Periodontal disease recording and statistical analysis

There are several approaches to recording periodontal disease as suggested by Hillson (2001). Recording the distance from the cemento-enamel junction (CEJ) to the alveolar crest (AC) is one suggested approach to understanding periodontal attachment loss brought on by disease, and it specifically focuses on the vertical loss of bone. Unfortunately, changes to the CEJ–AC distance can occur irrespective of periodontal disease, such as continuous or compensatory eruption (Whittaker et al., 1990; Danenberg et al., 1991). It becomes especially difficult to understand bone loss when periodontal disease and continuous/compensatory eruption may be occurring simultaneously but disentangling the processes is impossible (Wasterlain et al., 2009). CEJ–AC on undamaged buccal aspects of teeth still in sockets were recorded for this study, but then discarded given the problems in interpreting this measurement as evidence of periodontal disease.

Karn et al.'s (1984) recording scheme, also suggested by Hillson (2001), does differentiate between margin loss due to non-disease processes and periodontal disease. This method records the physical appearance of the defect (i.e. crater, ramp, trench, etc.) surrounding the tooth socket. However, the degree of bony changes are not recorded. Given that the severity of periodontal disease is important for understanding the progression of the disease within an individual, interpreting periodontal disease when using the Karn et al. (1984) method is difficult.

Instead of measuring the distance between the CEJ and the AC or the Karn method, changes to the interdental septum (the bony space between teeth) were recorded using the Kerr system (1991). Kerr's system focuses mainly on the interdental septum for the progression of foramina formation. This recording scheme does not record vertical bone loss that only affects the lingual or buccal aspects of a tooth. However, changes to the alveolar margin on the buccal and lingual aspects often can be seen when examining the interdental septa, and the thinness of the alveolar margins (Park et al., 2014) can leave the buccal and lingual margins unobservable due to post-mortem damage. Kerr's method records textural changes to the cortical surface and changes to the

Table 4.2. *Description of Kerr recording scheme. Modified from Kerr (1998:132).*

Category 0	Unrecordable: tooth on either side of the septum lost ante mortem or the septum damaged post mortem.
Category 1	Septal form characteristic of its region with the cortical surface continuous and virtually uninterrupted by foramina or grooves.
Category 2	Septal form characteristic of the region. Cortical surface showing a range from many small foramina and/or grooves to larger foramina with prominent grooves or ridges.
Category 3	Septal form showing a breakdown of contour, the essential distinguishing feature being a sharp and ragged texture to the bone defect.
Category 4	Septal form showing breakdown of contour, the distinguishing feature being a porous or smooth honeycomb effect with all defects rounded.
Category 5	Presence of a deep intra-bony defect with sides sloping at 45°or more and with a depth of 3 mm or more.

contour of the area (Table 4.2). Using this method, the stage of periodontal disease is differentiated. Category 1 would be expected in alveolar margins that are free of disease. Category 2, according to Kerr, would be indicative of soft tissue inflammation above the bone (gingivitis) (Kerr 1998, 132). Categories 3 and 4 are approximately the same degree of severity, but Category 3 involves no remodelling of the bone while Category 4 shows some smoothing and rounding of the contour from remodelling. Kerr diagnosed Category 3 scoring as indicative of periodontal disease that was active at the time of death, while Category 4 is an acute burst of periodontitis that had settled into a quiescent phase. Category 5, presenting deep defects with steep slopes away from the tooth, is considered representative of more aggressive periodontal disease. An example of advanced periodontal disease is shown on Figure 4.11. Following Hillson's (2001) recommendations, interdental septa near tooth sockets showing signs of remodelling from AMTL were not recorded for periodontal disease, as the remodelling process changes the alveolar surface near the empty socket in a manner that cannot be easily differentiated from periodontal disease.

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. Descriptive data on the severity of periodontitis were tabulated. As categories 3 and 4 are representative of periodontal disease of the same severity, with the differences more concerned with whether the disease was active around time of death, these two categories are combined in this thesis to created three levels of disease, mild/gingivitis (Category 2), moderate (Categories 3 and 4), and severe (Category 5).

Figure 4.11. *Example of periodontal disease. With deep, sharply sloping sides, these periodontal defects (white arrows) that would be classified as Category 5 using the Kerr (1998) method. Image by author.*

An ordered logit model was used to understand the relationships between the severity of periodontal disease and other variables (e.g. sex, position in the jaw, dental arch, tooth type). If the assumption of parallel regression is violated, an ordered logit model will still be conducted but interpreted with caution. In order to conduct multi-level logistic regression, any evidence of periodontal changes rated as Category 3 or greater using the Kerr method were recorded as "present."

4.9.7 Alveolar lesions recording and statistical analysis

Alvolear lesions, whether periapical or periodontal, were noted when present. Differential diagnosis using the suggestions of Dias and Tayles (1997) is a difficult process. Cavities were recorded by location (closest to which tooth or teeth) and size (less than or equal to 3 mm, greater than 3 mm but less than 10mm, greater than 10 mm). Other descriptive information that may aid differential diagnosis, such as raggedness of the margin or texture of the cavity wall was noted. Descriptive statistics included frequency of periapical cavities per individual and for each burial site. For multi-level logistic regression, any presentation of an alveolar lesion was considered present.

Figure 4.12. *Ante-mortem tooth loss of the mandibular first and second molar. The third molar was lost post-mortem and so the socket shows no sign of remodelling. Image by author.*

4.9.8 Ante-mortem tooth loss recording and statistical analysis

AMTL was recorded as part of Hillson's general census (2001) and differentiated from post-mortem tooth loss (Figure 4.12). Whether the bone was fully remodelled to a level contour or in the process of remodelling was noted as per Hillson's suggestion (2001), but both states of remodelling were considered equal in this study. The number of sockets that show signs of remodelling was combined to create a total number of sockets showing signs of AMTL.

This total number of sockets with remodelling was compared to the number of sockets examined showing no signs of AMTL in order to create a frequency of teeth affected. In addition to the positions within the oral cavity considered when studying other oral conditions (e.g. anterior/posterior, mandibular/maxillary), differences between the left and right sides were also compared in order to explore if violence was possibly a leading cause of AMTL. It has been suggested previously that a clear trend of tooth loss on the left side will be associated with face-to-face interpersonal violence (Lovell, 1997; Novak, 2000).

4.9.9 Recording teeth in subadults

Regarding the recording of deciduous teeth and the surrounding alveolar bone, most of the methodology used to examine permanent teeth was identical for deciduous teeth with a few notable exceptions. Caries, calculus, wear, occlusal surface chipping, and periapical cavities were recorded in subadults. Permanent teeth that were partially erupted were not recorded for occlusal wear. Teeth still in their crypt were not recorded for dental caries, attrition, or chipping. Root exposure and periodontal changes were

Table 4.3. *Assessment of agreement using Cohen's kappa. Adapted from Landis and Koch (1977).*

Kappa ($\varkappa$)	Strength of agreement
< 0.00	Poor
0.01–0.20	Slight
0.21–0.40	Fair
0.41–0.60	Moderate
0.61–0.80	Substantial
0.81–1.00	Almost Perfect

not examined: the changes to the alveolar margin as deciduous teeth are replaced with permanent teeth obscures all but the grossest of disease-based changes (Hillson, 1996, 2001). Deciduous molars were recorded using the Smith (1984) system instead of the Scott (1979a) system used for permanent molars due to the different cusp morphology of deciduous teeth (van Beek, 1983).

For subadults, prevalence of conditions within the 'Atele burial mounds were compared using chi-squared tests. Oral conditions prevalence were also compared between permanent and deciduous teeth in subadults using chi-squared tests. As multi-level and logistic ordinal regression models included sex and adult age categories, subadults could not be included in these models. With only one subadult in the Bourewa assemblage, only oral conditions in the 'Atele subadults were tabulated. Permanent teeth from subadults were included when presenting overall oral condition prevalences by site, burial mound, tooth type, or jaw position.

4.9.10 Intraobserver error

Testing intraobserver reliability evaluates both the clarity of the methods I chose for this project and the consistency of my observations. Without these aspects, the results cannot be trusted to be valid and reliable. All categorical data were tested for intraobserver agreement using Cohen's kappa. Acceptable agreement was determined using the commonly accepted criteria (Landis and Koch, 1977) (Table 4.3). Intraobserver agreement regarding ordinal and continuous data were tested using both correlation analyses (Spearman's rank correlation coefficient for ordinal data and Pearson product-moment correlation for continuous data) and Student's t-tests. Neither of these tests are necessarily ideal for intraobserver agreement (Barnhart et al., 2007), but used together they provide an acceptable means of assessing reliability.

Two months after the collection of oral condition data from the 'Atele assemblage, a

subsample (n= 8) of individuals were randomly chosen and re-recorded. Overall intraobserver agreement was acceptable for all methods. The general census of tooth presence (including ante-mortem tooth loss) was almost perfect, $\varkappa$=0.77 (std. error = 0.02, $p<$ 0.001). Chipping observations had a substantial agreement, $\varkappa$=0.46 (std. error=0.08, p<0.001). Calculus observations (gingival and subgingival combined) had an 85.14% intraobserver agreement, $\varkappa$=9.69 (std. error=0.057, p<0.001). Caries observation had a 98.88% intraobserver error agreement ($\varkappa$=0.83, std. error=0.0189, p<0.001). Though Spearman's correlation for wear (Smith and Scott methods combined) shows acceptable agreement (ρ=0.83, p<0.001), paired Student's t-test shows a significant difference between observations $t(181)$ 2.18, p=0.031. Periodontitis using the Kerr recording method had a 76.15% intraobserver agreement, $\varkappa$=0.56 (std. error = 0.07, p<0.001).

4.10 Results

4.10.1 General

In the Bourewa assemblage, 24 individuals were examined with a total of 253 teeth, 172 interdental septa, and 141 empty tooth sockets. Five individuals were edentulous, either from ante-mortem or post-mortem tooth loss. Fifty-three empty tooth sockets appeared to have been the result of post-mortem loss. There were significant differences regarding post-mortem loss and tooth type, $\chi^2(3) = 99.75$, $p < 0.001$, with incisors most often lost post-mortem (Figure 4.13).

From the 'Atele assemblage, 89 individuals were examined for oral indicators of diet with a total of 1244 teeth, 1026 interdental septa, and 880 empty tooth sockets examined. Eight individuals were edentulous, either because of ante-mortem tooth loss or because the individual was below six months of age and their teeth had not erupted. Two hundred and seventy empty tooth sockets showed no signs of remodelling and were attributed to post-mortem loss. There were significant differences regarding post-mortem loss and tooth type, $\chi^2(3) = 92.05$, $p < 0.001$. As in the Bourewa assemblage, incisors were most often lost post-mortem (Figure 4.14).

4.10.2 Caries

For Bourewa, 248 teeth (2,403 surfaces) were observed in the 19 individuals with teeth. Of the 248 teeth, 39 (15.7%) had at least one cavitated carious lesions. Regarding individual prevalence in the Bourewa assemblage, 68.4% (13/19) of individuals experienced at least one carious lesion. For 'Atele, 1,105 teeth (10,223 surfaces) were observed in the

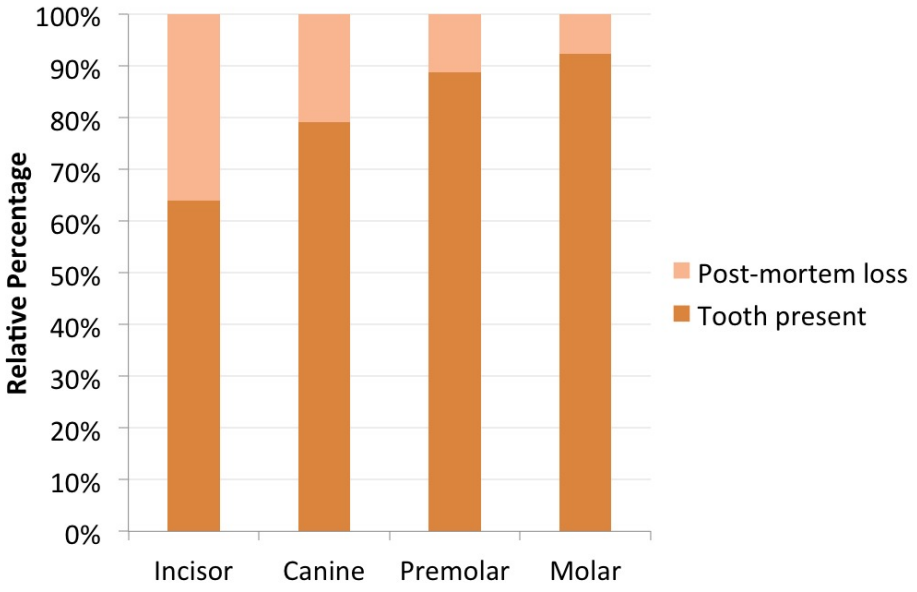


Figure 4.13. *Relative percentage of teeth lost post-mortem in the Bourewa assemblage, by tooth type.*

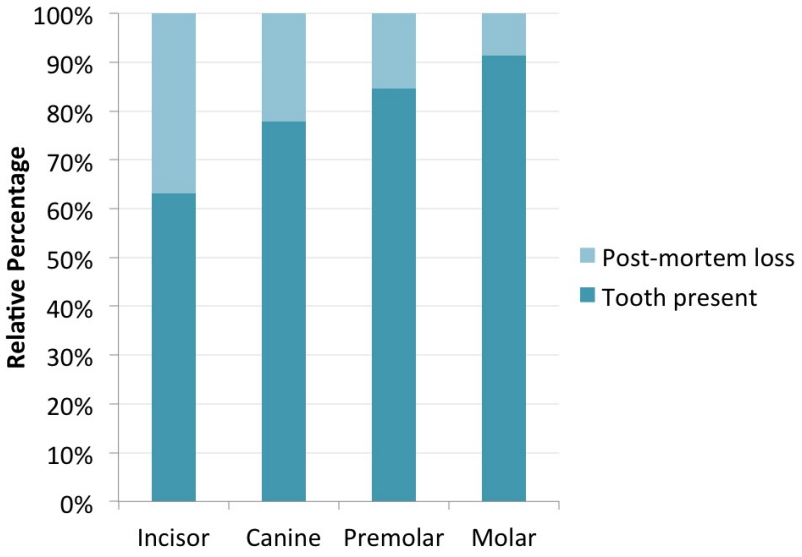


Figure 4.14. *Relative percentage of teeth lost post-mortem in the 'Atele assemblage, by tooth type.*

81 individuals with teeth. Of the 1,105 teeth, 125 (11.3%) had at least one cavitated carious lesions and 39.3% (33/84) of individuals experienced at least one carious lesion. Table 4.4 the caries prevalence by site and sex. Examining the crude prevalence, males experienced more caries than females in Bourewa and the To-At-1 assemblage than at To-At-2.

Before testing the relationship between caries severity and certain demographic variables, an approximate likelihood-ratio test of proportionality of odds across the dependent variable (caries severity) found a violation of proportional odds assumption ($\chi^2(6) = 27.36$, $p < 0.001$). Despite this violation, an ordered logit model was still conducted. Table 4.6 displays the results between burial sites, sex, and adult age categories. Males are significantly less likely to experience more severe caries than females. 'Atele individuals have significantly higher odds of increased caries severity than Bourewa, when other factors are constant. Middle-aged and old adults experience greater odds of increased caries severity than young adults, but there were no significant differences between middle-aged and old adults.

Table 4.7 displays the results between burial mounds, sex, and adult age in the 'Atele assemblage. As with the site-combined data, 'Atele males are significantly less likely to experience more severe caries than females. Individuals from To-At-2 have decreased odds of more severe carious lesions than To-At-1 individuals. As with the site-combined data, middle-aged and old adults experience greater odds of increased caries severity than young adults, but there are no significant differences between middle-aged and old adults.

Kruskal-Wallis tests showed no significant differences between tooth types regarding caries severity in the Bourewa assemblage, $\chi^2(3) = 4.86$, $p = 0.182$ or in the 'Atele assemblage, $\chi^2(3) = 1.63$, $p = 0.653$. There were no differences between the left and right sides regarding caries severity for the Bourewa assemblage, $\chi^2(3) = 2.24$, $p = 0.524$ or the 'Atele assemblage, $\chi^2(3) = 1.51$, $p = 0.679$.

Caries by Surface

Table 4.8 presents the severity of carious lesions by surface for Bourewa and 'Atele. Carious lesions that opened the pulp chamber or root canals only occurred on the occlusal surfaces, occlusal attrition sites, or on the roots. Figures 4.15 and 4.16 show the percentage prevalence of carious lesions for each surface type, regardless of the severity of the lesion. Qualitative examination of the figures shows the percentage prevalence of the different surface areas are similar for each site, though Bourewa displays more than twice the percentage of occlusal attrition facet caries (3.9% compared to 0.9%).

Table 4.4. *Carious lesions of males and females by site and burial mound.*

	Absent (%)	Penetrates enamel (%)	Penetrates dentine (%)	Open pulp chamber or root canals (%)	Total carious (%)	Total observed
Bourewa	209 (84.3)	5 (2)	19 (7.7)	15 (6.1)	39 (15.7)	248
ʻAtele	980 (88.7)	20 (1.8)	86 (7.8)	19 (1.7)	125 (11.3)	1105
To-At-1	378 (90.2)	8 (1.9)	27 (6.4)	6 (1.4)	41 (9.8)	419
To-At-2	476 (87.7)	8 (1.5)	46 (8.5)	13 (2.4)	67 (12.3)	543
Bourewa						
Females	79 (92.9)	1 (1.2)	5 (5.9)	0 (0)	6 (7.1)	85
Males	49 (75.4)	1 (1.5)	4 (6.2)	11 (16.9)	16 (24.6)	65
ʻAtele						
Females	325 (82.7)	5 (1.3)	53 (13.5)	10 (2.5)	68 (17.3)	393
Males	188 (88.7)	3 (1.4)	12 (5.7)	9 (4.3)	24 (11.3)	212
To-At-1						
Females	126 (87.5)	4 (2.8)	12 (8.3)	2 (1.4)	18 (12.5)	144
Males	67 (79.8)	3 (3.6)	10 (11.9)	4 (4.8)	17 (20.2)	84
To-At-2						
Females	199 (79.9)	1 (0.4)	41 (16.5)	8 (3.2)	50 (20.1)	249
Males	121 (94.5)	0 (0)	2 (1.6)	5 (3.9)	7 (5.5)	128

Table 4.5. *Carious lesions of adults of estimated age by site and burial mound.*

	Absent (%)	Penetrates enamel (%)	Penetrates dentine (%)	Open pulp chamber or root canals (%)	Total carious (%)	Total observed
Bourewa						
Young	49 (89.1)	3 (5.5)	2 (3.6)	1 (1.8)	6 (10.9)	55
Middle	51 (96.2)	0 (0)	0 (0)	2 (3.8)	2 (3.8)	53
Old	16 (88.9)	0 (0)	1 (5.6)	1 (5.6)	2 (11.1)	18
'Atele						
Young	288 (94.7)	7 (2.3)	6 (2.0)	3 (1.0)	16 (5.3)	304
Middle	116 (70.3)	0 (0)	43 (26.1)	6 (3.6)	49 (29.7)	165
Old	61 (71.8)	0 (0)	14 (16.5)	10 (11.8)	24 (28.2)	85
To-At-1						
Young	146 (94.2)	7 (4.5)	2 (1.3)	0 (0)	9 (5.8)	155
Middle	31 (55.4)	0 (0)	19 (33.9)	6 (10.7)	25 (44.6)	56
To-At-2						
Young	142 (95.3)	0 (0)	4 (2.7)	3 (2.0)	7 (4.7)	149
Middle	85 (78)	0 (0)	24 (22)	0 (0)	24 (22)	109
Old	61 (71.8)	0 (0)	14 (16.5)	10 (11.8)	24 (28.2)	85

Table 4.6. *Ordered logit model for caries severity. Site, sex, and adult age categories are the predictor variables.n = 649.*

	Odds ratio	**Std. Err.**	***p***
Site			
Bourewa	1		
‘Atele	4.57	2.07	0.001*
Sex			
Female	1		
Male	0.51	0.14	0.015*
Adult Age			
Young adult	1		
Middle adult	7.33	2.22	<0.001*
Old adult	5.63	1.91	<0.001*
Old–Middle	0.77	0.24	0.406

Table 4.7. *Ordered logit model for caries severity. Burial mound, sex, and adult age categories are the predictor variables. n = 554.*

	Odds ratio	**Std. Err.**	***p***
Burial Mound			
To-At-1	1		
To-At-2	0.37	0.11	0.001*
Sex			
Female	1		
Male	0.30	0.09	<0.001*
Adult Age			
Young adult	1		
Middle adult	15.32	5.53	<0.001*
Old adult	11.98	5.07	<0.001*
Old–Middle	0.78	0.27	0.481

Table 4.8. *Severity and surface site of caries for Bourewa and ʻAtele.*

	Absent (%)	Penetrates enamel (%)	Penetrates dentine (%)	Open pulp chamber or root canals (%)
Bourewa				
Smooth	488 (98.8)	6 (1.2)	0 (0)	0 (0)
Contact	482 (98.3)	8 (1.6)	0 (0)	0 (0)
Occlusal surface	161 (97.6)	1 (0.6)	0 (0)	3 (1.8)
Occlusal attrition	199 (96.1)	0 (0)	3 (1.5)	5 (2.4)
Pit	60 (95.4)	3 (4.8)	0 (0)	0 (0)
Root	939 (95.4)	—	23 (2.3)	22 (2.2)
ʻAtele				
Smooth	2157 (99.2)	18 (0.8)	0 (0)	0 (0)
Contact	2159 (99.5)	10 (0.5)	0 (0)	0 (0)
Occlusal surface	687 (98.6)	6 (0.9)	1 (0.1)	3 (0.4)
Occlusal attrition	685 (99.1)	0 (0)	1 (0.1)	5 (0.7)
Pit	163 (95.9)	7 (4.1)	0 (0)	0 (0)
Root	4151 (96.1)	—	129 (3.0)	41 (1.0)

Examining differences in caries prevalence by surface between the two burial mounds 4.17, only To-At-2 adults are affected by occlusal attrition facet caries or pit caries. In both burial mounds, more than 50% of all caries occur on root surfaces.

Table 4.9 presents the percentage prevalence of carious surfaces by tooth type. Premolars are most likely to be affected on the smooth and contact surfaces than other tooth types (Figure 4.18). Molars were more affected than other tooth types on the other surfaces (occlusal surface, occlusal attrition facets, pits, and root surfaces). Though 41 lingual pits were observed in incisors, none were affected by caries. Figures 4.19 and 4.20 display the percentage prevalence of carious surfaces by sex for each assemblage. There are no overarching trends between the two assemblages: in Bourewa individuals, males display a higher prevalence of all surface caries while in ʻAtele individuals, males display relatively more smooth, contact, occlusal surface and occlusal attrition caries compared to ʻAtele females who display a higher prevalence of pit and root caries.

Multi-level regression of caries

Table 4.10 presents the results of the three multi-level logistic regression models. In the first model, there are no significant differences regarding burial site, jaw, or sex. There were significantly increased odds for caries for posterior teeth compared to anterior teeth. Adult age categories could not be included in Model 2a as age predicted caries

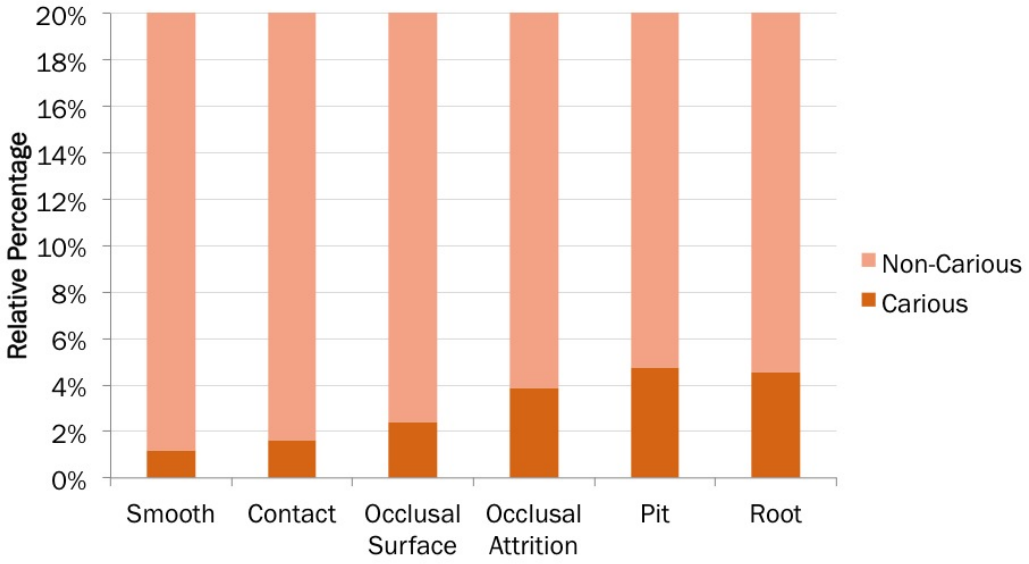


Figure 4.15. *Percentage of surfaces affected by caries for entire Bourewa assemblage. Note that y-axis is only to 20%.*

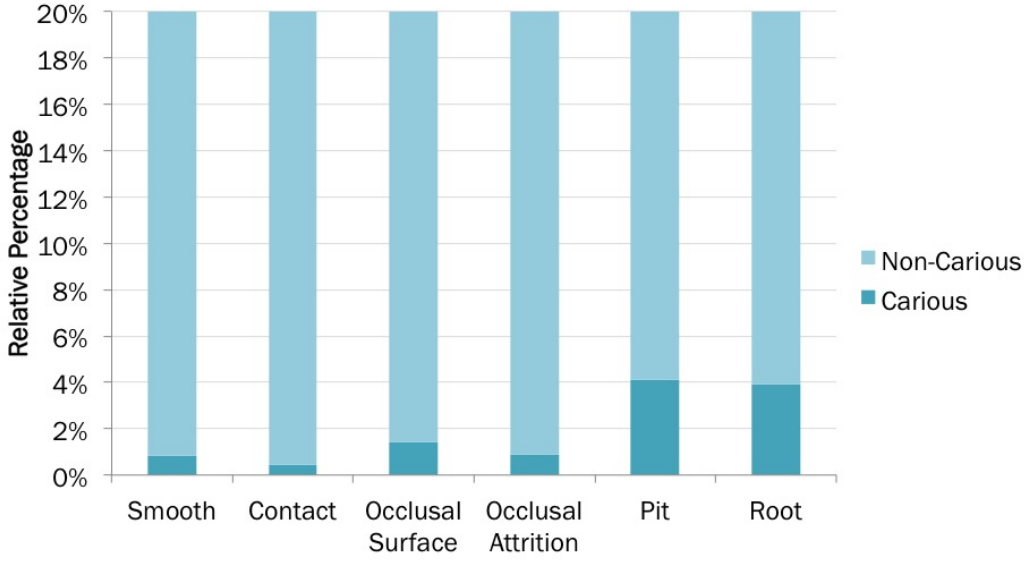


Figure 4.16. *Percentage of surfaces affected by caries for entire 'Atele assemblage. Note that y-axis is only to 20%.*

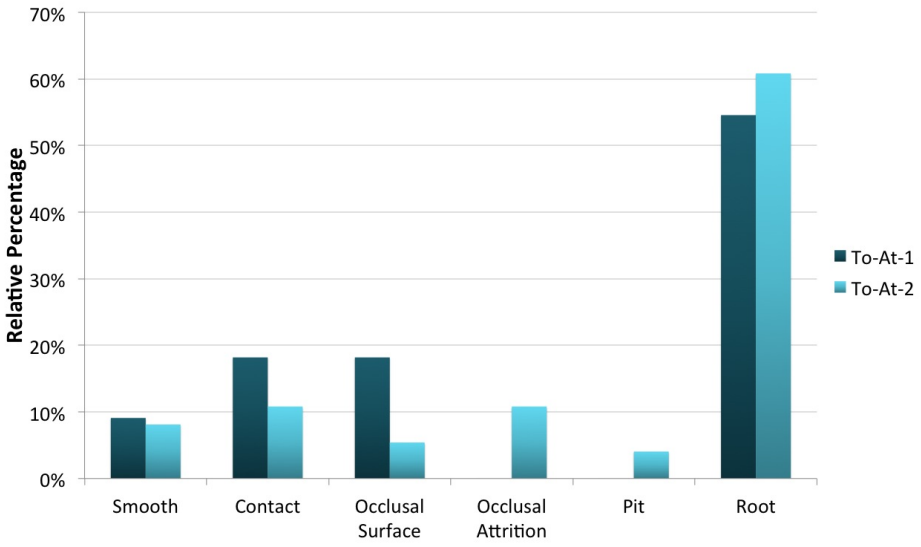


Figure 4.17. *Relative percentage of caries by surface for the two 'Atele burial mounds. Note that y-axis is only to 70%.*

Table 4.9. *Percentage prevalence of carious surfaces by tooth type.*

	Incisor (%)	**Canine (%)**	**Premolar (%)**	**Molar (%)**
Smooth	9/659 (1.4)	3/479 (0.6)	17/1029 (1.7)	5/1165 (0.4)
Contact	7/656 (1.1)	2/482 (0.4)	14/1022 (1.4)	8/1163 (0.7)
Occlusal surface	—	—	7/508 (1.4)	15/582 (2.6)
Occlusal attrition	3/255 (1.2)	0/196 (0)	8/309 (2.6)	8/305 (2.6)
Pit	0/41 (0)	—	—	11/266 (4.1)
Root	36/1285 (2.7)	35/928 (3.6)	74/2041 (3.6)	138/2332 (5.9)

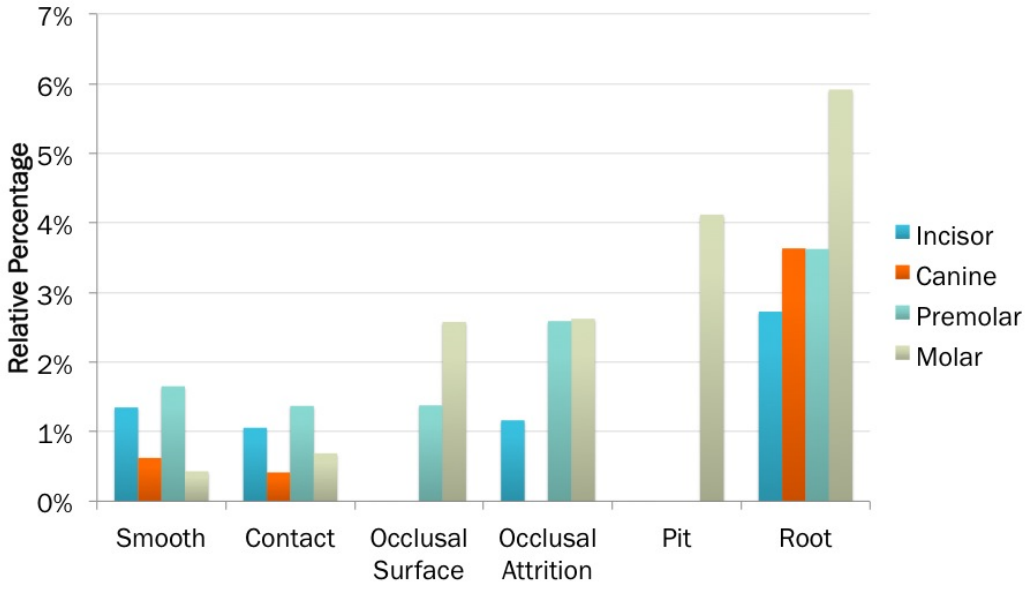


Figure 4.18. *Percentage prevalence of carious surfaces by tooth type, both 'Atele and Bourewa combined. Note that y-axis is only to 7%.*

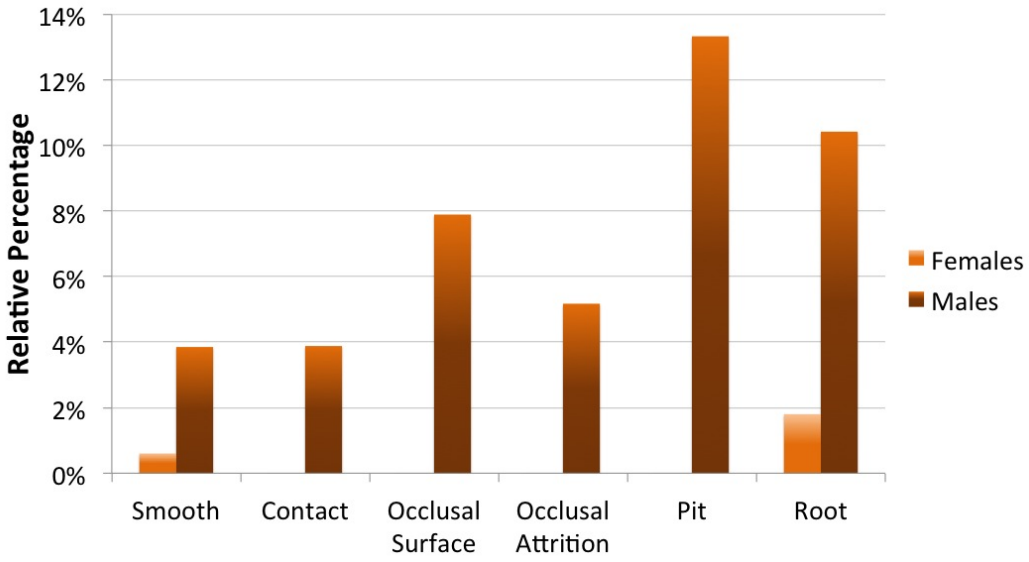


Figure 4.19. *Percentage prevalence of carious surfaces by sex, Bourewa assemblage. Note that y-axis is only to 14%*

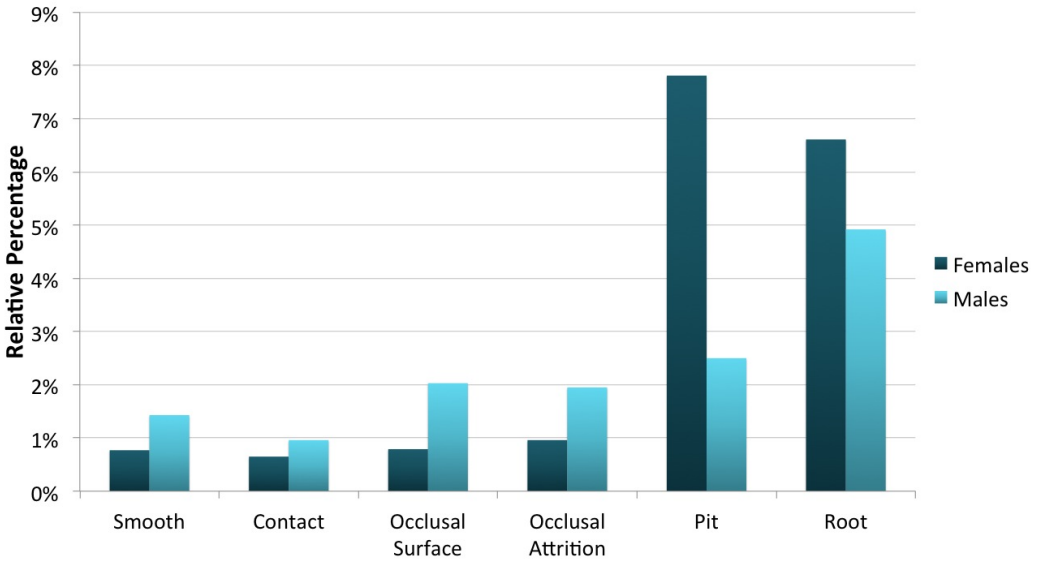


Figure 4.20. *Percentage prevalence of carious surfaces by sex, 'Atele assemblage. Note that y-axis is only to 9%*

perfectly. There were no sex-related differences in the Bourewa assemblage. In Model 2b, there were no significant differences beyond increased odds as age increased.

4.10.3 Calculus

Subgingival calculus was rare; 15/831 (1.8%) roots examined displayed subgingival calculus. The small amount of subgingival calculus present did not allow for statistical testing, no trends seemed to be present from an informal assessment of the distribution of subgingival calculus across tooth type, age, sex, or any other demographic delineation.

Regarding supragingival calculus, the descriptive frequencies are displayed on Table 4.11. For Bourewa, 33.3% of teeth (80/240) and 68.4% of individuals (13/19) had some amount of calculus. In the 'Atele assemblage, 54% of teeth (581/1077) and 76.5% of individuals (62/81) displayed some degree of calculus. The actual calculus prevalence as experienced by the living population was likely even higher and the severity even greater than what is displayed here, but handling of the remains had obviously resulted in the inadvertent removal of calculus from some of the teeth. Due to the small amount of grade 3 supragingival calculus present, statistical tests using the three grades of severity were not possible. Instead, supragingival calculus presence is collapsed into a present/absent system for statistical testing.

Table 4.10. *Multi-level regression models for caries. Adult age categories could not be included in Model 2a as age predicted caries perfectly. Significant results marked with *.*

	Model 1			**Model 2a**			**Model 2b**		
	$n = 649$			$n = 150$			$n = 554$		
	Odds ratio	Std. err.	p	Odds ratio	Std. err.	p	Odds ratio	Std. err.	p
Burial site									
Bourewa	1								
‘Atele	3.61	4.17	0.266						
Dental arch									
Anterior	1								
Posterior	2.43	0.87	0.003*						
Jaw									
Maxillary	1								
Mandibular	0.75	0.30	0.987						
Adult age									
Young	1			—			1		
Middle	14	6.86	0.035*	—			33.77	19.98	0.003*
Old	37.40	19.12	0.011*	—			84.61	65.42	0.003*
Old-Middle	2.67	2.83	0.478	—			2.51	3.27	0.460
Sex									
Female	1			1			1		
Male	1.18	0.83	0.944	6.19	7.81	0.148	0.38	0.35	0.292
Burial mound									
To-At-1							1		
To-At-2							0.29	0.17	0.075

Table 4.11. *Supragingival calculus severity by site, sex, and burial mound.*

	Absent (%)	Mild (%)	Moderate (%)	Severe (%)	Total with calculus (%)	Total observed
Bourewa	160 (66.7)	77 (32.1)	3 (1.3)	0 (0)	80 (33.3)	240
ʻAtele	496 (46.1)	510 (47.4)	61 (5.7)	10 (0.9)	581 (53.9)	1077
To-At-1	190 (47)	184 (45.5)	24 (5.9)	6 (1.5)	214 (53)	404
To-At-2	286 (54)	215 (40.6)	27 (5.1)	2 (0.4)	244 (46)	530
Bourewa						
Female	60 (73.2)	20 (24.4)	2 (2.4)	0 (0)	22 (26.8)	82
Male	34 (54.8)	27 (43.6)	1 (1.6)	0 (0)	28 (45.2)	62
ʻAtele						
Female	177 (45.9)	174 (45.1)	33 (8.6)	2 (0.5)	209 (54.2)	386
Male	61 (29.3)	139 (66.8)	7 (3.4)	1 (0.5)	147 (70.7)	208
To-At-1						
Female	60 (42)	74 (51.8)	9 (6.3)	0 (0)	83 (58)	143
Male	4 (4.8)	73 (86.9)	6 (7.1)	1 (1.2)	80 (95.2)	84
To-At-2						
Female	117 (48.2)	100 (41.2)	24 (9.9)	2 (0.8)	126 (51.9)	243
Male	57 (46)	66 (53.2)	1 (0.8)	0 (0)	67 (54)	124

Multi-level regression of calculus

Table 4.12 presents the results of the three multi-level logistic regression models regarding calculus. In the first model, posterior teeth have significantly lower odds of displaying calculus. In Model 2a, middle-aged adults have significantly lower odds of having calculus than young adults, while older adults have significantly increased odds of displaying calculus than middle-aged adults (but no significant differences between old and young adults). In Model 2b, middle-aged adults have significantly increased odds of displaying calculus than young adults, but there are no differences between old adults and young adults, or old adults and middle-aged adults. To-At-2 shows strongly decreased odds of displaying calculus, though not to a significant degree ($p = 0.051$).

4.10.4 Occlusal wear

Mean, standard deviation, and the number of observations for wear are presented on Table 4.13. After collapsing the wear data to a four-level scale (none, mild, moderate, and severe), ordered logit regression analyses were conducted. The results are displayed on Tables 4.14 and 4.15. An approximate likelihood-ratio test of proportionality of odds across the dependent variable (wear severity) found a violation of proportional odds assumption ($\chi^2(6) = 29.53$, $p < 0.001$), so the results must be interpreted with caution.

Table 4.12. *Multi-level regression models for calculus. Significant results marked with *.*

	Model 1			**Model 2a**			**Model 2b**		
	$n = 635$			$n = 91$			$n = 544$		
	Odds ratio	Std. err.	p	Odds ratio	Std. err.	p	Odds ratio	Std. err.	p
Burial site									
Bourewa	1								
‘Atele	10.43	15.49	0.114						
Dental arch									
Anterior	1								
Posterior	0.56	0.15	0.025*						
Jaw									
Maxillary	1								
Mandibular	1.52	0.38	0.095						
Adult Age									
Young	1			1			1		
Middle	4.02	4.68	0.231	0.03	0.03	0.001*	12.86	15.63	0.036*
Old	2.66	3.68	0.481	1.94	3.11	0.680	5.93	8.79	0.229
Old-Middle	0.66	1.01	0.786	65.88	77.42	<0.001*	0.46	0.75	0.635
Sex									
Female	1.00			1.00			1.00		
Male	1.16	1.26	0.890	0.27	0.32	0.261	1.05	1.15	0.964
Burial mound									
To-At-1							1.00		
To-At-2							0.12	0.13	0.051

In order to test whether there were significant differences in wear between left and right sides, both the right and left first molars (either maxillary or mandibular pairs) were recorded in a subsample of individuals from the ‘Atele assemblage. There were no differences in wear severity between left and right molars, $t(16) = -0.45$, $p = 0.662$.

‘Atele individuals have significantly reduced odds of severe wear than Bourewa individuals. When sites are combined, there were no significant differences between young and middle-aged adults, but old adults have significantly increased odds of more severe wear than middle-aged or young adults. When examining ‘Atele adults only, To-At-2 individual have significantly decreased odds of severe wear. As with the combined sites, there were no significant differences in the odds of severe wear between young and middle-aged adults, but old adults have significantly increased odds compared to middle-aged and young adults.

Table 4.13. *Mean occlusal wear by site, sex, and burial mound.*

	Incisors, canines, and premolars			Molars		
	n	x̄	S.D.	*n*	x̄	S.D.
Bourewa	90	3.7	1.7	62	15.2	7.2
‘Atele	376	2.4	1.0	224	10.5	5.8
To-At-1	116	2.6	1.0	88	11.8	7.3
To-At-2	186	2.4	1.0	103	10.0	4.4
Bourewa						
Female	32	4.4	1.4	20	16.7	6.1
Male	22	4.1	1.8	15	14.3	9.2
‘Atele						
Female	150	2.8	1.1	95	11.7	6.7
Male	72	2.3	0.7	50	11.0	4.1
To-At-1						
Female	49	2.8	1.2	43	12.9	8.5
Male	26	2.6	0.7	24	11.6	4.7
To-At-2						
Female	101	2.7	1.0	52	10.7	4.4
Male	46	2.2	0.7	26	10.5	3.4

Table 4.14. *Ordered logit model for wear severity. Site, sex, and adult age categories are the predictor variables. n = 390.*

	Odds ratio	Std. err.	*p*
Burial Site			
Bourewa	1		
Tonga	0.21	0.06	<0.001*
Sex			
Female	1		
Male	0.64	0.15	0.066
Adult Age			
Young adult	1		
Middle adult	1.55	0.39	0.082
Old adult	3.30	1.03	<0.001*
Old–Middle	2.12	0.71	0.025*

Table 4.15. *Ordered logit model for wear severity in Atele. Burial mound, sex, and adult age categories are the predictor variables. n = 335.*

	Odds ratio	**Std. err.**	***p***
Burial Mound			
To-At-1	1		
To-At-2	0.40	0.12	0.002*
Sex			
Female	1		
Male	0.71	0.20	0.22
Adult Age			
Young adult	1		
Middle adult	0.89	0.26	0.706
Old adult	6.79	2.57	<0.001*
Old–Middle	7.59	3.19	<0.001*

Multi-level regression of wear

Table 4.16 presents the results of the multi-level regression models for occlusal wear. In Model 1, there were no differences between the burial sites, sexes, adult age categories, or jaws. Posterior teeth are significantly less likely to have dentine exposure than anterior teeth. In Model 2a, there are significant differences between adult age categories in the Bourewa assemblage, which middle-aged and old adults more likely to experience exposed dentine than young adults. There were no differences between old and middle-aged adults or between males and females. With the ‘Atele assemblage on its own (Model 2b), there were no differences between young and middle-aged adults, but old adults have significantly higher odds than middle-aged and young adults. There were no significant differences between the sexes or between burial mounds.

Principal axis analysis of wear

Table 4.17 shows the results of the principal axis analyses on paired first and second molars. Three molar pairs in the ‘Atele assemblage were excluded from analysis; in these pairs, the second molar was recorded as more worn than the first molar. No sex-based comparisons were conducted on the Bourewa assemblage due to small subgroup sizes.

4.10.5 Chipping

In the Bourewa assemblage, 223 teeth were examined for chipping. Of the 223 teeth, 29 (13%) were chipped on the occlusal edge. Regarding individual prevalence in the

Table 4.16. *Multi-level regression models for occlusal wear. Significant results marked with *.*

	Model 1			**Model 2a**			**Model 2b**		
	$n = 390$			$n = 55$			$n = 335$		
	Odds ratio	Std. error	p	Odds ratio	Std. error	p	Odds ratio	Std. error	p
Burial site									
Bourewa	1								
‘Atele	0.20	0.20	0.101						
Dental arch									
Anterior	1								
Posterior	0.12	0.04	<0.001*						
Jaw									
Maxillary	1								
Mandibular	0.79	0.23	0.428						
Adult age									
Young	1			1			1		
Middle	0.96	0.77	0.96	24.00	24.00	0.001*	0.68	0.48	0.579
Old	2.95	2.73	0.244	25.45	33.84	0.015*	6.17	5.37	0.036*
Old-Middle	3.07	3.16	0.276	1.06	0.93	0.946	9.14	8.96	0.024*
Sex									
Female	1			1			1		
Male	0.46	0.34	0.297	2.73	2.55	0.283	0.59	0.38	0.421
Burial mound									
To-At-1							1		
To-At-2							0.35	0.22	0.101

Table 4.17. *Mean wear scores, n, Principal axis slopes (b), and principal axis equations. Principal axis equations based on sex are for ‘Atele individuals only.*

	$\bar{x}$ M_1	$\bar{x}$ M_2	n	b (95% CL)	Equation
‘Atele	15.7	11.3	37	0.50 (0.40, 0.61)	$0.50y + 3.17$
Bourewa	17.9	12.2	14	0.53 (0.34, 0.75)	$0.53y + 2.77$
Sex					
Females	15.7	11.3	18	0.39 (0.23, 0.57)	$0.39y + 5.19$
Males	16.8	11.4	10	0.40 (0.31, 0.50)	$0.40y + 4.69$
Burial mound					
To-At-1	15.7	10.6	17	0.43 (0.27, 0.60)	$0.43y + 3.88$
To-At-2	11.7	9.6	20	0.65 (0.51, 0.87)	$0.65y + 1.65$

Table 4.18. *Occlusal edge chipping by site, sex, and burial mound.*

	Not chipped (%)	Chipped (%)	Total observed
Bourewa	194 (87)	29 (13)	223
‘Atele	863 (82.7)	181 (17.3)	1,044
To-At-1	332 (87.4)	48 (12.6)	380
To-At-2	414 (79.3)	108 (20.7)	522
Bourewa			
Female	67 (85.9)	11 (14.1)	78
Male	41 (80.4)	10 (19.6)	51
‘Atele			
Female	273 (75.6)	88 (24.4)	361
Male	166 (81.8)	37 (18.2)	203
To-At-1			
Female	111 (86.7)	17 (13.3)	128
Male	64 (81)	15 (19)	79
To-At-2			
Female	162 (69.5)	71 (30.5)	233
Male	102 (82.3)	22 (17.7)	124

Bourewa assemblage, 55.5% (10/18) of individuals experienced at least one chipped tooth. Of the 1,044 teeth observed in the ‘Atele assemblage, 181 (17.3%) were chipped. In the ’Atele assemblage, 64.6% (51/79) of individuals experienced at least one chipped tooth. Table 4.18 presents chipping prevalence by site and sex.

There are some seemingly large differences in percentage prevalence of chipping between tooth types (Figure 4.21). However, when the average age of eruption for these teeth are plotted against percentage prevalence, it becomes clear that teeth that erupt earlier (such as the first incisor and first molar) are more likely to be chipped than teeth that are exposed later.

Table 4.19 shows by-tooth chipping ratios as in the style of Scott and Winn (2011) with their comparative data. Chi-squared tests were used, in order to maintain consistency with the comparative data. There were no significant trends in the Bourewa assemblage. In the ‘Atele assemblage maxillary teeth were more often chipped than mandibular, $\chi^2(1) = 6.08$, $p = 0.014$, and anterior teeth were chipped more than posterior teeth, $\chi^2(1) = 4.61$, $p = 0.032$.

Multi-level regression of chipping

Table 4.20 presents the results of the multi-level logistic regressions using chipping as the dependent variable. There were no significant trends in the first model. In Model

Figure 4.21. *Percentage prevalence (%) of chipping by tooth type with approximate age of eruption in years for each tooth (mandibular and maxillary averaged) plotted as line. Age of eruption from van Beek (1983).*

Table 4.19. *Comparative chipping ratios in sex, jaw, and dental arch. Comparative ratios calculated by Scott and Winn (2011) with Morocco data from Bonfiglioli et al. (2004) and Italy data from Belcastro et al. (2007). Bonfiglioli et al. (2004) did not provide chipping data tabulated by jaw and so could not be calculated. Significant results marked with *.*

	Male:Female	**Maxillary: Mandibular**	**Anterior: Posterior**
Bourewa	1.39	0.65	0.80
‘Atele	0.75	1.32*	1.37*
Inuit (hunting-gathering)	1.32*	1.04	0.77*
Norway (agriculture)	1.00	1.24*	3.40*
Spain (agriculture)	1.66	1.73	3.40*
Morocco (hunting-gathering)	1.47	—	0.64*
Italy 1st-4th c. C.E. (agriculture)	1.16	1.14	1.50*
Italy 7th c. C.E. (agriculture)	1.08	1.17	1.68*

Table 4.20. *Multi-level regression models for occlusal edge chipping. Significant results marked with *.*

	Model 1			**Model 2a**			**Model 2b**		
	$n = 608$			$n = 84$			$n = 524$		
	Odds ratio	Std. error	p	Odds ratio	Std. error	p	Odds ratio	Std. error	p
Burial site									
Bourewa	1								
‘Atele	0.83	0.44	0.725						
Dental arch									
Anterior	1			1			1		
Posterior	0.66	0.15	0.061				0.59	0.14	0.026*
Jaw									
Maxillary	1			1			1		
Mandibular	0.67	0.15	0.063				0.61	0.14	0.030*
Adult age									
Young	1			1			1		
Middle	0.44	0.19	0.058	11.82	10.68	0.006*	0.30	0.12	0.004*
Old	1.22	0.61	0.691	33.79	42.32	0.005*	0.86	0.40	0.740
Old-Middle	2.79	1.60	0.073	2.86	2.77	0.279	2.90	1.61	0.054
Sex									
Female	1			1			1		
Male	1.14	0.46	0.747	11.64	10.55	0.007*	1.08	0.40	0.844
Burial mound									
To-At-1							1		
To-At-2							2.10	0.77	0.044*

2a, there are significantly increased odds of chipping in middle- and old-aged adults compared to young adults, but no significantly different odds between middle- and old-aged adults. Males in the Bourewa assemblage have significantly increased odds of having chipped teeth. In Model 2b, anterior teeth are significantly more likely to be chipped, as are maxillary teeth. Middle-aged adults in the ‘Atele assemblage are significantly less likely to have chipped teeth than young adults. To-At-2 individuals are significantly more likely to display chipped teeth than To-At-1 individuals.

4.10.6 Periodontal disease

Table 4.21 presents periodontitis prevalence by site and sex. In the Bourewa assemblage, 172 interdental septa were examined for periodontal disease. Of the 172 septa, 22

Table 4.21. *Periodontal disease by site, sex, and burial mound.*

	Healthy (%)	Mild (%)	Moderate (%)	Severe (%)	Moderate/severe total (%)	Total observed
Bourewa	61 (35.5)	89 (51.7)	20 (11.6)	2 (1.2)	22 (12.8)	172
‘Atele	165 (17.5)	647 (68.8)	72 (7.7)	57 (6.1)	129 (13.8)	941
To-At-1	103 (30.1)	200 (58.5)	14 (4.1)	25 (7.3)	39 (11.4)	342
To-At-2	59 (13.1)	326 (72.4)	35 (7.8)	30 (6.7)	65 (14.5)	450
Bourewa						
Female	28 (57.1)	18 (36.7)	1 (2.0)	2 (4.1)	3 (6.1)	49
Male	2 (3.9)	37 (71.2)	13 (25.0)	0 (0)	13 (25.0)	52
‘Atele						
Female	56 (15.4)	256 (70.3)	25 (6.9)	27 (7.4)	52 (14.3)	364
Male	34 (14.9)	156 (68.4)	16 (7.0)	22 (9.7)	38 (16.7)	228
To-At-1						
Female	44 (29.0)	94 (61.8)	7 (4.6)	7 (4.6)	14 (9.2)	152
Male	14 (16.1)	55 (63.2)	5 (5.8)	13 (14.9)	18 (20.7)	87
To-At-2						
Female	12 (5.7)	162 (76.4)	18 (8.5)	20 (9.4)		212
Male	20 (14.2)	101 (71.6)	11 (7.8)	9 (6.4)	20 (14.2)	141

(12.8%) showed moderate or severe periodontal disease. Regarding individual prevalence in the Bourewa assemblage, 56.3% (9/16) of individuals experienced at least one interdental septa with moderate or severe periodontal changes. Six individuals in the Bourewa assemblage also showed bony changes related to gingivitis (categorised as “mild” periodontitis in this study’s recording scheme).

For ‘Atele, 941 interdental septa were examined. Of these 941 septa, 129 (13.8%) displayed changes of mild or moderate periodontal disease. In the ’Atele assemblage, 59% (36/61) of individuals experienced at least one interdental septa with moderate or severe periodontal changes. Twenty-four individuals also showed mild periodontal changes associated with gingivitis, increasing the percentage of individuals displaying any bony changes to 98.4% (60/61).

In order to compare severity of periodontitis between sub-groups, ordered logit model was conducted. There was no violation of the proportional odds assumption, $\chi^2 = 8.18$, $p = 0.225$ when including burial site, sex, and adult age as predictor variables. The results of this ordered logit model are displayed on Table 4.22. ‘Atele individuals have significantly higher odds of severe periodontitis than Bourewa individuals (Figure 4.22). Males have higher odds of more severe periodontitis than females when all other variables in the model are held constant. As the adult age category increases from young to old and middle-aged to old adults, the odds of more severe periodontitis increases significantly. There are, however, no significantly different odds between young and

Table 4.22. *Ordered logit model of periodontitis severity in both sites. n = 620. Significant results marked with *.*

	Odds ratio	**Std. err.**	***p***
Burial site			
Bourewa	1		
'Atele	2.40	0.63	0.001*
Sex			
Female	1		
Male	1.31	0.11	0.002*
Adult age			
Young			
Middle	0.82	0.16	0.319
Old	4.46	1.15	<0.001*
Old-Middle	5.41	1.53	<0.001*

middle-aged adults.

Table 4.23 presents the results of ordered regression model with burial mound, sex, and adult age as predictor variables. As with the first periodontitis ordered logit model, there was no violation of the proportional odds assumption, $\chi^2 = 10.85$, $p = 0.093$. When only 'Atele individuals are included in the model, there are no significant differences in odds between the sexes or the burial mounds. Examination of Figure 4.23 indicates that Bourewa males have a much higher proportion of moderate periodontal changes compared to Bourewa females, the likely cause of significant differences between the sexes when sites are combined. There remain increased odds of periodontitis severity as the adult age category increases, with the exception between young adults and middle-aged adults.

Multi-level regression of periodontal disease

Table 4.24 presents the results of the multi-level regression models. In Model 1, posterior septa are significantly more likely to have periodontal changes than anterior teeth, as are maxillary septa. There are no significant differences between young and middle-aged adults with both assemblages combined, but old aged adults are significantly more likely to have periodontal disease than young or middle-aged adults. There are no significant differences between the sexes.

In Model 2a, adult age could not be included as a predictor variable, as only two interdental septa were recorded in old adults in the Bourewa assemblage (many alveoli areas were near sockets undergoing remodelling from AMTL, and so could not

Table 4.23. *Ordered logit model of periodontitis severity in 'Atele. n = 545. Significant results marked with *.*

	Odds ratio	Std. err.	*p*
Burial mound			
To-At-1	1		
To-At-2	1.49	0.31	0.057
Sex			
Female	1		
Male	1.33	0.28	0.164
Adult age			
Young	1		
Middle	1.23	0.28	0.356
Old	3.42	0.97	<0.001*
Old-Middle	2.78	0.84	0.001*

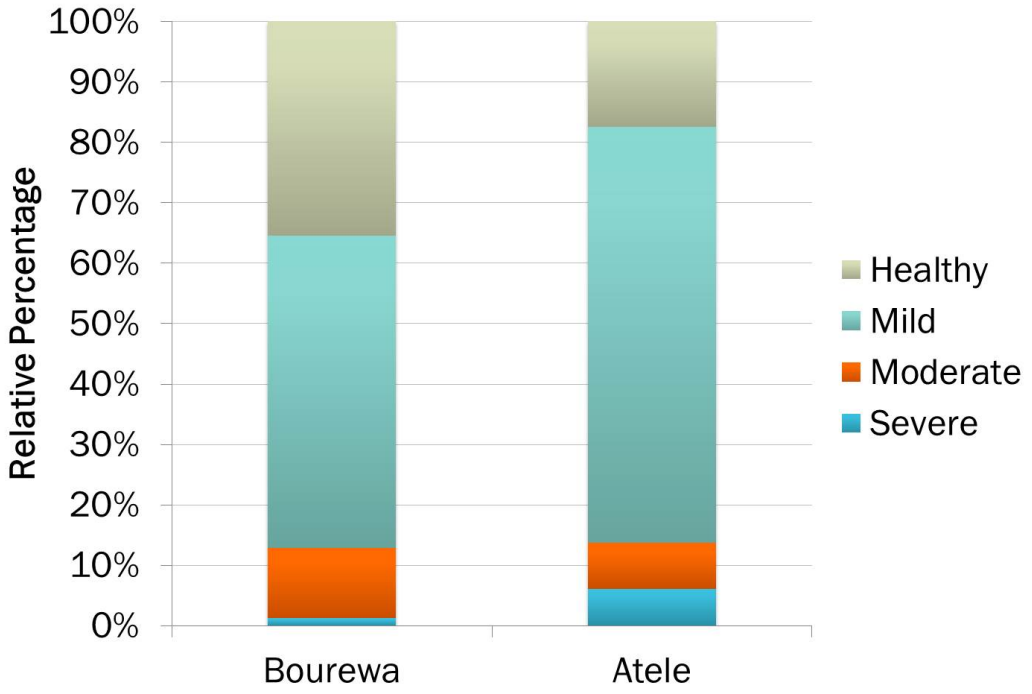


Figure 4.22. *Periodontitis severity by site.*

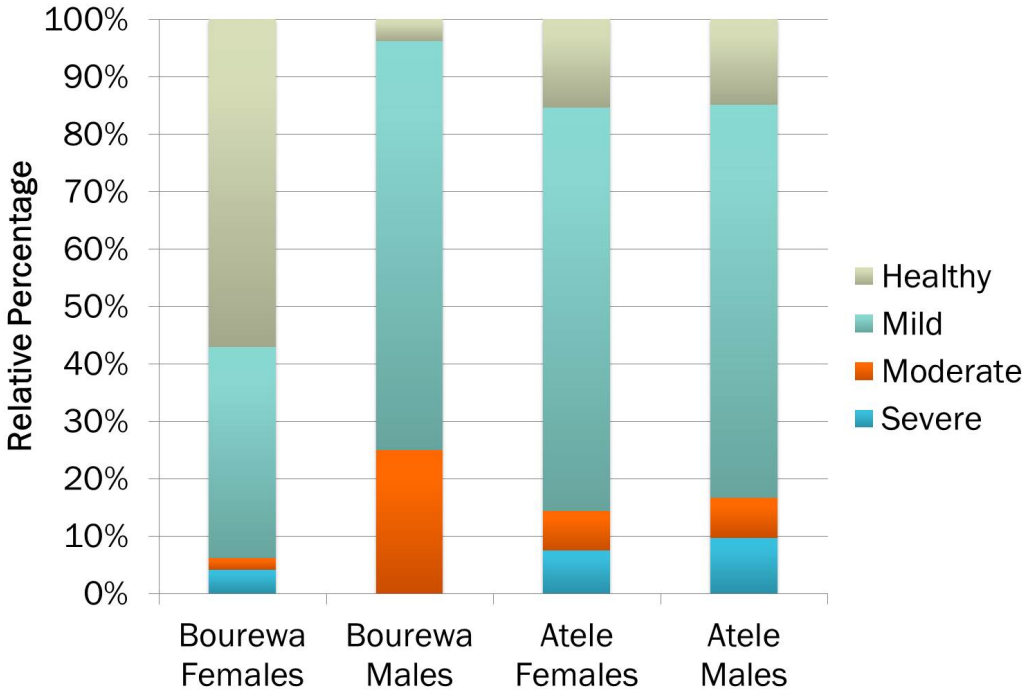


Figure 4.23. *Periodontitis severity by sex and site.*

be recorded). In Model 2b, there were no significant differences between adult age categories, sexes, or burial mounds.

4.10.7 Alveolar lesions

All alveolar lesions observed in both assemblages were periapical (rather than periodontal). There were too few instances of periapical cavities to conduct any statistical analyses, so they were examined qualitatively. In the Bourewa assemblage, three cavities were observed in 332 periapical areas (0.9%), all less than 3 mm in diameter. In the 'Atele assemblage, nine cavities were observed in 1,283 alveolar periapical areas observed (1.4%). Six of these cavities were less than 3 mm in diameter and three were greater than 3mm but less than 10 mm in diameter. The percentage prevalence of cavities between sites is similar (Figure 4.24) There appear to be no sex-based trends in periapical cavities and no subadults displayed evidence of this pathology. No periapical cavities were present in To-At-1 individuals from 'Atele, and the To-At-2 sample displayed a prevalence rate of 1.2%. There appear to be no trends regarding position in the oral cavity (Figure 4.25).

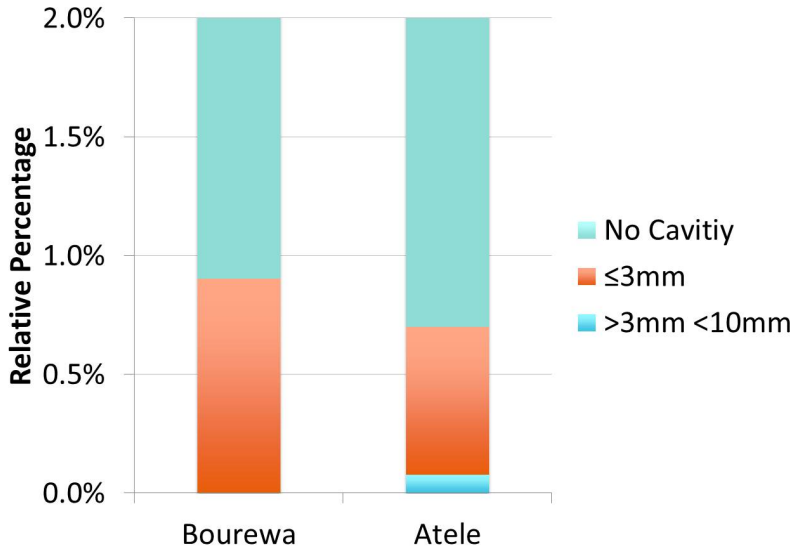


Figure 4.24. *Percentage prevalence of cavities by site. Note that y-axis maximum is 2%.*

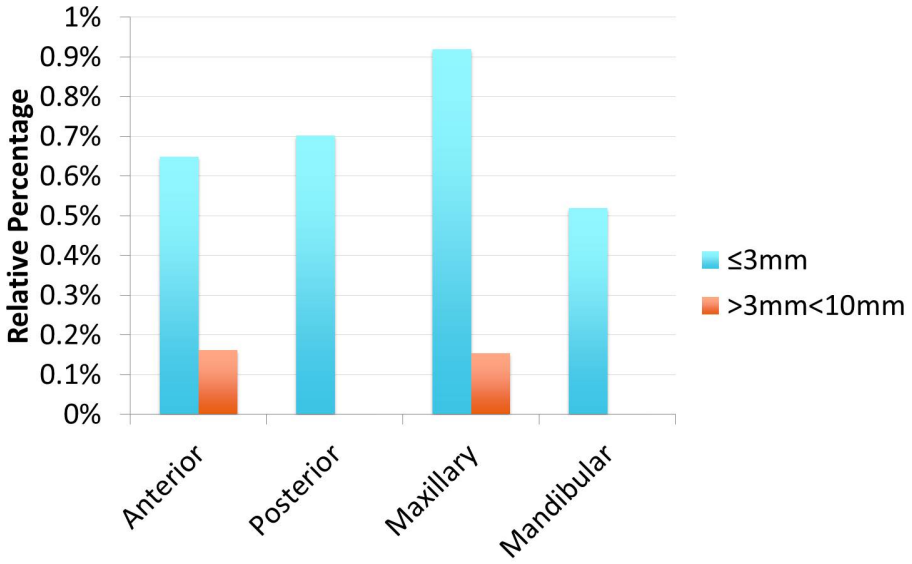


Figure 4.25. *Percentage prevalence of cavities by position (anterior/posterior and maxillary/mandibular). Note that y-axis maximum is 1%.*

Table 4.24. *Multi-level regression models for periodontal disease. As only two interdental septa were recorded in old adults in the Bourewa assemblage, age could not be included as a factor. Significant results marked with *.*

	Model 1			**Model 2a**			**Model 2b**		
	$n = 608$			$n = 84$			$n = 524$		
	Odds ratio	Std. error	p	Odds ratio	Std. error	p	Odds ratio	Std. error	p
Burial site									
Bourewa	1								
‘Atele	0.74	0.80	0.781						
Dental arch									
Anterior	1								
Posterior	2.07	0.61	0.014*						
Jaw									
Maxillary	1								
Mandibular	0.42	0.12	0.003*						
Adult age									
Young	1			—			1		
Middle	1.27	1.01	0.767	—			1.85	1.59	0.476
Old	10.20	9.93	0.017*	—			7.62	8.34	0.064
Old-Middle	8.06	8.32	0.043*	—			4.12	4.60	0.204
Sex				—					
Female	1			1			1		
Male	2.46	1.83	0.227	2.51	1.75	0.186	2.06	1.60	0.353
Burial mound									
To-At-1							1		
To-At-2							0.85	0.70	0.843

4.10.8 Ante-mortem tooth loss

In the Bourewa assemblage, 88 of the 391 sockets examined displayed remodelling indicative of AMTL (22.5%). Regarding individual prevalence in the Bourewa assemblage, 54.2% (13/24) of individuals had at least one remodelled socket. For ‘Atele, 1,615 sockets were observed in the 89 individuals with jaws. Of the 1,615 sockets, 101 (6.3%) showed signs of remodelling. In the ’Atele assemblage, 23.6% (21/89) of individuals displayed at least one remodelled socket. Table 4.26 presents AMTL prevalence by site, sex, and burial mound.

There are no differences between left and right sides of the mouth regarding AMTL in the Bourewa assemblage $\chi^2(1) = 0.03$, $p = 0.868$, or in the ‘Atele assemblage $\chi^2(1)$

Table 4.25. *Periapical cavities by site, sex, and burial mound.*

	No cavity (%)	≤3mm (%)	<10mm >3mm (%)	Total observed
Bourewa	329 (99.1)	3 (0.9)	0 (0)	332
Atele	1,274 (99.3)	8 (0.6)	1 (0.1)	1,283
To-At-1	526 (100)	0 (0)	0 (0)	526
To-At-2	589 (98.8)	6 (1)	1 (0.2)	596
Bourewa				
Female	109 (99.1)	1 (0.9)	0 (0)	110
Male	89 (98.9)	1 (1.1)	0 (0)	90
'Atele				
Female	424 (99.3)	3 (0.7)	0 (0)	427
Male	276 (98.6)	3 (1.1)	1 (0.4)	280
To-At-1				
Female	179 (100)	0 (0)	0 (0)	179
Male	106 (100)	0 (0)	0 (0)	106
To-At-2				
Female	245 (98.8)	3 (1.2)	0 (0)	248
Male	170 (97.8)	3 (1.7)	1 (0.6)	174

= 0.73, $p = 0.393$.

Multi-level regression of AMTL

Table 4.27 presents results of the multi-level logistic regression models. In Model 1, posterior teeth are significantly more likely to have been lost ante-mortem. Middle- and old-aged adults have significantly higher odds of AMTL than young adults, and old adults are significantly more likely to have lost teeth ante-mortem than middle-aged adults.

In Model 2a, adult age could not be included because it predicted AMTL in Bourewa individuals perfectly. There were no differences between males and females in the Bourewa assemblage. In Model 2b, adult age predicts AMTL the same manner as Model 1. There were no significant differences between the sexes or the burial mounds.

4.10.9 Subadult teeth: deciduous and permanent

Table 4.28 presents prevalence of the oral conditions examined in 'Atele subadults. Chi-square tests were conducted between the two burial mounds regarding oral condition prevalence in subadults. The percentage of subadult teeth affected by carious lesions differed by burial mound, $\chi^2(1,\ n = 286) = 5.66$, $p = 0.017$, with To-At-2 subadults

Table 4.26. *AMTL by site, sex, and burial mound.*

	Not lost ante-mortem (%)	AMTL (%)	Total observed
Bourewa	303 (77.5)	88 (22.5)	391
Tonga	1,514 (93.8)	101 (6.3)	1,615
To-At-1	638 (96.4)	24 (3.6)	662
To-At-2	671 (91.5)	62 (8.5)	733
Bourewa			
Female	106 (75.7)	34 (24.3)	140
Male	68 (73.1)	25 (26.9)	93
'Atele			
Female	478 (90.5)	50 (9.5)	528
Male	264 (88.9)	33 (11.1)	297
To-At-1			
Female	202 (93.5)	14 (6.5)	216
Male	107 (93.9)	7 (6.1)	114
To-At-2			
Female	276 (88.5)	36 (11.5)	312
Male	157 (85.8)	26 (14.2)	183

displaying a higher prevalence of carious lesions. There were no significant differences between the burial mounds concerning calculus prevalence, $\chi^2(1,\ n = 269) = 0.191$, $p = 0.662$. There were also no significant differences between the burial mounds concerning occlusal wear prevalence in subadults, $\chi^2(1,\ n = 267) = 0.05$, $p = 0.818$. No subadults displayed observable periapical cavities in either burial mound.

Examining carious lesions in more detail (Figure 4.26), there is a difference in the severity of carious lesions affecting subadults in the different burial mounds. One carious lesion (1.4% of the teeth observed in To-At-2 subadults) penetrated the dentine on the occlusal surface of a lower first molar. To-At-2/1a, a child aged 2.5 years, is the individual with this carious lesion.

There appear to be differences in which surfaces are more affected by carious lesions between deciduous teeth, subadult permanent teeth, and adult permanent teeth (Table 4.29). Examining the percent of surfaced affected (Figure 4.27), only adult permanent teeth are affected by root caries or occlusal attrition facet caries.

Although the sample size is too small for any statistical testing, a tendency towards posterior teeth chipping is evident in deciduous teeth as six of the eight teeth affected were molars. The other two teeth were 1st incisors, no deciduous canines were affected by chipping.

Table 4.27. *Multi-level regression models for AMTL. Adult age could not be included in Model 2a as age predicted AMTL perfectly in the Bourewa assemblage. Significant results marked with *.*

	Model 1			**Model 2a**			**Model 2b**		
	$n = 608$			$n = 84$			$n = 524$		
	Odds ratio	Std. error	p	Odds ratio	Std. error	p	Odds ratio	Std. error	p
Burial site									
Bourewa	1								
‘Atele	0.48	0.48	0.266						
Dental arch									
Anterior	1								
Posterior	2.59	0.76	0.001*						
Jaw									
Maxillary	1								
Mandibular	1.58	0.47	0.127						
Adult age									
Young	1			—			1		
Middle	16.49	19.13	0.016*	—			16.23	17.62	0.010*
Old	438.03	550.06	<0.001*	—			427.05	552.27	<0.001*
Old-Middle	26.57	27.61	0.002	—			26.31	29.61	0.004*
Sex									
Female	1			1			1		
Male	1.59	1.41	0.600	2.32	5.07	0.7	0.74	0.65	0.728
Burial mound									
To-At-1							1		
To-At-2							0.30	0.31	0.238

Table 4.28. *Prevalence of oral conditions in teeth from ‘Atele subadults.*

	‘Atele		**To-At-1**		**To-At-2**	
	Deciduous A/O (%)	Permanent A/O (%)	Deciduous A/O (%)	Permanent A/O (%)	Deciduous A/O (%)	Permanent A/O (%)
Caries	6/144 (4.3)	2/142 (1.4)	0/82 (0)	1/72 (1.4)	6/62 (9.7)	1/70 (1.4)
Calculus	4/132 (3)	29/137 (21.2)	1/71 (1.4)	15/69 (21.7)	3/61 (4.9)	14/68 (20.6)
Wear	70/82 (14.6)	5/81 (6.2)	6/45 (13.3)	3/37 (8.1)	6/37 (16.2)	2/44 (4.6)
Chipping	9/132 (6.8)	13/135 (9.6)	3/70 (4.3)	9/66 (13.6)	6/62 (9.7)	4/69 (5.8)
Cavities	0/192 (0)	0/142 (0)	0/122 (0)	0/75 (0)	0/70 (0)	0/67 (0)

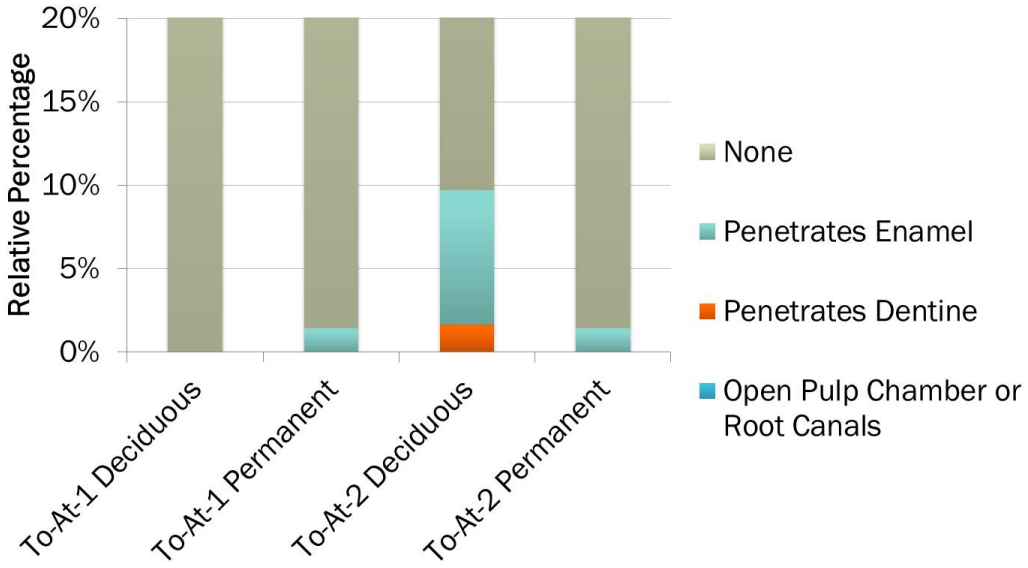


Figure 4.26. *Caries severity for deciduous and permanent teeth of 'Atele subadults. Note that y-axis goes to 20%.*

Table 4.29. *Prevalence of caries by surface in deciduous and permanent teeth of subadults, and permanent teeth of adults in the 'Atele assemblage.*

	Deciduous) A/O (%)	**Permanent A/O (%)**	**Adult A/O (%)**
Smooth	4/271 (1.5)	1/276 (0.4)	13/1623 (0.8)
Contact	1/279 (0.4)	0/270 (0)	9/1619 (0.6)
Occlusal surface	1/67 (1.5)	0/89 (0)	9/540 (1.7)
Occlusal attrition	0/14 (0)	0/42 (0)	6/635 (0.9)
Pit	0/0 (0)	1/32 (3.1)	6/138 (4.4)
Root	0/554 (0)	0/551 (0)	170/3216 (5.3)

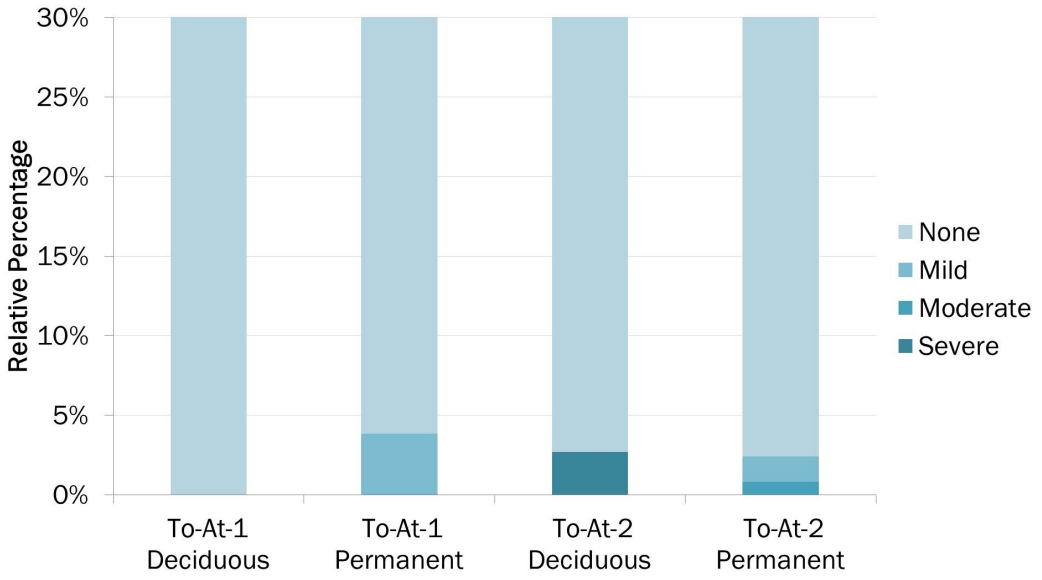


Figure 4.27. *Percent prevalence (%) of examined surfaces affected by carious lesions in deciduous teeth, subadult permanent teeth, and adult permanent teeth.*

Though there are no differences concerning occlusal wear between burial mounds when wear is examined as a presence/absence variable, examining wear in terms of severity shows some differences (Figure 4.28). While teeth in To-At-1 subadults are only mildly worn at most, there are three severely worn teeth with the To-At-2 subadults. The severely worn deciduous tooth (an incisor) is from the same child affected by the only deciduous tooth with a dentine-penetrating carious lesion, To-At-2/1a.

4.11 Discussion

The aims relevant to this chapter were:

- To characterise the diet of prehistoric Tongans and Fijians as diet is intricately tied with all aspects of the social landscape in Remote Oceania
- To compare inter- and intra-populational differences between and within the two sites to gain a more nuanced understanding of differences between late prehistoric Tonga and Fiji and certain groups within these sites such as those of different age categories, sexes, or social status

The hypotheses relevant to this chapter were:

- **H_5:** Due to the larger island size of Viti Levu, the Bourewan individuals will have a larger terrestrial component in their diet compared to the 'Atele individuals as

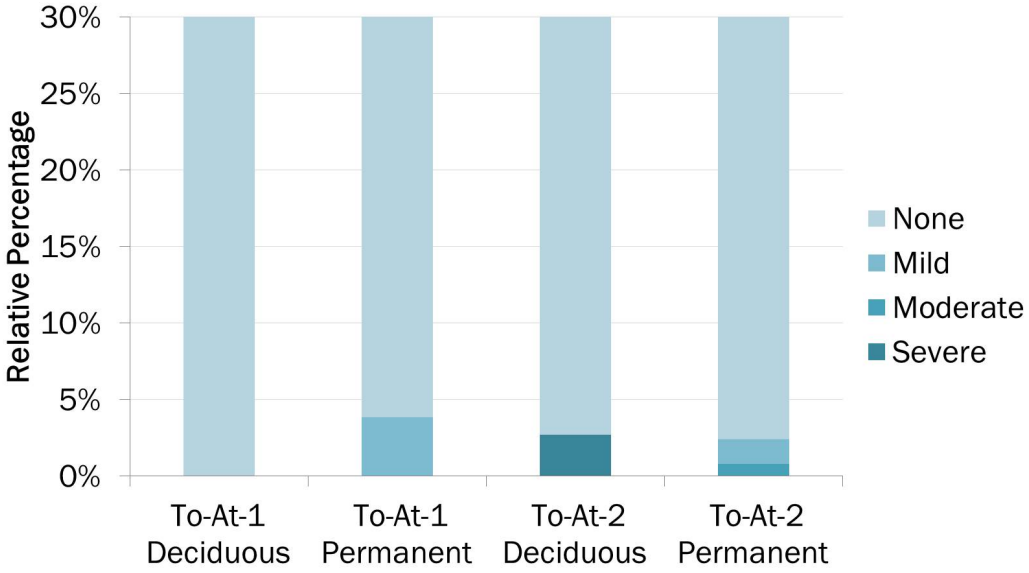


Figure 4.28. *Wear severity for deciduous and permanent teeth of 'Atele subadults.*

evidenced by isotope analysis and oral indicators of diet

- **H_6:** With no previous studies finding differences between the two burial mounds at 'Atele, there will be no differences regarding diet or movement discerned in this study

- **H_{10}:** Using isotope analysis and oral indicators of diet, males and females will display similar diets due to the practice of communal meals in these islands as evidenced in ethnographic studies (Pollock, 1992; Jones, 2009)

A summary of findings from this chapter are presented on Table 4.30.

4.11.1 Logistic regression as a means of understanding patterns in oral conditions

It is difficult to ascertain which method of parsing the dental data provides a more accurate understanding of diet. Collapsing the data to binary variables allows more robust analytical models to be utilised and enables the same test to be used for each oral condition, but at cost of understanding severity patterns. In addition, the cut-off points I employed for the oral conditions (as detailed in the methods section of Chapter 4) may have affected the inferential analyses and interpretations. For example, any molars with a cusp quadrant graded 5 or greater was deemed "worn," though grade 5 wear is vastly different from grade 10 where the quadrant is worn to the root. Ordered logit models,

Table 4.30. *Summary of questions addressed and findings from analysis of oral conditions.*

Research question	**Findings**	**Hypothesis addressed**
Differences between sites?	Bourewa have decreased odds of severe caries, more severe wear, less severe periodontitis	H_5
Burial mound differences in ‘Atele?	To-At-1 individuals have increased caries severity, more severe wear, and decreased odds of chipped teeth	H_6
Sex differences in Bourewa?	Males have increased odds of chipping	H_{10}
Sex differences in ‘Atele?	Females have increased caries severity, males have increased periodontal disease severity	H_{10}
Morphological trends?	Molars more affected by root caries. Posterior teeth more affected by caries, calculus, and AMTL, less affected by wear. More severe periodontal disease in posterior and maxillary teeth	

which allows the comparison of the severity of oral conditions and does not require collapsing the data to presence/absence, has its own strengths and weaknesses. Ordered logit regression requires a much more robust sample size and the Bourewa assemblage sometimes was not large enough for this kind of test. In addition, logit models expect similar "jumps" between grades of severity. Biologically, changes between certain grades of severity are not equal: the difference between a carious lesion affecting enamel and affecting dentine is a small change for the individual affected and the tooth's structure, but the difference between a carious lesion affecting dentine and one that has opened the pulp chamber is large.

4.11.2 Morphological trends

While discussing morphological trends within oral conditions does not directly address the aims and hypotheses of this thesis, understanding these patterns is important in order to differentiate between diet-related causes of oral conditions and other factors. The increased number of incisors lost post-mortem makes anatomical sense given their shorter roots compared to canines and premolars and their single roots compared to molars and some premolars. There were no differences in caries severity between tooth types, but molars were more affected by root caries (and posterior teeth were more likely to be affected by caries in general). Increased root exposure would be a possible explanation regarding the surface trends in molars, especially since more posterior teeth were affected by periodontal disease. Difficulty in cleaning posterior teeth in prehistory might be the underlying cause behind the increased prevalence in both of these diseases. The morphological complexity of the posterior teeth also tends to leave these teeth more susceptible to carious lesions (König, 1963; Juhl, 1983). 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 greater odds of periodontal disease in maxillary teeth, however, are more difficult to explain. There are currently no physiological explanations in the clinical literature explaining this pattern.

Calculus deposits occur most often on the lingual surface of the anterior maxillary teeth in a clinical setting (Corbett and Dawes, 1998), which is opposite to the anterior/posterior calculus patterns observed in the 'Atele and Bourewa assemblages. Difficulty in cleaning may explain the increased odds of calculus in the posterior teeth. The low prevalence of periapical cavities throughout both assemblages is possibly associated with the low rate of occlusal wear (Dias and Tayles, 1997). Though cavities can form as a result of carious infections travelling 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 (Taylor, 1963; Kieser et al., 2001).

Regarding wear, the posterior teeth were less likely to display exposed dentine. This pattern might not be related to diet or the mechanics of tooth use but to cusp morphology. Molars typically have thicker enamel compared to other tooth types (Vellini-Ferreira et al., 2012), and so using dentine exposure as a means of comparing tooth types for dental wear may not be ideal. However, since both dental wear recording methods employed in this study use dentine exposure as a means of scoring wear, there is not necessarily a method which avoids the under-representation of worn molars compared to other tooth types.

There were no differences between anterior/posterior or mandibular/maxillary teeth regarding chipping when both sites were combined for multi-level logistic modelling, but the ‘Atele assemblage on its own had significantly more maxillary and anterior teeth chipped. All comparative populations display higher rates of maxillary teeth chipped than mandibular and Bourewa is the only exception to this trend. Decreased odds of chipping in maxillary teeth could be expected, as they are more fracture-resistant than mandibular teeth (Schatz et al., 2001). Increased chipping in maxillary teeth could be a result of the biomechanics of chewing as the mandible has more mobility, it is easier to adjust the mandible and mandibular teeth in response to tougher food particles. Examining patterns within the dental arch, Bourewa has more posterior teeth chipped while ‘Atele has more anterior teeth chipped.

However, the basic theory behind anterior/posterior chipping as an indicator of subsistence relies on agricultural foods not causing posterior chipping. While many agricultural plants in Europe, Africa, and the Middle East may be softer than hunting-gathering resources, this chipping hypothesis does not account for an arboriculture that uses tree nuts as a substantial portion of the diet. Perhaps the heavy posterior chipping in the Bourewa assemblage does not imply hunting-gathering, but a greater reliance on tree nuts for subsistence (Kirch, 1989)? Dental chipping could also be caused by sand particles not removed from roots, bulbs, and molluscs (Robinson, 1954), though the relatively low rates of occlusal wear in the assemblages leaving sand and grit in the diet as an unlikely cause of the occlusal edge chips. Recording the size of the chip in future research may be useful for determining the cause. Within many Oceanic populations, grit remaining in marine resources would likely contribute small “nibbling" chips, while larger chips could occur in populations who ate nuts such as *Canarium*. Non-masticatory use of teeth might also have contributed to dental chipping, such as

opening shells and exoskeletons.

There were no differences in AMTL between the left and right sides. If there was a clear tendency towards a side affected by AMTL especially the left quadrants, interpersonal violence may have been considered as a leading cause (Lovell, 1997; Novak, 2000). Multi-level regression also displayed that posterior teeth were more likely to be lost ante-mortem rather than anterior teeth. If tooth ablation (intentional tooth removal) was a common occurrence in prehistoric Tonga or Fiji, more anterior teeth would have been expected to be lost. As such, a more likely explanation is the exfoliation of teeth due to dental disease.

4.11.3 Inter-site comparisons

There were no statistically significant site-based differences when comparing oral conditions as presence/absence variables. There are, however, some differences when oral conditions are examined in more detail. The Bourewa individuals are less likely to display severe carious lesions and display more occlusal attrition facet caries. The decreased odds of severe caries are difficult to explain, but the increased prevalence of occlusal attrition facet caries is expected given that the Bourewa assemblage consists of an older population with more severe wear. The decreased odds of severe periodontitis in the Bourewa assemblage may be related to the decreased odds of severe caries, though there is still no satisfactory explanation to posit regarding why there are site-based differences in severity.

While the violation of the assumption of parallel regression occurred in the models with caries and wear severity as the dependent variables and calls into question the validity of the model, ordinal logistic regression was the only way to address questions regarding the relationship between disease severity and demographic variables without individual age affecting other factors. The fact that adult age significantly increases the odds of severity for all diseases implies that these tests are producing useful results, if interpreted with caution.

In trying to address Hypothesis 5 of this thesis (that Bourewan individuals will have a larger terrestrial component in their diet), there appear to be two possible interpretations. With no site-based differences using multi-level logistic regression, perhaps there are no discernible differences in diet using oral conditions as evidence. With more subtle, though significant, variations in caries and wear severity between the two sites, there may be some inferred dietary differences. However, decreased caries severity and increased attrition in the Bourewa assemblage would traditionally be interpreted as an increased reliance on marine resources rather than terrestrial resources

(Littleton and Frohlich, 1993). In either scenario, hypothesis 5 would be rejected using oral indicators of diet.

The dietary differences between the sites may be too small to have greatly 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 and its contribution to caries prevention within these assemblage cannot be considered as there have been no studies of environmental fluoride levels on these islands.

4.11.4 Comparisons to past studies of oral conditions

The caries rates reported in this study for both ‘Atele and Bourewa are high relative to global prehistoric populations. With a mean per-tooth caries prevalence of 15.7% in Bourewa and 11.3% in ‘Atele, the Pacific populations experienced carious lesions at a prevalence comparable to many Pre-Industrial mono-crop agricultural societies (Turner, 1979; Larsen, 1995). Comparing the assemblages in this study with those from past research, it becomes clear that, as expected, 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 ranges between 9.8% in prehistoric Hawai‘i (Keene, 1986) to 31% in Lapita-era Vanuatu (Kinaston, 2010).

Table 4.32 presents the ‘Atele and Bourewa wear rates and the wear rates of other sites that have been analysed. The confidence levels for b produced for ‘Atele and Bourewa are similar to, if not smaller than, those from other studies (Chattah and Smith, 2006; Watson et al., 2013; Mickleburgh, 2014). Principal axis analysis may be subject to issues with different eruption times between individuals. Although eruption is strongly genetically-controlled within a given population, populational differences may

Table 4.31. *Comparative caries prevalence by-tooth in tropical Pacific populations.*

Location	Date	Caries A/O (%)	Reference
Bourewa	750–150 BP	39/248 (15.7)	this study
ʻAtele	500–200 BP	125/1105 (11.3)	this study
Rapa Nui	1680–1880 C.E.	118/450 (26.2)	Owsley and Miles (1985)
Hawaiʻi	1700–150 BP	1895/19425 (9.8)	Keene (1986)
Sigatoka, Fiji	1750–150 BP	91/1142 (8.0)	Visser (1994)
Marianas Islands	1000–1521 C.E.	157/1591 (9.9)	Pietrusewsky et al. (1997)
Fiji	c. 1850 C.E.	31/198 (15.6)	Valentin et al. (2006)
Taumako	750–300 BP	63/1679 (4.0)	Kinaston (2010)
Teouma, Vanuatu	3000–2900 BP	46/149 (31)	Kinaston (2010)

leave comparisons to other assemblages difficult (Savara and Steen, 1978; Virtanen et al., 1994; Al-Jasser and Bello, 2003; Folayan et al., 2007). The sites in this study display the lowest wear rates of all, barring the Campbell Site examined by Scott (1979b). These results suggest that the relatively low rates of wear in the populations are not just products of demographic discrepancies between sites, but actually indicative of softer foods in these Pacific Islands diets. This is expected if the main part of their diet consisted of root vegetables cooked until soft which is consistent with the ethnohistoric records of diet in Fiji and Tonga.

Unfortunately, no principal axis analyses have been conducted on modern populations for comparative purposes. The Campbell and Hardin sites in the United States and some of the Chilean individuals in Watson's Chilean populations (2013) are from time periods of European contact, though the exact extent of dietary changes in these areas are unknown. The Campbell site is a late prehistoric/early historic site from southeastern Missouri (O'Brien and Wood, 1998). Scott (1979b) proposes no explanations for why the Campbell assemblage displays such a low rate of wear. The site contained artefacts of iron, brass, and glass suggesting contact with the Spanish explorers in the 1540s (O'Brien and Wood, 1998). The inclusion of European foods in the diet may explain the lower wear rate in the Campbell site compared to other Native North American assemblage, or an increased proportion of soft foods from the local diet (e.g. beans, squash and gourds) compared to coarser foods such as maize. Understanding the proportions of food types in Native American groups is difficult due to conflicting ethnohistoric accounts (Larsen, 1994) and outside of the scope of this project. Nonetheless, principal axis analysis has demonstrated just how soft the diets of the individuals in this study are when comparing wear rates globally.

Table 4.32. *Comparative wear rates in other populations. Scott (1979) displayed principal axis equations from maxillary and mandibular teeth; only maxillary equations presented here.*

Population/ Geographic Area	**Slope (b)**	**Source**
‘Atele (500–200 BP)	0.51	this study
Bourewa (750–0 BP)	0.53	this study
Native N. America: Campbell site (1400–1650 CE)	0.47	Scott (1979b)
Native N. America: Indian Knoll site (5500–2000 BCE)	1.06	Scott (1979b)
Native N. America: Hardin site (1500–1625 CE)	0.89	Scott (1979b)
Australian Aborigines (date unknown)	0.87	Richards (1984)
Southern Levant: Wadi Makkukh site (6500–5500 BP)	1.51	Chattah and Smith (2006)
Southern Levant: Peqi’in site (6500–5500 BP)	1.28	Chattah and Smith (2006)
Chile: Coastal (1500 BCE–500 CE)	0.73	Watson et al. (2013)
Chile: Valley (1500 BCE–500 CE)	0.67	Watson et al. (2013)
Caribbean (400 BCE–600/800 CE)	1.21	Mickleburgh (2014)
Caribbean (600/800–1500 CE)	1.04	Mickleburgh (2014)

4.11.5 Comparisons between the ‘Atele burial mounds

Overall, Hypothesis 6 (that there will be no differences between the two burial mounds) would be rejected when examining oral conditions. To-At-1 adults displayed increased odds of more severe caries, more severe wear and more calculus. Periodontitis severity and caries severity do not seem to be related between burial mounds, as To-At-1 displayed lower odds of periodontal severity (though not quite to a significant degree). It is interesting that, while To-At-1 adults displayed increased odds of more severe occlusal wear, only To-At-2 adults had occlusal attrition facet caries.

Using principal axis analysis, To-At-2 individuals experienced faster wear rates than To-At-1 individuals (0.65 slope compared to 0.43) even though To-At-1 individuals displayed increased odds of dentine exposure and more severe wear when examining the result of multi-level logistic regression and ordinal logistic regression. All analyses used for comparing wear should take age into account, although regression models three-level adult age categories which may have been subject to problems with precision and/or accuracy. Principal axis analysis, in examining the difference in wear between the first and second molars, bypasses the subject's age entirely (although it still may be vulnerable to differences between individuals regarding eruption times).

4.11.6 Age group comparisons

Comparing different age categories could have addressed the third aim of the thesis, comparing different social groups within the assemblages. However, it is impossible to try to meaningfully compare oral conditions between different adult age groups as the majority of oral conditions are progressive and do not remodel with time. Adult age contributed greatly to the odds of a person experiencing any given oral condition. As this is well-known in health literature, including adult age in the regression models was not to explore these age-related trends, but to account for adult age when exploring other variables. For example, a simple Pearson's chi-squared test between the sexes in Bourewa shows females displaying more caries $\chi^2(2,\ n = 150) = 9.07,\ p = 0.003$. However, there are relatively more old-aged females and less young adult females and so age is likely affecting the caries rate more than sex.

Subadults displayed lower prevalences of all oral conditions compared to adults, which is also expected. Comparing the burial mounds, To-At-2 deciduous teeth were more affected by caries, calculus, wear, and chipping than To-At-1 deciduous teeth. This is in contrast to the patterns observed in the adults, where To-At-1 adults displayed increased odds for caries, calculus, and wear.

Comparing deciduous and permanent teeth in subadults to adult teeth, there was a difference concerning surface caries prevalence (other than the generally lower prevalence in subadults): subadults displayed no root caries. This is likely because subadults had no root exposure from continuous/compensatory eruption or periodontal disease in life.

To address the final aim of the thesis (to understand age-at-weaning and weaning food practices in prehistoric Tongans), the oral conditions in ʻAtele subadults can be compared to those recorded in other archaeological sites around the world on Table 4.33. The caries prevalence in ʻAtele is similar to that found by Keene and Keene (1985) in prehistoric Hawaiian subadults, and to hunter-gatherers in North America. The Taumako assemblage, recorded by Kinaston (2010), displays a much higher caries prevalence than ʻAtele and Hawaiʻi. Caries prevalences appear to be much higher in agricultural sites compared to hunter-gatherer or horticultural societies, which is consistent with adult caries rates in relation to subsistence practices.

Though there are large differences in caries prevalence in deciduous teeth between the Pacific populations and agricultural Southeast Asia as evidenced in Table 4.33, modern supplementary weaning foods in tropical Southeast Asia are similar to those in tropical Remote Oceania: mashed bananas, taro, and yams (Jelliffe, 1968; King, 2008; Halcrow et al., 2013). As mentioned previously, these complementary foods are sticky and possibly cariogenic. But, the fact that they are weaning food staples in two cultural areas with vastly different caries prevalences suggests that these foods are possibly not to blame for the higher caries rates in tropical Southeast Asia. The addition of glutinous rice to the Southeast Asian diet, which is not a part of prehistoric Remote Oceanic horticulture, may be the cause of these differences. Rice, though likely less cariogenic than other agricultural staple crops such as maize (Tayles et al., 2000), may be more cariogenic when made into a rice gruel and used as a complementary food compared to mashed root crops (Halcrow et al., 2013). This is difficult to prove, as the complementary foods used in modern Southeast Asia and the Pacific may not be the complementary foods used in the past. Prolonged breastfeeding does not seem to affect caries susceptibility (Kramer et al., 2007; Iida et al., 2007; Mohebbi et al., 2008), so differences in age of weaning between Southeast Asia and Remote Oceania populations are an unlikely cause of the variance.

Caries rates are consistently lower across all comparative sites in subadult permanent teeth compared to to deciduous teeth. Weaning foods of greater relative cariogenicity compared to adult foods could be the cause. Lower levels of mineralisation in deciduous teeth could leave them more susceptible to carious demineralisation (Wilson and Beynon, 1989). There appear to be few trends regarding surface lesions on deciduous teeth

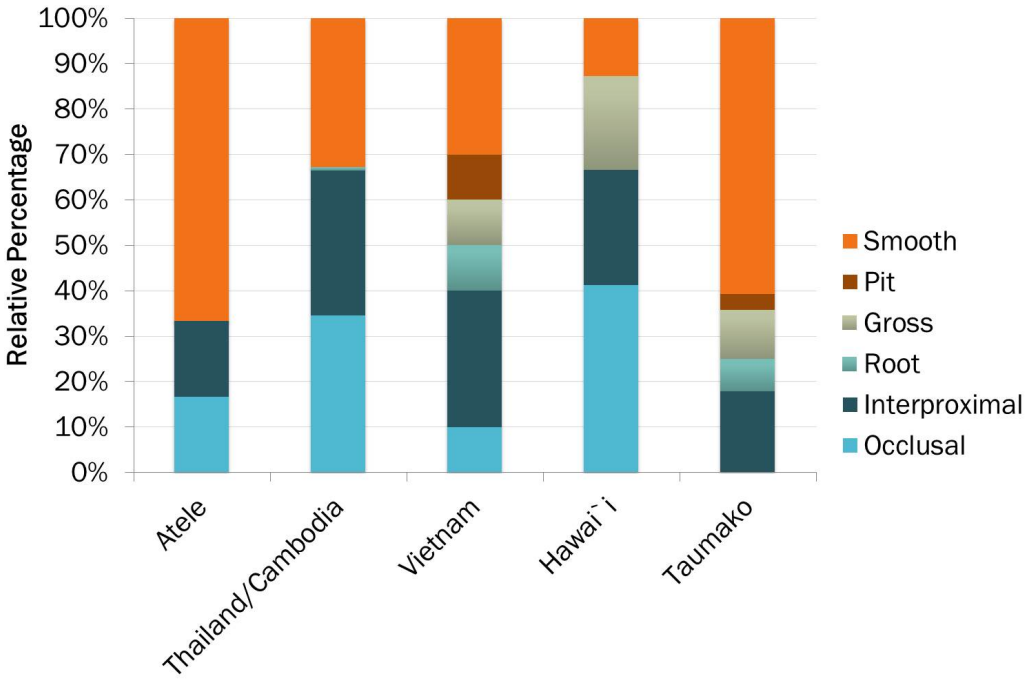


Figure 4.29. *Relative caries prevalence by surface for deciduous teeth. Comparative data from Halcrow et al. (2013); Oxenham and Domett (2011); Keene and Keene (1985); Kinaston (2010).*

(Figure 4.29). In Southeast Asia and Taumako pit and root caries are present in deciduous teeth, and in Vietnam, Hawai'i, and Taumako are carious lesions affecting multiple surfaces (gross caries). 'Atele and Taumako both display a high proportion of smooth surface caries compared to the other assemblages. Both of these assemblages were examined by Buckley (2001) in her Ph.D. thesis, where she concluded that the high prevalence of smooth surface caries may be related to enamel defects from childhood stress. In Kinaston's re-examination of caries in the Taumako assemblage (2010), Kinaston found that the smooth surface caries in Taumako deciduous teeth do not appear to be related to enamel defects, but does not rule out the possibility. As this thesis did not record enamel defects, it is impossible to concur with or argue against Buckley's conclusions. However, the high prevalence of smooth caries in Taumako and 'Atele in contrast to the other assemblages in Table 4.33 may hint that childhood health, rather than childhood diet, may have influenced caries prevalence in these two Remote Oceanic sites.

Table 4.33. *Caries prevalence in deciduous and permanent teeth for 'Atele and other archaeological subadults. Sciulli (1997) did not provide subadult permanent teeth prevalences.*

			Caries		
Site/ area	**Time period**	**Subsistence**	Deciduous, A/O (%)	Permanent, A/O (%)	**Reference**
'Atele	500–200 BP	Horticulture	6/144 (4.2)	2/142 (1.4)	This study
Hawai'i	1700–150 BP	Horticulture	63/1855 (3.4)	0/999 (0)	Keene and Keene, 1985
Taumako	750–300 BP	Horticulture	12/114 (11)	28/115 (24)	Kinaston, 2010
Thailand/ Cambodia	4000–1500 BP	Agriculture	113/972 (11.6)	27/538 (5)	Halcrow et al., 2013
Vietnam	Neolithic	Hunting-gathering/ agriculture	10/270 (3.7)	0/163 (0)	Oxenham and Domett, 2011
Native N. American	1500–1000 BP	Hunting-gathering	2/62 (3.2)		Sciulli, 1997
Native N. American	1000–300 BP	Agriculture	356/2237 (15.9)		Sciulli, 1997

4.11.7 Comparisons between the sexes

Overall, there were few differences in oral conditions between the sexes. Males displayed a higher wear rate compared to females in the ‘Atele assemblage. Males in the Bourewa assemblage had increased odds of chipped teeth compared to females, although there were no differences between the sexes in the ‘Atele site. Males had more severe periodontal disease compared with females in the ‘Atele assemblage, but there were no differences in severity between the sexes in the Bourewa assemblage. Females were more likely to be affected by more severe caries, though there are no differences between the sexes when caries is collapsed to a presence/absence variable for both assemblages.

The most interesting finding from this chapter is the lack of statistically significant sex-based differences regarding caries risk in both the Bourewa and ‘Atele assemblages. It is possible that the dietary differences between the sexes, like those between sites, are too subtle to have significantly affected oral conditions. Intriguingly, no studies comparing caries prevalence between the sexes in prehistoric Pacific Islanders have found significant differences (Douglas et al., 1997; Owsley and Miles, 1985; Kinaston, 2010). 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. Few medical studies of oral health in living populations have explored sex-based differences. On Pukapuka Island (Cook Islands), caries rates were significantly higher in females (Davies, 1952, 1956). Sinclair et al. (1950) did not report sex differences in caries rates, but presented their data so thoroughly that a Pearson’s chi-squared could be conducted and there were no differences concerning caries rates between males and females.

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 or are generally unaffected by the hormonal and genetic causes for increased caries susceptibility in females as elsewhere in the world. Dietary differences seem an unlikely cause, given that the isotope 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-adolescent females display higher rates of oral disease in clinical studies (Stoughton and Meaker, 1932; Lukacs and Largaespada, 2006). 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 subadult (estimated around 13 years of age). 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 predispositions that are leaving them as susceptible to caries and other oral conditions as females? A clinical 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 to 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. Overall, it is difficult to determine whether the oral indicators of health rejected or failed to reject hypothesis 10 (that there would be no dietary differences between the sexes). While there were some differences between the sexes, complex interactions between hormones, sex-linked heritability, and possibly culturally-influenced access to certain foods leave understanding sex-based dietary patterns difficult.

4.12 Summary

There were few differences in diet between the sites and sexes, which is in conflict with the isotope analyses of diet presented in the previous chapter. While the examination of dental markers of diet can contribute to the characterisation of diet, combining this approach with isotope analysis will create a clearer picture of diet in these assemblages. The two data sets will be examined together in Chapter 6 (Dietary Reconstruction)

and hypothesis 4 of this thesis (that the two methods of assessing diet will agree) will be addressed therein. How movement (Chapter 5, Isotopic Analysis of Movement) may have affected diet and vice versa in prehistoric Tonga and Fiji will be considered in the discussion and conclusion for the thesis (Chapters 6 and 7).

Chapter 5

Isotope Analysis of Movement ($^{87}Sr/^{86}Sr$)

"Who we are cannot be separated from where we're from."
Malcolm Gladwell, *Outliers, the Story of Success*

In this chapter, I address two aims of the thesis: first, to understand individual mobility and population movement in these sites in order to consider cultural aspects that may have affected migration and second, to compare inter- and intra-populational differences between the two sites and certain subgroups. In order to address these aims, strontium analysis ($^{87}Sr/^{86}Sr$) will be conducted to provide evidence of individual movement. Movement between subpopulations (e.g. sex, burial sites, burial mounds, age groups) will be compared. The tissue used for $^{87}Sr/^{86}Sr$ analysis, tooth enamel, and the diagenetic processes specific to the mineral portion of teeth and bone will be described. Next, the principles of strontium analysis will be outlined, including how $^{87}Sr/^{86}Sr$ analysis can be used to interpret human movement. Other isotope analyses that provide direct evidence of individual movement will be discussed, as will the reasons why they were not used in this study. Then, past studies of prehistoric Pacific movement using $^{87}Sr/^{86}Sr$ analysis will be reported. The analytical methods relevant to this part of the thesis will be described, along with an explanation of the statistical methods used for interpreting $^{87}Sr/^{86}Sr$ ratios. Finally, I present and briefly discuss the results specific to $^{87}Sr/^{86}Sr$ analysis.

The Bourewa $^{87}Sr/^{86}Sr$ data are presented and discussed in Stantis et al. (2015a). The data used to explore human movement in 'Atele was first presented and discussed in Stantis et al. (2015b).

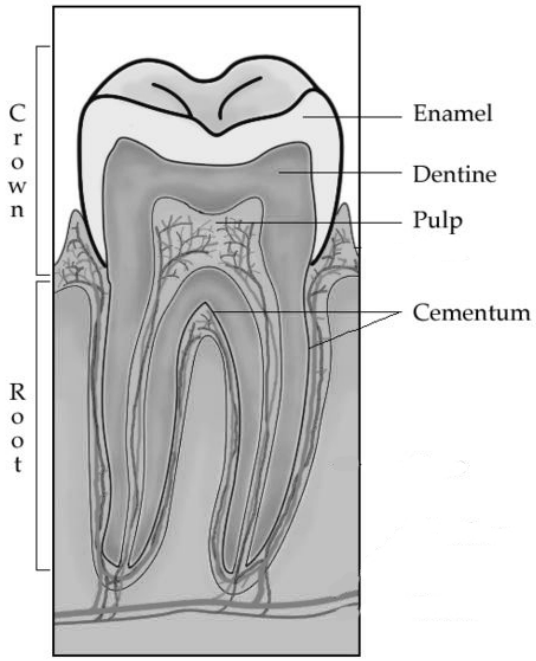


Figure 5.1. *Cross-section of a tooth, with different tissues (enamel, dentine, cementum, and pulp) and anatomical areas (crown and root) labelled. Original digital image by Sam Fentress licensed under CC BY-SA 2.0.*

5.1 Enamel

Human tooth enamel is the hardest tissue in the human body, composed of approximately 98% mineral (mostly hydroxyapatite), 2% organic material, and a small amount of water (Hillson, 1996). Enamel forms the outer layer of the tooth crown, protecting the less mineralised tissues (Figure 5.1). Although enamel is strong due to its high proportion of inorganic material, it is also brittle, and the underlying dentine is necessary to maintain structural integrity and resist fracture (Nanci, 2013).

The formation of the enamel matrix by cells known as ameloblasts occurs before tooth eruption and can be divided into two steps (Hillson, 2006). The first step of enamel formation (or amelogenesis) is sometimes called the apposition step (Bath-Balogh and Fehrenbach, 2006), when enamel matrix is secreted by ameloblasts onto the basement membrane (the structure which mineralises into the dentinoenamel junction). Enamel matrix is laid down as a rod-like structure as the ameloblasts "retreat" from the dentinoenamel junction at a roughly perpendicular angle (Mahoney, 2014). These rods are the crystalline structures that are the basic histological unit of enamel. During the apposition step of amelogenesis, enamel matrix is only approximately 30% mineralised

(Bath-Balogh and Fehrenbach, 2006). The apposition stage of amelogenesis occurs over a period of 70 to 80 days (Dean, 2009).

During the second phase of amelogenesis, the maturation stage, ameloblasts (now located on the enamel surface) replace most of the organic component of enamel with mineral. The maturation stage occurs over several years (Hillson, 1996). After eruption, the ameloblasts are removed from the enamel surface, never to be replaced. Without living cells in enamel, this tissue can never be repaired by the body (Hillson, 2006). There is a period of posteruptive mineralisation despite the death of the ameloblasts, as minerals in saliva such as calcium and fluoride are deposited into hypomineralised enamel (Bath-Balogh and Fehrenbach, 2006).

Isotopic analysis of enamel is typically limited to the mineral portion, as enamel contains scant amounts of Type I collagen for collagen analysis (Açil et al., 2005), though the $\delta^{13}C$ values of carbonate from enamel have been utilised to investigate the whole diet of organisms (Balasse et al., 2003; Passey et al., 2005). As with primary dentine (described in Chapter 3), tooth enamel does not remodel once formed (Hillson, 1996). As such, isotope analyses conducted on tooth enamel will represent the place of origin during formation (Bentley, 2006), the timing of which is strongly genetically controlled with few environmental factors playing a strong role (Cardoso, 2007; Brook, 2009).

5.1.1 Diagenesis of enamel

The mineral portion of teeth and bone is subject to three diagenetic mechanisms in the burial environment: precipitation of new substances, dissolution of elements into groundwater, and restructuring of compounds due to chemical reactions (Sandford, 1993; Goffer, 2007). Although strontium has been found to be relatively unaffected by diagenesis compared to other elements (Edward and Benfer, 1993), the two main diagenetic effects that alter $^{87}Sr/^{86}Sr$ ratios are the leaching of strontium from these tissues and the precipitation of strontium into the teeth and bones from groundwater and soil (Bentley, 2006). Although the bones of the very young and very old can be more at risk for soil contamination in regards to some trace elements, the individual's age has little effect regarding strontium contamination (Lambert et al., 1979).

Biogenic and diagenetically-deposited apatite are structurally very similar and thus difficult to separate (Trickett et al., 2003), and so analysing tissue types that are least likely to incorporate diagenetic material is crucial. Enamel's dense mineral structure makes this tissue especially resistant to diagenetic effects in comparison with bone (Chiaradia et al., 2003; Trickett et al., 2003; Bentley, 2006). Enamel apatite is less

prone to molecular substitution (e.g. CO_3^{2-} for PO_4^{3-}) and displays higher crystallinity, density, and higher-order structures compared to bone (Lee-Thorp, 2008). Although pre-treatment (surface abrasion and chemical leaching) can remove most (approximately 95%) diagenetic strontium from enamel, these processes may remove as little as 20% of contaminants in bone (Hoppe et al., 2003). Although $^{87}Sr/^{86}Sr$ analysis of bone could provide information regarding movement during the past few years of the person's life, just as paleodietary isotope analyses can provide dietary information from that time, the diagenetic issues involving the mineral portion of bone are too problematic (Price et al., 1992). As such, only strontium isotope analysis on enamel samples was conducted for this study.

5.2 Principles of strontium isotope analysis

Many of the basic concepts of isotope analysis introduced in the paleodietary isotopes chapter are relevent for this chapter. ^{87}Sr contains one more neutron that ^{86}Sr, causing a difference in kinetic isotopes effect between the two isotopes (Sharp, 2007). Both ^{86}Sr and ^{87}Sr are stable, although ^{87}Sr is also radiogenic in that it is formed from the decay of the radioactive isotope of rubidium (^{87}Rb) (Goffer, 2007; Knudson et al., 2010).

There is a relatively smaller difference between ^{87}Sr and ^{86}Sr in terms of mass compared to nitrogen and carbon stable isotopes. ^{87}Sr is 1.16% heavier than ^{86}Sr while the mass differences between the carbon and nitrogen isotopes used in this thesis are 8.33% and 7.14%, respectively. The smaller scale of difference between the two strontium isotopes necessitates the use of more precise instrumentation compared to light element analysis (Fietzke and Eisenhauer, 2006; Knudson et al., 2010). The relative mass difference also reduces the kinetic effects between the two isotopes, leaving strontium isotope fractionation at a given temperature almost a tenth of that of nitrogen or carbon (Burton, 2008). When examining $^{87}Sr/^{86}Sr$ ratios to determine residential mobility, the small level of fractionation can be accounted for by correcting $^{87}Sr/^{86}Sr$ ratios using the constant value of $^{86}Sr/^{88}Sr$, 0.1194 (Steiger and Jäger, 1977).

Delta notation (δ) is often only used for lighter elements and heavier elements (such as strontium) are typically presented as a decimal fraction of absolute isotope abundance. As such, international standards are not necessary for these elements. Internal standards with known isotopic composition are still important for maintaining instrumental accuracy and precision (Sharp, 2007; Hoefs, 2009).

Table 5.1. *The isotopic compositions of the element examined in this thesis for interpreting movement. Strontium has more than two naturally occuring isotopes but only the isotopes used for this study are listed. From Berglund and Wieser (2011); Böhlke et al. (2005).*

Element	Isotope	Number of protons	Number of neutrons	Relative atomic mass	Natural abundance (%)
Strontium	^{86}Sr	38	48	85.909260	9.86
	^{87}Sr	38	49	86.908877	7.0

5.3 Interpreting movement using $^{87}Sr/^{86}Sr$ analysis

Strontium isotope analysis was first used on archaeologically-derived individuals for understanding movement by Ericson (1985) in two prehistoric California assemblages. By examining the $^{87}Sr/^{86}Sr$ ratios in skeletal apatite, Ericson extrapolated the location where an individual spent their childhood (using tooth enamel) and most of the last years of their life (using apatite from bone). The interpretation of movement using isotope analysis rests upon the assumption that a local population's enamel values will reflect the isotopic values of the underlying geology in which they lived during childhood (Montgomery et al., 2005; Bentley, 2006). Organisms synthesise their tissues out of components from their local environment, from the food they eat and the water they drink, and those components stay in their skeletal and dental tissues once deceased (Montgomery et al., 2010). By sampling teeth, an individual who moved to an area with a different underlying geology after childhood will likely be identifiable as a non-local by his or her aberrant $^{87}Sr/^{86}Sr$ ratios when compared to the 'local' signatures of people who grew up in the area.

As strontium has an atomic radius similar to the atomic radius of calcium (215 pm and 197 pm, respectively) and belongs to the same periodic group of alkaline earth elements, strontium readily replaces calcium in minerals, including calcium carbonate in chalk, limestone, and marble in geological formations, and calcium in the body (Bentley, 2006; Burton, 2008). Erosion of the underlying geological formations is the major contributor to the $^{87}Sr/^{86}Sr$ ratios of individuals who lived in that area; the underlying geology contributes to the strontium isotope values of the soil and groundwater, and these values directly affect the isotopic composition of the local food web (Bentley, 2006). There is no known metabolic fractionation of $^{87}Sr/^{86}Sr$ in organisms; thus, examination of the $^{87}Sr/^{86}Sr$ ratios in human enamel can be linked to the $^{87}Sr/^{86}Sr$ ratios of where a person lived during childhood (Blum et al., 2000; Bentley, 2006).

Plants display strontium concentrations nearly identical to the soil in which they were grown (Evans et al., 2010). Vertebrates, however, preferentially excrete strontium from their system relative to calcium, lowering the amount of strontium in their body relative to their diet (Spencer et al., 1973). As approximately 99% of calcium and strontium in the body are routed to bone (Bhagavan, 2002, 873–900), meat eaters generally do not gain strontium from consuming their prey and so strontium concentrations and trophic level are negatively correlated. The process of decreasing strontium levels relative to calcium (Sr/Ca ratios) in nutrient pathways is known as biopurification and can be used to understand an organism's trophic level in ecological studies (Balter, 2004). The measurement of Sr/Ca ratios provides one of the first applications of bone chemistry in archaeology (Burton and Wright, 1995).

5.3.1 Determining the local $^{87}Sr/^{86}Sr$ signature

Establishing a local strontium baseline aids in interpreting human movement. One method involves empirically testing the exact strontium compositions of the underlying geology. The isotopic compositions of multiple geological formations in an area are mixed together, along with non-bedrock contributors such as loess or seaspray (saltwater spray from the waves crashing or high winds) (Bentley, 2006). The world's seawater has a homogeneous $^{87}Sr/^{86}Sr$ ratio at any given time, due to the circulation of the oceans (Evans et al., 2010). While the isotopic composition of seawater has changed over time from varying mixing effects from the Earth's continental crust and upper mantle, the $^{87}Sr/^{86}Sr$ ratio of seawater from the beginning of the Holocene (11,700 BP) through to today is 0.7092 (Elderfield, 1986; Veizer et al., 1997).

Geological formations can display a variety of strontium isotopes ratios, typically between 0.702 and 0.750 (Faure and Powell, 1972). Coralline limestone islands will display $^{87}Sr/^{86}Sr$ ratios similar to the seawater composition when they were formed, thus fluctuating around 0.707 and 0.709 within the last 500 million years (Veizer, 1989; McArthur, 1994). Volcanic materials formed from the uplifting of the earth's mantle will display a lower $^{87}Sr/^{86}Sr$ ratio between 0.702 to 0.704 (Bentley, 2006).

The underlying geology of the Tongan and Fijian archipelagos were outlined briefly in Chapter 2. While Tongatapu is an uplifted coral reef, the island of Viti Levu is composed of several geological formations (Figure 5.2). The strontium isotopic composition of the underlying geology of the Tongan, Fijian, and Samoan archipelagos are available for comparison for this study (Gill, 1984; Wright and White, 1987; Ewart et al., 1998; Bromfield and Renema, 2011) and show distinct isotopic compositions between the archipelagos (Figure 5.3). It should be noted that the Tongan $^{87}Sr/^{86}Sr$ ratios come

from the western island chain, the volcanic arc. The reef limestone islands in the eastern island arc have yet to be sampled for geological $^{87}Sr/^{86}Sr$ composition. Unlike Fiji and Tonga, Samoa lies east of the Andesite line, the eastern limits of the continental shelves of Australia and Asia (Thomas, 1963; Clark et al., 2014). While islands west of the Andesite line typically consist of basalts of continental origin, volcanic islands east of the Andesite site will be composed of Central Pacific basalt. These two basalt types contain different elemental compositions and possibly varying $^{87}Sr/^{86}Sr$ compositions (Thomas, 1963; Smith et al., 1977). The Fijian geological samples display two distinct clusters around 0.704 and 0.708, as Gill (1984) sampled from areas of the archipelago consisting of basalts and andesites while Bromfield and Renema (2011) sampled a limestone island from the Lau Group. As would be expected between the three islands, the Tongan and Fijian volcanic islands display a similar strontium composition while the Samoan islands east of the Andesite line display higher $^{87}Sr/^{86}Sr$ ratios.

Unfortunately, the use of geological data as proxies for understanding mobility may not yield accurate interpretations (Laffoon et al., 2012). It is often difficult to predict the mixing effects in any area with multiple underlying bedrocks with different $^{87}Sr/^{86}Sr$ ratios and varying weathering rates (Bentley, 2006). In a coastal area, the bioavailable strontium (the strontium isotopic composition of living organisms in an area) is influenced by sea spray (Whipkey et al., 2000) and potentially marine-based diets (Burton and Price, 1999; Bentley et al., 2007) in addition to the underlying bedrock. As such, an empirical assessment of biospheric strontium ratios may be a more accurate representation of what a local individual's $^{87}Sr/^{86}Sr$ ratio is likely to be (Evans et al., 2010). With this method, recording $^{87}Sr/^{86}Sr$ ratios in plants or animals with small home ranges is an effective way of establishing a local baseline, with no need to account for environmental mixing effects. Plants (Evans et al., 2010; Kinaston et al., 2014a), pigs (Bentley and Knipper, 2005), dogs (Kinaston et al., 2013c), and snails (Evans et al., 2009) have all been used for this purpose.

The use of animal strontium ratios as a baseline proxy can be problematic, as animals are not always as non-migratory as assumed. For example, using pigs as proxies in the Pacific has proven problematic as pigs, a symbol of social status, may have been moved long distances for trade (Shaw et al., 2009). Modern domesticates might consume non-local food and/or water imported onto the island and so will be inappropriate as a proxy. Snail shells have also proven difficult as shells may be more reflective of the strontium composition of rainwater rather than the underlying geology (Evans et al., 2009, 2010). Plants are more acceptable references as geographical proxies; they will reflect the mixed geological contributors, along with non-bedrock contributors, and

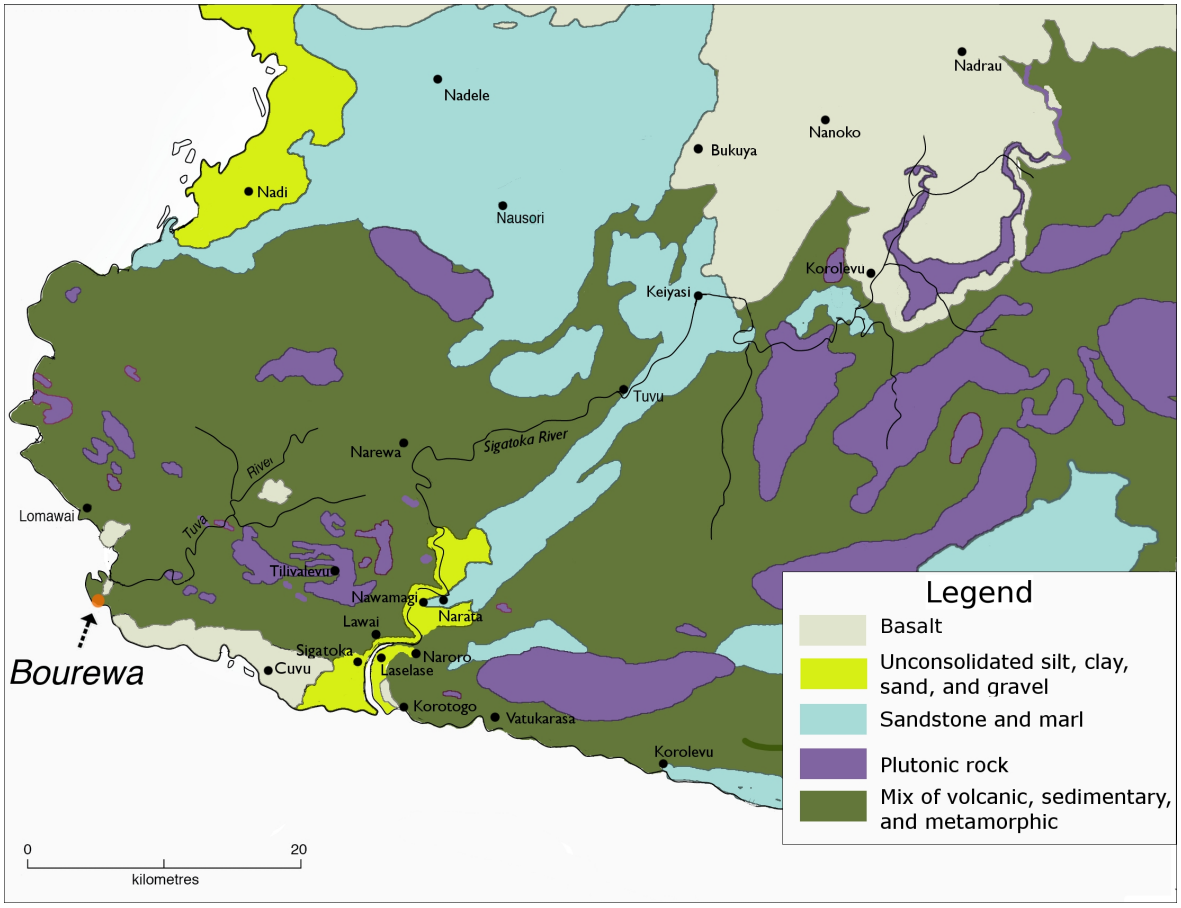


Figure 5.2. *Geological formations of southwestern Viti Levu. Modified to include Bourewa site (orange dot) and geological data from Rodda (1967). Image by author and is a derivative of original by CartoGIS, College of Asia and the Pacific, The Australian National University and licensed under CC BY-NC-SA 3.0 AU.*

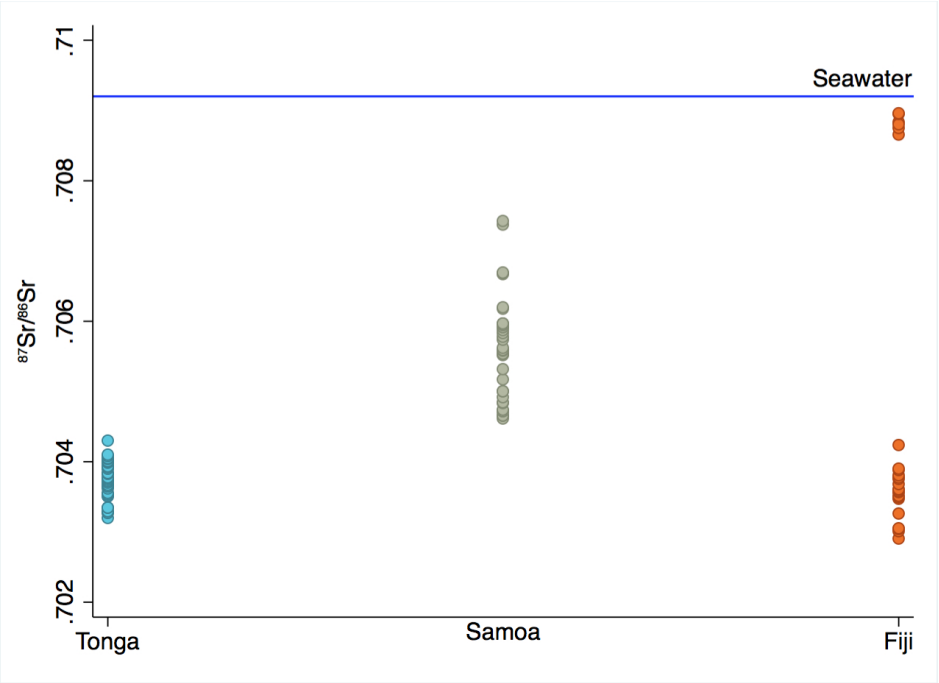


Figure 5.3. *$^{87}Sr/^{86}Sr$ isotopic compositions of Tonga, Samoa, and Fijia. Solid line is $^{87}Sr/^{86}Sr$ ratio of modern seawater (0.7092). Data from Gill, 1984; Wright and White, 1987; Ewart et al., 1998; Bromfield and Renema, 2011.*

there is no need to account for trophic level biopurification (Evans et al., 2010; Kinaston et al., 2014a).

There are currently no published data for bioavailable $^{87}Sr/^{86}Sr$ ratios in West Polynesia or nearby Fiji. In the absence of bioavailable strontium baseline data non-locals have been identified by falling outside two standard deviations of the average $^{87}Sr/^{86}Sr$ ratios of the burial assemblages values (Price et al., 2002; Bentley et al., 2003, 2004). While somewhat arbitrary, this approach has proven effective in Pacific studies to differentiate between locals and non-locals (i.e. Bentley et al., 2007; Shaw et al., 2009, 2010; Kinaston et al., 2014a).

5.3.2 Other isotope analyses of mobility

Lead ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$)

Like strontium, Pb^{2+} ions are preferentially substituted for calcium in hydroxyapatite and other bone minerals (MacDonald et al., 1951; Grandjean and Patterson, 1988). Lead isotope analysis is different from other types of isotope analyses of movement, in that three isotope ratios rather than two ($^{206/204}Pb$, $^{207/204}Pb$, and $^{208/204}Pb$) can be plotted to determine a person's origin. While a prehistoric Polynesian population

has no exposure to anthropogenic sources of lead (other than modern taphonomic exposure while buried), lead isotope analysis could prove useful if any individuals were exposed to significantly variable geological lead sources. Lead studies are usually conducted on populations that were exposed to anthropogenic lead sources (Carlson, 1996; Montgomery et al., 2010) though there are notable exceptions (Valentine et al., 2008; Turner et al., 2009). The geologic variance in lead isotope values in Polynesian islands (Thomas, 1963) means lead analysis could be used in conjunction with $^{87}Sr/^{86}Sr$ in order to further refine an individual's geographic affinity in Polynesia.

To date, the only lead isotope study focused on archaeological remains the author is aware of in the tropical Pacific is an unpublished thesis (Jarić, 2004). This study used samples provenanced from a Solomon Island rockshelter and from the 'Atele burial mounds. Jarić (2004) argues that lead isotope analysis are crucial to understanding movement in the Pacific. Jarić also argues that strontium isotope ratios between islands are too similar to pinpoint island groups; not only are the geological composition of the Pacific islands similar, but the $^{87}Sr/^{86}Sr$ ratio of seaspray has been shown to contribute to 50–80% of soil strontium ratios (Chadwick et al., 1999; Whipkey et al., 2000). Lead isotope values, Jarić asserts, were varied enough to determine a finer understanding of childhood location than strontium alone and seem to be less affected by sea spray aerosol. While lead isotope analysis may hold a promising future for migration studies in a bioarchaeological setting similar to strontium analysis, there is still more to be done before it is as well-established as $^{87}Sr/^{86}Sr$ analysis. As a relatively untested method, lead isotope analysis was not conducted in this study.

Oxygen ($\delta^{18}O$)

Originally used to examined paleoclimate in fossil specimens (Epstein et al., 1951, 1953; McCrea, 1950; Urey et al., 1951), oxygen isotope analysis is another common method of examining movement. Unfortunately, the averaging effect of oceanic rainfall creates homogeneous $\delta^{18}O$ values across the tropical Pacific (Bowen et al., 2013). While some larger islands in Near Oceania have shown some variation due to rivers (Bentley et al., 2007; Shaw et al., 2010, 2011), detecting variation in Remote Oceania is unlikely. Many smaller islands, Tongatapu included, have no moving water and used to be solely supplied with freshwater by precipitation (Orbell, 1983). Oxygen isotope analysis will not be used in this study to examine movement.

5.4 Isotopic studies of prehistoric human movement in the Pacific

Table 5.2 displays the annotated analyses of $^{87}Sr/^{86}Sr$ studies in the Pacific. Budd et al. (1996) were the first to discuss using strontium (and lead) isotopic compositions to understand population movement in the Pacific. While ethics and sampling strategies were discussed by Budd et al. (1996), results were not published in the book chapter and have yet to be published in any other form.

The first study to use isotope analyses to examine Pacific movement is a PhD thesis, mentioned above in the lead isotopes section (Jarić, 2004). Strontium and lead isotope analyses were used in this thesis, analysing 11 teeth scattered in a rockshelter in the North Solomon Islands and 16 individuals from the ‘Atele burial mounds. While the 16 individuals Jarić tests from To-At-1 and To-At-2 could have been invaluable comparative samples, Jarić does not provide the individual burial numbers for the Tongatapu individuals using the original notation. Instead, Jarić uses a personal identification system in her thesis without referring to the original system and so it is impossible to know which individuals were sampled. For this reason, all individuals from the ‘Atele burial mounds meeting the necessary criteria (outlined below) were sampled for this study.

Four of the 16 ‘Atele individuals Jarić (2004) analysed were found to have $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios outside two standard deviations of the population mean. Jarić concludes that these individuals must be non-locals, and the tightly clustered $^{87}Sr/^{86}Sr$ ratios prove that $^{87}Sr/^{86}Sr$ analysis is not a useful tool in Pacific studies. The two individuals displaying $^{87}Sr/^{86}Sr$ ratios two standard deviations outside the population mean, Jarić states, are not necessarily non-locals as their strontium ratios are still within the range of the underlying basalt and thus provides little information. However, as pointed out by Shaw (2009), Jarić (2004) does not present the $^{87}Sr/^{86}Sr$ ratios for the lead outliers so we cannot know what could have been inferred from the $^{87}Sr/^{86}Sr$ ratios. In addition, the lead outliers are still well within the lead ratios of the underlying geology of the Tongan archipelago, leaving lead analysis an unsatisfactory means of determining non-locals if we were to accept Jarić’s argument against strontium analysis.

Bentley et al. (2007) present the first published isotope analyses of human mobility in the prehistoric Pacific, examining 17 individuals from Teouma in Vanuatu, the oldest known Pacific cemetery, c. 3000–2700 BP (Petchey et al., 2014). Acknowledging that people with strongly marine-based diets throughout the Pacific may display high

Table 5.2. *Review of previous isotope studies exploring human movement in prehistoric Pacific individuals.*

Reference	Analysis type(s)	Site(s)	Location(s)	Time frame (BP)	Sample size	Comparisons analysed?	Note
Budd et al. (1996)	None						
Jarić (2004)	Sr, Pb	Sohono Rock Shelter; ‘Atele	North Solomons; Tongatapu	Middle Lapita Ceramic; 500–200	11 (Sohono) 16 (‘Atele)	None	
Bentley et al. (2007)	Sr, Ba/Sr, O	Teouma	Vanuatu	3000–2500	17	None	
Shaw et al. (2009)	Sr	Kamgot; Balbalankin	Bismarck Archipelago	3300–2700	1;4	Temporal, spatial	pigs also analysed
Shaw et al. (2010)	Sr, Ba/Sr, O	SAC; Lafafaesing	Bismarck Archipelago	2750–2500	15; 5	Spatial	pigs also analysed
Shaw et al. (2011)	Sr, Ba/Sr, O	Nebira	Papua New Guinea	720–300	27	Temporal, spatial, sex	pigs also analysed
Kinaston et al. (2013c)	Sr	Wairau Bar	New Zealand	c. 670	24	Temporal	bioavailable Sr using archaeologically-derived dogs
Kinaston et al. (2014a)	Sr	Uripiv	Vanuatu	2800–150	15	Temporal	bioavailable Sr using modern plants
Fenner et al. (2015)	Sr, O	J28 (Aponima); To-At-36	Tongatapu, Tonga	late prehistoric/ protohisotoric	17 (J28) 4 (To-At-36)	Spatial, status	bioavailable Sr,O using pig and rats

$^{87}Sr/^{86}Sr$ ratios, thus appearing to have lived in the same location, Bentley et al. (2007) also conduct Ba/Sr trace element analysis, $\delta^{18}O$ analysis, and $\delta^{13}C$ analysis on the apatite portion of tooth enamel. Bentley et al. (2007) found four outliers using strontium and oxygen isotope analysis. They claim that these potential non-locals are also outliers in terms of diet, more terrestrial on average when examining the $\delta^{13}C$ and Ba/Sr results. However, when looking at the plotted carbon and Ba/Sr values (p. 653, Figure 4), while the Ba/Sr values of the non-locals implies a more terrestrial-based diet, the $\delta^{13}C$ values of the outliers are actually *less* negative, which suggests a more marine diet in these individuals. These contradictory findings muddle Bentley et al.'s conclusion that the locality outliers are consuming a more terrestrial diet than the rest of the assemblage.

Shaw et al. (2009) examine movement using $^{87}Sr/^{86}Sr$ analysis on two Lapita-era sites (Balbalankin and Kamgot) in Papua New Guinea, one early Lapita (c. 3300–3000 BP) and one Middle Lapita (c. 3000–2700 BP). Both sites are from small islands off the coast of New Ireland, 23 km^2 and 87 km^2 in area. In addition to human tooth enamel, Shaw et al. (2009) conduct $^{87}Sr/^{86}Sr$ analysis on pig enamel to test if pigs could be used as a proxy of the local bioavailable strontium. Instead, pigs were the only outliers outside 2SD of the population mean, leading the researchers to conclude that oxygen and/or lead analyses should be incorporated into any future studies in the Pacific as a means of increasing the resolution of analysis.

Following Bentley et al. (2007), Shaw et al. (2010) utilise $^{87}Sr/^{86}Sr$, Ba/Sr, and $\delta^{18}O$ analyses in order to understand movement patterns in Late and Late/Post-Lapita sites in the Bismarck archipelago. From the Late Lapita site of SAC on Watom Island, Biskmarck Archipelago, Shaw et al. (2010) set out to address archaeological questions regarding Late Lapita and whether these communities were still maintaining long-distance interaction with founding communities or whether these interactions waned as settlements became more established. Human teeth from the Late/Post Lapita site of Lifafaesing (also Bismarck Archipelago) were included for comparison. None of the human teeth ($n = 15$) from Watom were outside 2SD of the population mean for $^{87}Sr/^{86}Sr$ or Ba/Sr ratios, though one Watom Island female (burial 9) displays an oxygen isotopic composition outside the population average. The individuals from the Late/Post-Lapita site of Lifafaesing ($n = 5$) display much higher $^{87}Sr/^{86}Sr$ ratios than the Watom Island individuals, nearer the ratio of seawater. The differences between the underlying geology of these two islands (Lifafaesing is from a limestone island while Watom Island is volcanic in origin) was predicted by the researchers as the cause for the differences in $^{87}Sr/^{86}Sr$ ratios. Watom Island pigs displayed much more varied isotope and trace element values than humans. Shaw et al. (2010) identify this as evidence of

long-distance trade and interaction between communities during the Late Lapita period, and, like Shaw et al. (2009), stress that pigs should not be used as bioavailable baseline proxies in the Pacific because of the possibility that they may have been imported from other locales.

Humans from the site of Nebira, Papua New Guinea (c. 720–300 BP), analysed for dietary patterns by Kinaston et al. (2013a), have also been examined for mobility using $^{87}Sr/^{86}Sr$ Ba/Sr, and $\delta^{18}O$ analyses (Shaw et al., 2011). In the assemblage of 27 individuals, Shaw et al. (2011) find five individuals with much higher $^{87}Sr/^{86}Sr$ ratios (outside 2SD). There appear to be no sex-related trends in non-locals, with outliers consisting of two females, two males, and one subadult. None of the five outliers were outliers for Ba/Sr or $\delta^{18}O$. Unlike the previous work by Shaw et al. (2009), Shaw et al. (2011) conclude that oxygen isotope analysis might not be useful in the Pacific, at least not without more baseline and comparative archaeological data.

A highly mobile lifestyle was hypothesized for the early Maori of Wairau Bar in New Zealand (Kinaston et al., 2013c). The Wairau Bar assemblage, dated c. 670 BP, contains individuals from three burial groups with the first burial group (Group 1) possibly part of a founding colony of New Zealand. Burial Groups 2 and 3 appear to be later. The six individuals from Group 1 all displayed lower $^{87}Sr/^{86}Sr$ ratios than the local mean which was determined from prehistoric Wairau Bar dog $^{87}Sr/^{86}Sr$ ratios, with a mean $^{87}Sr/^{86}Sr$ ratio of 0.7075 compared to the dogs' 0.7089 average ratio. However, highly varied diets in individuals from Groups 2 and 3, as interpreted through paleodietary isotope analyses ($\delta^{13}C$ and $\delta^{15}N$), suggests that these people lived and ate in a variety of different locations before being buried at Wairau Bar. Kinaston et al. (2013c) demonstrate the importance of combining the analyses of human diet and mobility to more thoroughly understand the cultural processes that may be affecting both of these aspects of life (a model which is applied in the discussion and conclusion of this thesis).

Kinaston et al. (2014a) examine movement in prehistoric individuals from the small island (<1 km^2) of Uripiv in Vanuatu. The island was used throughout several eras of occupation: the middle/late Lapita period (c. 2800–2500 BP, roughly 200 years after the use of the Teouma cemetery on Efate, Vanuatu), post Lapita (2500–2000 BP), and late prehistoric/early historic (300–150 BP). This study is the first in the Pacific to use modern plant samples to determine the bioavailable $^{87}Sr/^{86}Sr$ signatures of Uripiv and the nearby islands of Malakula and Efate. Using short-, medium- and deep-rooted plants following the suggestions of Evans et al. (2010), only individuals from the Post-Lapita period displayed $^{87}Sr/^{86}Sr$ ratios of non-locals. Kinaston et al.

(2014a) interpret this pattern as increased permeance between settlements on Vanuatu after the initial colonisation phases during the Lapita period. Though the post-Lapita individuals comprised the largest temporal subsample ($n = 11$), small sample sizes preclude interpretations regarding sex or differences between mid- and late-Lapita periods.

Sites from Tongatapu that are contemporaneous with the 'Atele burial mounds provide a welcome means of comparison (Fenner et al., 2015). J28 (known as Aponima) is a *langi* located in the Lapaha district, the centre of the Tongan chiefdom where the Tu'i Tonga ruled in late prehistory (Clark et al., 2008). Fenner et al. (2015) also analysed a few individuals from To-At-36, a possible *fa'itoka* of similar construction to To-At-1 that is located near the 'Atele burial mounds. $^{87}Sr/^{86}Sr$ analysis was conducted on 17 individuals from J28 and four individuals from To-At-36. $\delta^{18}O$ analysis was also conducted on four individuals from each site. Six rat teeth and one pig tooth from archaeological sites all over Tongatapu were analysed for $^{87}Sr/^{86}Sr$ ratios to provide a faunal baseline.

Two individuals from J28 displayed $^{87}Sr/^{86}Sr$ ratios 2SD from the faunal average. One ratio (from burial 6) was discounted on the grounds of possible contamination, but Burial 24 displayed much lower values and appeared contaminant-free. Fenner et al. (2015) posit that this individual may been an immigrant to Tongatapu. $\delta^{18}O$ analysis showed no potential outliers, but Burial 24 was not included in the analysis and sample size was small for oxygen analysis with only four individuals analysed. Fenner et al. (2015) compare their results to those of Jarić (2004), unfortunately not realizing the potential problems with Jarić's data; Fenner et al. do not review any of the mobility research by Shaw and colleagues (2009) who were critical of Jarić's findings, or any other Pacific island paleomobility research for that matter. In trusting Jarić's anomalous $^{87}Sr/^{86}Sr$ data, Fenner et al. (2015) conclude that the individuals from the 'Atele burial mounds might be a population entirely composed of immigrants.

Though the faunal baseline from Fenner et al. (2015) could be used in this thesis as a proxy for the Tongatapu bioavailable $^{87}Sr/^{86}Sr$ ratio, the pig tooth cannot be included due to the issues with using pigs as proxies as pointed out by Shaw et al. (2009). The rats may also have been non-local animals, unintended (or intended) passengers on ships (Matisoo-Smith and Robins, 2004). As pointed out by the Fenner et al. (2015), the rats used in their study might also be modern rats that have invaded the archaeological record. Due to these potential problems, these faunal remains will not be used as proxies in this present study.

5.5 Methodology

5.5.1 Choosing and isolating the tooth enamel

In the 'Atele assemblage, the same teeth used for dietary isotope analyses of dentine were sampled for tooth enamel for $^{87}Sr/^{86}Sr$ analysis. All of these teeth were premolars (first or second) or molars (first or second), with a preference for second molars. The teeth could be mandibular or maxillary. Premolars and second molars undergo initial crown calcification around 2–3 years of age and complete crown formation around 5–8 years of age (van Beek, 1983). Other than third molars, these teeth are the last to form and the least likely to contain any maternal signals from *in utero* or breastfeeding (Hillson, 1996). First molars, sampled in two individuals when no premolars or second molars were available, are less preferable as they undergo initial calcification perinatally and complete calcification around 2½–3 years of age and are more likely to contain a maternal signal (van Beek, 1983; Hillson, 1996). The roots and crowns were separated at the University of Otago Anthropology Laboratory (Dunedin, New Zealand) using a Dremel® 300 Series rotary tool with a 545 Diamond Wheel after photographing and moulding the crown of the teeth (as described in Chapter 3) for archival purposes.

The crowns were then placed in sealed, labelled containers and shipped to the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, where all steps of the strontium preparation and analysis were conducted following the protocol created at the institute. The crown of each tooth was sandblasted with a BEGO Duostar Plus with Korox® 50 aluminium oxide to remove the outer layer that is most likely to contain diagenetic strontium. Then, a small piece of enamel was cut from the tooth using a dental rotary tool. Any dentine attached to the sample was ablated with a diamond-tipped engraving cutter so that only enamel was analysed. Between teeth, the saw and cutter were sonicated for five minutes in acetone, and the cutting area, dental drill, and tweezers were wiped down with ethanol (70% v/v) to prevent cross-contamination.

For the Bourewa assemblage, teeth were chosen and sampled by another researcher previous to this study. Some of the teeth chosen for strontium analysis were canines or third molars and thus were inappropriate for understanding childhood diet. As such, some of the teeth sampled for strontium analysis were not used for paleodietary analysis, and instead premolars and first/second molars were sampled and sent to Iso-Analytical, Ltd. (as described in the paleodietary isotopes methodology section). Since strontium analysis had already been conducted on the Bourewa individuals previous to

the beginning of this thesis, it was not duplicated.

5.5.2 $^{87}Sr/^{86}Sr$ analysis

The same protocols were conducted for both the Bourewa and 'Atele samples and are described below. The ideal dry weight of the enamel was 5–10 mg. After weighing, the samples were placed in a 2 mL microcentrifuge tube along with 1 mL of acetone. The samples were then sonicated for 10 minutes. Next, the samples were rinsed three times with ultrapure Milli-Q® water and placed in a drying rack at 45 °C overnight.

The acid digestion step, or dissolution step, occurred the next day. The samples were transported to a clean room (ISO14644-1 standard 2) and placed in 5 mL Teflon® beakers. Blanks were included for the remainder of the chemical preparation, as was 10 mg of the working reference standard SRM 1486 Bone Meal (NIST, Gaithersburg, MD, USA). In each beaker, 2 mL 65% HNO_3 was pipetted in order to dissolve the enamel. To facilitate dissolution, the lidded beakers were placed on a 120 °C hotplate for two hours. The lids were then removed to allow evaporation, and placed back on the 120 °C hotplate for ten hours.

Evaporation of the solution should leave only a small, white pellet in the beaker. Added to the beaker was 1 mL 3M HNO_3 (important for the next stage), and the lidded beakers were placed on the 120 °C hotplate for another hour. The solution was finally pipetted into a 2 mL microcentrifuge tube, ending the dissolution step.

The next stage is known as the column step. The purpose of this stage is the extraction of pure strontium from the sample following the method outlined by Deniel and Pin (2001). First, Eichrom® 2 mL empty columns with frits (porous glass filters) were cleaned by soaking overnight in 6M HCl. These columns were then rinsed twice in ultrapure water. Cleaned extraction chromatographic resin (Eichrom®) suspended in ultrapure water was added to the column. The water passes through the frit, but the resin remains. A specific volume of resin was not added; rather, enough resin was added to create a resin filter 0.5 cm deep once the water had filtered through.

The resin was cleaned with ultrapure water twice. Next, the resin was conditioned with 3 mL 3M HNO_3 to ensure no H_2O remained in the column. Removing any water from the column is important as strontium will preferentially bind to H_2O rather than the resin, rinsing the strontium through the column. After conditioning, the sample solution was pipetted into the column. The resin caught strontium as it passes through, and microcentrifuge tubes underneath the columns caught the solution as it filtered through the resin and frit. The solution was reloaded three more times to allow optimum strontium extraction. The column was then washed thrice with 400

µL HNO_3 to rinse any solution from the column walls and to move unwanted solutes through the resin. The column was then placed over a labelled Teflon® beaker. Next, elution occurred by running 1.5 mL Milli-Q® H_2O through the column, rinsing the now-purified strontium into the labelled beaker. Then, the elute was evaporated by placing the beaker, uncovered, on a 120 °C hotplate for eight hours. After evaporation, only a small, yellowish speck should remain in the beaker; this is the purified strontium. The strontium was resolved with 2M 3% HNO_3 on the 120 °C hotplate for one hour. After pipetting the solution into labeled microcentrifuge tubes, the samples were ready for mass spectrometer analysis.

5.5.3 Analytical procedure by mass spectrometer

The samples, SRM 1486, and blanks were analysed using a Thermo Fisher Neptune™ plasma ionization multicollector mass spectrometer (PIMMS). Repeated measurement of international standard SRM 987 (NIST) was used to ensure accuracy of data, and samples were adjusted using the published value of SRM 987, 0.710240 (Johnson et al., 1990; Terakado et al., 1988). Isotope dilution analysis was used to obtain Sr concentration (reported in ppm). A concentration calibration line was created by running the internal standards in each batch at three concentrations, 100 ppb, 400 ppb, and 700 ppb.

The presence of ^{87}Rb in samples can cause signal interference, as a mass collector calibrated for 87 mass cannot differentiate between ^{87}Rb and ^{87}Sr. To account for rubidium interference, ^{85}Rb was also measured. By examining the signal of ^{85}Rb, the percentage of ^{87}Rb was estimated using natural abundance percentages of isotopes, and the ^{87}Rb interference was then corrected. The presence of ^{86}Kr causes the same problems with ^{86}Sr, and was corrected by measuring ^{83}Kr and ^{82}Kr.

When measuring samples using a PIMMS, the samples are ionised using plasma. The ionisation process in the mass spectrometer varies linearly with mass, creating its own mass-dependent isotopic fractionation. This mass bias needs to be separated from the natural mass-dependent isotopic fractionation being measured in the samples. By measuring for ^{88}Sr and using the natural $^{88}Sr/^{86}Sr$ ratio of 8.375209, instrumental mass bias was normalised.

5.5.4 Statistical analysis

Shapiro-Wilk tests for normal distribution were conducted on the $^{87}Sr/^{86}Sr$ ratios for each burial site. In order to understand differences between sexes, adults/subadults,

Table 5.3. *$^{87}Sr/^{86}Sr$ results by site, sex, and burial mound.*

	$\bar{x}$	SD	*n*
Bourewa	0.7085	0.0005	17
‘Atele	0.7088	0.0001	41
To-At-1	0.7088	0.0001	19
To-At-2	0.7089	0.0001	22
Bourewa			
Female	0.7082	0.0008	6
Male	0.7081	0.0003	3
‘Atele			
Female	0.7088	0.0001	21
Male	0.7088	0.0001	9
To-At-1			
Female	0.7088	0.0002	8
Male	0.7088	0.0001	5
To-At-2			
Female	0.7088	0.0001	13
Male	0.7088	0.0002	4

burial sites, and burial mounds, Student's t-tests were conducted if the data were normally distributed. Differences between two subgroups in a non-normal distribution were tested using Wilcoxon rank-sum tests (a nonparametric test that does not assume normality). If the data were normally distributed and homoscedastic (as tested using a Levene's test), ANOVA could be used to examine multiple predictor variables or variables with more than two outcomes. If the data were heterogeneous for variance, Kruskal-Wallis tests were to be used instead.

5.6 Results

The $^{87}Sr/^{86}Sr$ results (mean, standard deviation, and n) for both burial sites, with sex and burial mound, are described on Table 5.3. In Bourewa, the $^{87}Sr/^{86}Sr$ ratios range between 0.7079 to 0.7090, with a mean of 0.7087±0.0003. The $^{87}Sr/^{86}Sr$ ratios in the ‘Atele assemblage ranged between 0.7085 and 0.7091, with a mean of 0.7088±0.0001. The $^{87}Sr/^{86}Sr$ ratio for both sites are displayed on Figure 5.4. $^{87}Sr/^{86}Sr$ ratios were normally distributed for ‘Atele, but not for Bourewa. In comparing ‘Atele ($n = 41$) and Bourewa ($n = 17$), a Wilcoxon rank-sum test indicated no differences between burial sites regarding $^{87}Sr/^{86}Sr$, W(57) = 1711, z = -1.75, $p = 0.080$. Examining Table 5.3 and Figure 5.4, there is a larger standard deviation and range of variables in the

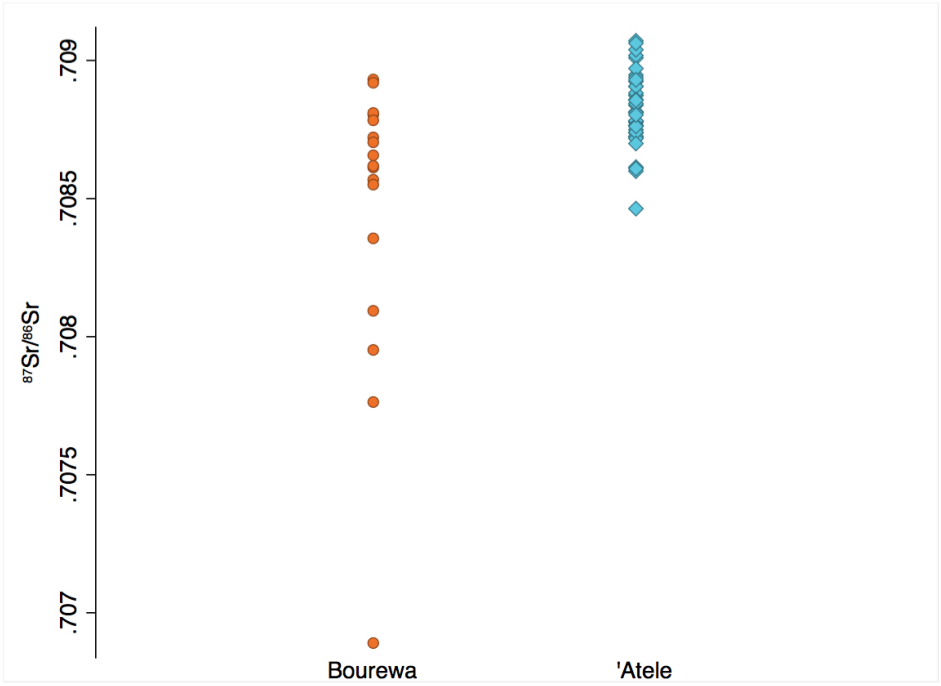


Figure 5.4. *$^{87}Sr/^{86}Sr$ ratios for the individuals from Bourewa and 'Atele.*

Table 5.4. *$^{87}Sr/^{86}Sr$ results in the Bourewa asemblage by age.*

	$\bar{x}$	SD	*n*
Subadult	0.7080	—	1
Young adults	0.7088	0.0002	2
Middle adults	0.7045	0.0009	2
Old adults	0.7085	0.0002	2
Adults, all	0.7085	0.0005	16

Bourewa assemblage than the 'Atele assemblage, with Bourewa displaying a standard deviation of 0.0003 compared to 0.0001 for 'Atele.

5.6.1 Bourewa $^{87}Sr/^{86}Sr$

There was one individual outside two standard deviations from the average in the Bourewa population, Burial 23 (Figure 5.5). The only subadult in the Bourewa assemblage, Burial 15, has the third-lowest $^{87}Sr/^{86}Sr$ values but is within two standard deviations of the population mean. Although females ($n = 6$) display a wider standard deviation than males ($n = 3$), 0.0008 SD compared to 0.0003 SD, there were no statistically significant differences between the sexes in the Bourewa assemblage, $\chi(2) = 0.07$, $p = 0.796$. There were only two individuals in each of the three adult age cohort

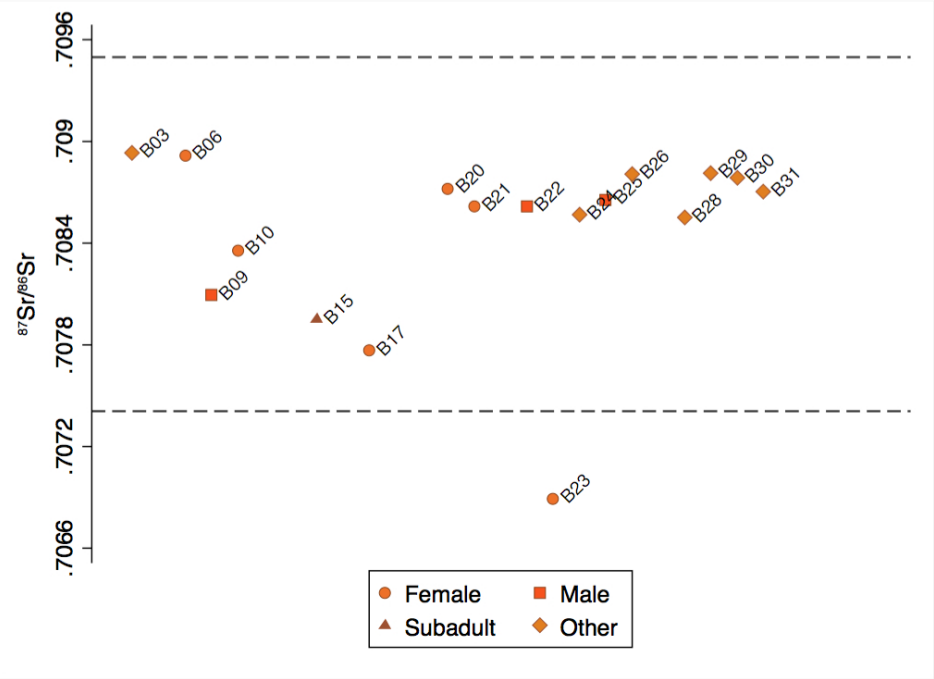


Figure 5.5. *$^{87}Sr/^{86}Sr$ ratios for Bourewa. "Other" category included adults of indeterminate sex and individuals of indeterminate age. Two standard deviations from mean delineated as dashed line.*

in the Bourewa assemblage with tooth enamel analysed for $^{87}Sr/^{86}Sr$ (Table 5.4), and so the Kruskal-Wallis test must be interpreted with caution, $\chi(2) = 3.71$, $p = 0.156$.

5.6.2 'Atele $^{87}Sr/^{86}Sr$

As with Bourewa, there was one individual outside two standard deviations from the average in the 'Atele assemblage, To-At-1/09 (Figure 5.6). There were no significant differences in $^{87}Sr/^{86}Sr$ ratios when conducting an ANOVA using both sex and burial mound as predictor variables, ($F(2,29) = 0.58$, $p = 0.567$). The variables, sex and burial mound, were also non-significant on their own ($F = 0.56$, $p = 0.459$ and $F = 0.37$, $p = 0.546$, respectively).

With no old adults in To-At-1 tested for $^{87}Sr/^{86}Sr$ values (Table 5.5), an ANOVA separating adult age categories by burial mounds was not appropriate. There was not a significant main effect of adult age on $^{87}Sr/^{86}Sr$ values for the three age categories when the burial mounds were combined ($F(2,21) = 0.67$, $p = 0.521$). There were no significant differences in $^{87}Sr/^{86}Sr$ values when conducting an ANOVA using both burial mound and age (adult versus subadult) as predictor variables, ($F(2,40) = 1.66$, $p = 0.204$). The variables, burial mound and age, were also non-significant on their own (F

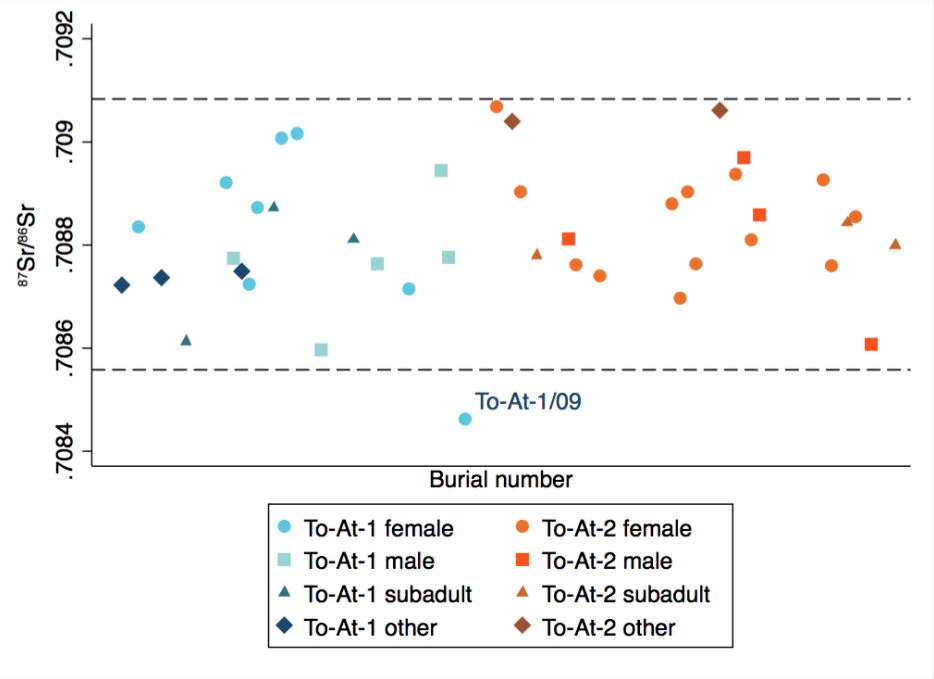


Figure 5.6. *$^{87}Sr/^{86}Sr$ ratios for the 'Atele burial mounds. "Other" category included adults of indeterminate sex and individuals of indeterminate age. Two standard deviations from mean delineated as dashed line.*

Table 5.5. *$^{87}Sr/^{86}Sr$ results in the 'Atele assemblage by age.*

	$\bar{x}$	SD	*n*
To-At-1			
Subadults	0.7088	0.0001	3
Young adults	0.7088	0.0002	7
Middle adults	0.7088	0.0002	3
Old adults	—	—	0
Adults, all	0.7088	0.0002	10
To-At-2			
Subadults	0.7088	0.0000	3
Young adults	0.7089	0.0001	6
Middle adults	0.7088	0.0001	4
Old adults	0.7089	0.0002	4
Adults, all	0.7088	0.0001	14
'Atele, overall			
Subadults	0.7088	0.0001	6
Young adults	0.7089	0.0002	13
Middle adults	0.7088	0.0001	7
Old adults	0.7089	0.0002	4
Adults, all	0.7088	0.0001	35

Table 5.6. *Summary of questions addressed and findings from migration analysis.*

Question	Significant?	Notes	Hypothesis addressed
Differences between the sexes in Bourewa?	No	Only outlier is a female.	H_1
Differences between adult age categories different in Bourewa?	No		
Differences between burial mounds in 'Atele?	No		
Differences between the sexes at 'Atele?	No	Only outlier is a female.	H_1
Differences between adult age categories in 'Atele?	No		
Differences between adults compared to subadults in 'Atele?	No		
Differences between the two sites?	No		H_2

= 2.80, $p = 0.103$ and F = 0.44, $p = 0.510$, respectively).

5.7 Discussion

This chapter addressed the thesis aim of understanding individual movement in the sites of Bourewa and 'Atele in order to consider cultural aspects affecting migration (such as marriage, political control of individuals' mobility, and inter-island trade). $^{87}Sr/^{86}Sr$ isotope analysis was conducted to detect movement in individuals and compare movement between subpopulations such as the sexes, 'Atele mounds, and sites. The main findings and hypotheses relevant to this part of the thesis are outlined on Table 5.6.

5.7.1 Human movement in Bourewa

Most of the individuals interred in Bourewa display $^{87}Sr/^{86}Sr$ ratios similar to seawater, not necessarily a surprise given the coastal location of the site. The single $^{87}Sr/^{86}Sr$ outlier within the Bourewa assemblage, Burial 23, is a middle-aged female. Burial 23 displayed no skeletal evidence of disease or trauma, beyond a periosteal reaction on the left tibia (Hallie Buckley 2014, personal communication). The $^{87}Sr/^{86}Sr$ value of Burial 23 is the lowest in the assemblage. Given the comparatively high $^{87}Sr/^{86}Sr$ value of seawater and low $^{87}Sr/^{86}Sr$ values of the underlying geology on Fiji, Burial 23 may have spent her childhood inland rather than on the coast, consuming foods and drinking water free of seawater.

As mentioned in Chapter 2, the Bourewa assemblage is dated to a phase of Fijian

prehistory where there is evidence of increased competition to control access to natural resources (Parry, 1987; Field, 2004, 2005). The presence of only one non-local in the cemetery makes sense within this context, as the increased territoriality would have made travel and long-term interactions across Viti Levu more difficult. As a female, Burial 23's outlier $^{87}Sr/^{86}Sr$ values could support the Fijian custom of patrilocality (Becker, 1995; Jones, 2009). Other females may have moved to (and been buried on) the Rove Peninsula as a result of marriage but, as mentioned in the previous section, if they originated from coastal communities they could have $^{87}Sr/^{86}Sr$ values similar to the Bourewa mean. Although the only non-local outside 2SD was female, there were no significant differences between males and females. This supports the first hypothesis of the thesis (that a greater proportion of non-locals will be females), though with only one observable non-local it may be difficult to use this data to determine with certainty the that Bourewa individuals practised a patrilocal marriage system.

There were no differences between adult age categories in Bourewa. This is expected, as the $^{87}Sr/^{86}Sr$ values from tooth enamel record where a person lived during their childhood, and it was not expected that childhood mobility would have affected age at death. No hypotheses were forwarded concerning age-at-death and childhood mobility, but inferential statistics still needed to be conducted between age groups to ensure there were no unexpected trends.

5.7.2 Human movement in 'Atele

The 'Atele outlier (To-At-1/09) is female, aged as a young adult (Buckley, 2001). To-At-1/09 presents no pathologies beyond some degenerative joint disease, mostly in the lower back (Hallie Buckley 2014, personal communication) and a few carious lesions in her teeth as observed in the oral indicators of diet portion of this thesis. Thus, her cause of death is unknown. Like the other individuals in the 'Atele burial mounds, she was buried with no grave goods that survived in the mound. There were the remains of an infant (burial To-At-1/09b) buried with or near To-At-1/09 displaying pathological lesions (Hallie Buckley 2014, personal communication). It is unclear whether the infant was buried with her or buried later so there is little to interpret regarding the relationship between To-At-1/09 and To-At-1/09b.

While the island of Viti Levu has a multitude of rivers, streams and lakes as sources of freshwater, as well as groundwater, the inhabitants of the island of Tongatapu would have only had access to ocean-derived rainwater (Orbell, 1983; Völkel, 2010). As aerosolised sea spray raises $^{87}Sr/^{86}Sr$ values compared to most Pacific Island geological isotopic compositions, it is likely To-At-1/09, with a lower $^{87}Sr/^{86}Sr$ value than any

other individuals from the ‘Atele assemblage, spent her childhood relatively inland. It is entirely possible that To-At-1/09 came from a larger landmass than Tongatapu that enabled individuals to live further inland. Though it cannot be said with certainty that To-At-1/09 came from Fiji, it appears the most likely scenario. Fiji is the closest area with large islands: the closest archipelagos that are of comparable size are New Caledonia and the North Island of New Zealand, both of which are roughly 1,900 km from Tongatapu compared to the 800 km separating Tongatapu and two large islands of Fiji. Trade and exchange between Tonga and Fiji is recorded in historic times (Mariner and Martin, 1827) and assumed to have occurred throughout occupation (Davidson, 1977). In addition, ethnohistoric sources speak of Tongan men valuing Fijian wives (Kaeppler, 1978).

If To-At-1 is a *tanu‘anga* as would be classified by McKern (1929), then To-At-1/09 would have been of the commoner class. The exchange network regulated by the Tongan maritime empire is classically defined as principally affecting the elites in Tongan society and not involving large numbers of the lower classes (Kirch and Green, 2001). If we follow this concept, it would be expected that the non-locals in Chiefdom Period Tongatapu would be most likely of higher status. However, it would be too simplistic to assume that non-chiefly Tongans were not involved in inter-island exchange at all. The involvement of lower-class retainers in the movement of goods is recorded in the ethnohistoric record (Mariner and Martin, 1827). Another possibility is that To-At-1 is not a *tanu‘anga* but *fa‘itoka* or burial mound for the chiefly class. Although there has been debate regarding the exact nature of the ‘Atele mounds (Davidson, 1969), this debate has always centred on whether or not To-At-2 is a *fa‘itoka* or not, and the method of construction of To-At-1 strongly suggests it was where those of lower status were interred.

With To-At-1/09 the only non-local as determined using $^{87}Sr/^{86}Sr$ analysis, the first hypothesis fails to be rejected regarding the ‘Atele assemblage, though the same precautions raised with the Bourewa assemblage are applicable here. As with Bourewa, there were no differences between adult age categories. Adults and subadults could also be compared in the ‘Atele assemblage and were found to be similar regarding $^{87}Sr/^{86}Sr$ values.

Comparison to movement of material goods in Tonga

Recent chemical analysis of stone tools from West Polynesia demonstrated direct evidence of the movement of prestige goods to Tongatapu from Fiji, Samoa, and as far away as the Society Islands (2500 km east of Tongatapu) (Clark et al., 2014). Clark

et al. (2014) posit that the Tongan maritime empire encouraged the establishment of specialised crafting sites that "formed important centres for the transmission of information, people, and material in prehistoric Oceania" (p. 10491), thus implying the movement of people as inferred through the movement of goods. Examining the movement of people through strontium isotope analysis of human tooth enamel provided an opportunity to directly test inter-island contact and mobility in people contemporaneous with the Chiefdom Period lithics analysed by Clark and colleagues.

Clark and colleagues' (2014) research demonstrates that Tonga was a centre of prestige goods movement during the Chiefdom Period, so why do we see so little individual movement as demonstrated by $^{87}Sr/^{86}Sr$ analysis of tooth enamel? The political environment of Viti Levu during this time period, one of increased inter-community tension, was not mirrored in the Tongan archipelago, and so the scenario that held credence in the Bourewa assemblage does not fit as well in the Tongan context. From the current analyses, it would appear that while non-local prestige goods were transported to the centre of the Tongan empire, either the people returning to Tongatapu with these goods were born on Tongatapu, or they were non-locals from other archipelagos who were not staying on Tongatapu. This second possibility must be made with the caveat that non-locals may have been buried in other ways and not accorded a 'Tongan-style' burial.

Both scenarios may have occurred. Junior ranking chiefs and second sons were leaving Tongatapu and going to outlying islands of the empire, securing their power with intermarriage in the local ruling families and ensuring the prestige goods returned to Tongatapu (Aswani and Graves, 1998). While these ruling chiefs would not necessarily return to Tongatapu, there are ethnohistoric accounts of their retainers, possibly from Tongatapu themselves, returning to the sacred centre of the empire with prestige goods (Mariner and Martin, 1827). Non-Tongans, representatives from other islands bringing tribute and trade goods to the Tu'i Tonga and his family, would also travel to Tongatapu. However, ethnohistoric accounts record the power of the maritime empire and the sacredness of the island was such that these non-Tongans were not allowed to travel to Tongatapu without escort and not permitted to stay (Mariner and Martin, 1827).

As an additional note, having only a single foreigner in the mound does not necessarily contrast with Clark et al.'s 2014 conclusions of frequent contact and exchange. To-At-1/09 is 2.5% of the mortuary sample sampled for $^{87}Sr/^{86}Sr$ (1 of 41 individuals). If the 'Atele burial mounds are demographically representative of the Tongatapu population during the Chiefdom period, and assuming 20,000 individuals lived on Tongatapu

during the chiefdom period (a modest number with the upper bounds of estimated pre-Contact population in the Tongan archipelago at 40,000 with most of the population on Tongatapu [Kirch, 1984a]), then the foreign population could be as high as 500 individuals. There are serious complications when trying to reconstruct the living profile of a community: a mortuary population can never be fully representative of the living population from whence it is derived (Wood et al., 1992; Waldron, 1994). In addition to the problems plaguing any cemetery sample, the ‘Atele burial mounds are particularly affected by sampling issues: as the main research focus of the original excavations was to determine the method of mound construction and types of mound use, neither mound was fully excavated (Davidson, 1969). Instead, trenches to the centres and on edges of the mounds were dug, and only 2.9% and 13.6% of the possible areas were excavated for the To-At-1 and To-At-2, respectively.

If there were a sizeable number of immigrants from Samoa or Fiji living on Tonga, they might have lived together. A modern example is the ‘Kapinga village on Pohnpei Island in the Federated States of Micronesia, where Polynesian migrants from Kapingamarangi Island form an insular community (Lieber, 1999). In this scenario, an as-of-yet unfound burial mound would inter the majority of non-locals on Tongatapu. Unfortunately, this is an untestable hypothesis using the current study's data but is an intriguing possibility to consider nonetheless.

5.7.3 Inter-site comparisons

The ‘Atele assemblage displays higher $^{87}Sr/^{86}Sr$ ratios than Bourewa, although not to a significant degree. Hypothesis 2 of the thesis, that Fijians will display a greater range of strontium ratios, fails to be rejected as the Bourewa assemblage displays a higher standard deviation and range of $^{87}Sr/^{86}Sr$ ratios compared to ‘Atele. The larger size of Viti Levu compared to Tongatapu (10,388 km^2 and 248 km^2, respectively) and greater geological complexity contribute a wider range of $^{87}Sr/^{86}Sr$ ratios.

When comparing the two sites included in this study and past $^{87}Sr/^{86}Sr$ studies (Figure 5.7), a few things become clear. First, the $^{87}Sr/^{86}Sr$ ratios produced by Jarić (2004) are much lower than any other values produced in prehistoric Pacific individuals. Other individuals from Papua New Guinea such as those from Shaw et al. (2009), and the individuals from ‘Atele analysed in this study, presumably some of the same individuals analysed by Jarić (2004), display much higher strontium ratios without any overlap in range. Without burial numbers in Jaríc's thesis is it impossible to know for certain that we analysed the same burials, but the fact that I sampled every ‘Atele individual that met my sampling criteria makes it unlikely that we did not sample

many or most of the same individuals. Though a review of Jarić's methodology does not reveal any outstanding errors, it can be safely assumed that, with $^{87}Sr/^{86}Sr$ ratios far different from any other values found in the Pacific, there may have been issues with Jaríc's methodology.

When comparing means (Table 5.7), only the individuals from the New Bismarck island of Lifaesang are higher than Bourewa and Tongatapu (Tongatapu individuals from this thesis and from Fenner et al. [2014]). Individuals from Uripiv, an uplifted coral limestone island <1 km^2 displayed slightly lower mean $^{87}Sr/^{86}Sr$ ratios than both Bourewa and 'Atele. This is surprising, as it would be expected that the small size and coralline geology would produce a bioavailable strontium reservoir similar to modern seawater. Though the coral limestone of Uripiv is Pleistocene (2.5 million to 11,700 years ago) in origin (Kinaston et al., 2014a), the $^{87}Sr/^{86}Sr$ ratios of seawater in this era were similar to modern seawater and higher in value than the individuals of Uripiv (Hodell et al., 1990).

Seawater may be affecting the $^{87}Sr/^{86}Sr$ ratios of Bourewa, 'Atele, the other Tongatapu sites, and Lifaesang more than other sites. The standard deviation of these three sites are among the lowest, ignoring Jarić's data. Relatively greater diversity in the underlying geology and/or increased mobility of individuals within the other assemblages are possibilities, as are the homogenising effects of seawater and marine-centred diets creating less variation within this study. As discussed previously, this issue does not contradict the concept that outliers with lower strontium ratios may have moved from more inland areas of large islands, but immigrants from other coastal areas and small coralline islands cannot be observed. The lower standard deviation may be because of fewer non-locals or due to a tighter range of $^{87}Sr/^{86}Sr$ ratios in the local bioavailable reservoir.

5.7.4 The difficulty of assigning childhood residency: a Samoan example

The relatively small islands comprising the archipelagos of Tonga, Samoa, and much of East Polynesia could all have similar $^{87}Sr/^{86}Sr$ ratios of bioavailable strontium reservoirs. Additionally, Samoans may have been travelling and utilising coastal resources to such an extent that they may have had $^{87}Sr/^{86}Sr$ ratios indistinguishable from Tongans. Samoa contains two islands much larger than any Tongan islands, Sava'i (1700 km^2) and Upolu (1125 km^2). Both islands are volcanic rather than coralline limestone, and these islands may be large enough that food and water from the inner regions are

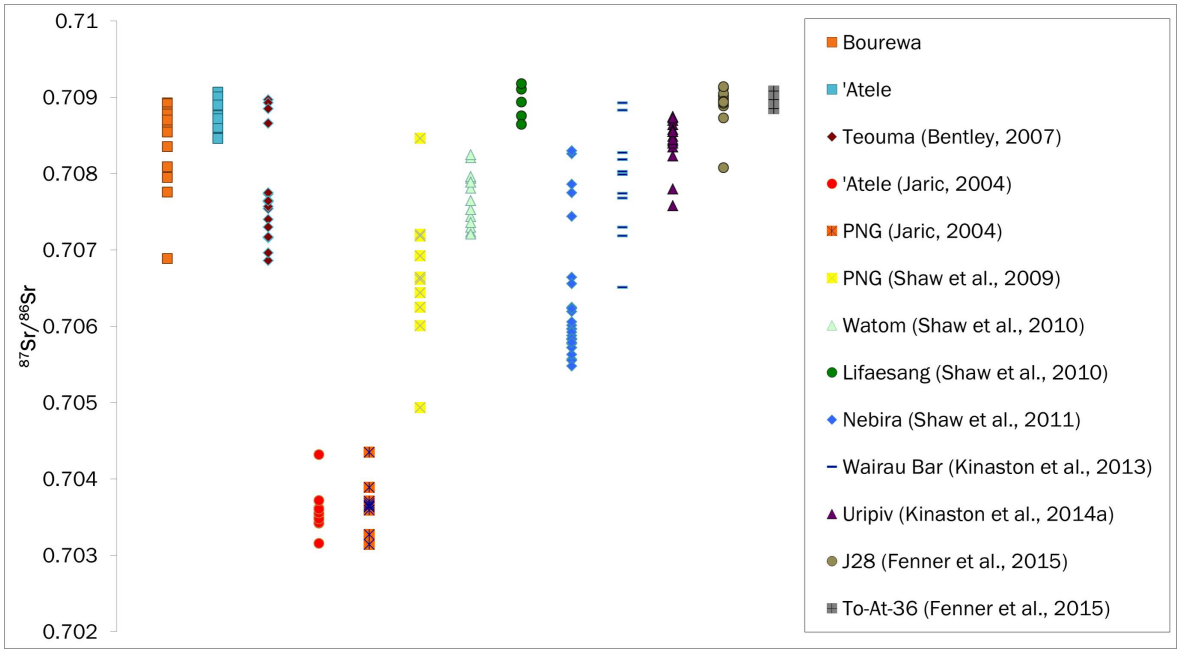


Figure 5.7. *$^{87}Sr/^{86}Sr$ results from this study and previous archaeological studies in the Pacific. Data from Bentley et al. (2007); Jarić (2004); Shaw et al. (2009, 2010, 2011); Kinaston et al. (2013c, 2014a); Fenner et al. (2015).*

Table 5.7. *Summary data of comparative studies in the prehistoric Pacific. Data from this thesis and Bentley et al. (2007); Jarić (2004); Shaw et al. (2009, 2010, 2011); Kinaston et al. (2013c, 2014a); Fenner et al. (2015).*

Site	Mean	SD	*n*
Bourewa	0.7085	0.00050	17
‘Atele	0.7088	0.00013	41
‘Atele (Jarić, 2004)	0.7036	0.00027	12
PNG (Jarić, 2004)	0.7037	0.00031	11
Teouma (Bentley et al., 2007)	0.7078	0.00068	17
PNG (Shaw et al., 2009)	0.7067	0.00091	10
Watom (Shaw et al., 2010)	0.7077	0.00034	15
Lifaesang (Shaw et al., 2010)	0.7089	0.00022	5
Nebira (Shaw et al., 2011)	0.7063	0.00085	27
New Zealand (Kinaston et al., 2013c)	0.7084	0.00033	15
Uripiv (Kinaston et al., 2014a)	0.7079	0.00071	11
Tongatapu (Fenner et al., 2015)	0.7089	0.00022	20

unaffected by seaspray. Though there were fortifications in the highlands of Samoa, according to oral tradition these were places of refuge from warring Tongans and not necessarily indicative of the level of territoriality and intraisland conflict found on Fiji (Pearl, 2004), and thus there is no reason to assume Samoans from inland communities were not in regular contact with goods from the coast. Although contact between Tonga and Samoa during the Chiefdom Period is recorded in ethnohistoric literature (Tuvale, 1918; Kaeppler, 1978) and evidenced in the archaeological record (Clark et al., 2014), it may be impossible to differentiate between Tongans and Samoans using $^{87}Sr/^{86}Sr$ analysis. The characterization of bioavailable strontium on these larger Samoan islands would help determine whether a prehistoric Samoan may have displayed lower ratios than an individual from Tongatapu, and the intriguing issue of whether the highland fortifications were used to protect inland Samoans from coastal residents or invading Tongans could possibly be answered with strontium analysis in future research.

Differentiating between Tongatapu and Rove Peninsula locals and non-locals from coastal or small island communities is difficult without the use of other analytical techniques. However, identifying non-locals who originated from more inland communities using $^{87}Sr/^{86}Sr$ analysis appears to be possible, and the information that can be gleaned is still valuable for understanding prehistoric movement.

5.7.5 Identifying non-locals using $^{87}Sr/^{86}Sr$ analysis

Without a baseline of bioavailable $^{87}Sr/^{86}Sr$ ratios, non-locals were determined as outliers 2SD from the population mean. Using this method within the ‘Atele site appears acceptable: the assemblage $^{87}Sr/^{86}Sr$ ratios were all tightly clustered and so the standard deviation within the assemblage was low relative to other Pacific sites (Table 5.7). In Bourewa, conversely, the SD was high relative to ‘Atele (though not as high as most other Pacific sites as discussed previously). The wider range of $^{87}Sr/^{86}Sr$ ratios may be because of a greater range of geological variation in $^{87}Sr/^{86}Sr$ ratios within the local area, but it could also be because there are other non-locals just within the cutoff of 2SD. Some individuals have low $^{87}Sr/^{86}Sr$ ratios very close to the 2SD cut-off, but are just within the range. The $\delta^{13}C_{dentine}$ $\delta^{15}N_{dentine}$, and $\delta^{34}S_{dentine}$ values of these potential non-locals need to be compared qualitatively to the $^{87}Sr/^{86}Sr$ results. Since non-locals could have consumed a different childhood diet from locals, paleodietary isotope analyses of dentine could also be used as a secondary line of evidence for detecting non-locals. The utility of childhood diet as a means of determining migration will be explored in the final chapters.

5.8 Summary

The first objective of this study was achieved: despite the difficulties that the averaging effect of seawater likely brings in the island Pacific, individual movement was detected using strontium isotope analysis and was compared between subpopulations. In both assemblages, the only non-locals detected were female, lending support to the first hypothesis that females would be more likely to immigrate into communities due to patrilocality. The second hypothesis, that the Bourewa individuals would display a wider range of ratios, was supported by the larger standard deviation although there were statistically no differences between the means of the two populations. The possibility of non-locals being determined using dietary isotopes rather than strontium isotope analysis will be discussed in the final discussion of this thesis.

Chapter 6

Integrating the Different Data: Isotopes and Oral Conditions

Oku hangēʻa e tangata ha fala lālanga.
Mankind is like a mat being woven.
Tongan saying

The previous three chapters were each dedicated to different bioarchaeological tools for understanding diet and movement: paleodietary isotopes, oral indicators of diet, and isotopic evidence of paleomobility. In this chapter, the different data will be examined together to explore possible relationships between them. One hypothesis of this thesis, H_4 (the two methods of assessing diet, isotope analyses and oral indicators, will agree), will be tested here. While the two methods have been compared in a qualitative manner by some researchers (e.g. Valentin et al., 2006; Kinaston, 2010; Tomczyk et al., 2013), few studies have compared the two means of understanding paleodiet using inferential statistics. Since stable isotope analyses and oral conditions are both used by bioarchaeologists to examine the same aspect of lives in the past (i.e. paleodiet), presumably the two methods of assessing diet would agree when compared quantitatively. A lack of agreement between the two methods might be indicative of one (or both) of the methods not accurately representing past dietary patterns: the oral conditions could be affected more strongly by non-dietary influences, or the

oral conditions might be more affected by low protein foods which are overshadowed in stable isotope analyses of collagen. Like the two methods of assessing diet, the potential relationship between the paleodietary and paleomobility isotope results will be compared both quantitatively and qualitatively. The comparison of stable isotope analyses of paleodiet and oral condition frequencies presented in this thesis chapter were first introduced and discussed in the Routledge chapter (Stantis et al., in press). The relationship between paleodietary and paleomobility isotopes for the Bourewa assemblage have been presented and discussed in the article submitted for publication in the American Journal of Physical Anthropology.

6.0.1 The relationship between paleodietary isotope analyses and oral indicators of diet

The only published research to statistically compare oral conditions to the dietary isotopic values (other than publications arising from this thesis) is a study of 70 adults from a burial site in Machu Picchu, Peru (Turner, 2013a). Turner (2013a) recorded caries, AMTL, and occlusal macrowear. Using Pearson's correlation coefficients, she compared caries rates within an individual to stable isotope values from previous research: $\delta^{13}C_{bone}$, $\delta^{15}N_{bone}$, $\delta^{15}N_{dentine}$, and $\delta^{13}C_{apatite}$ (Burger et al., 2003; Turner et al., 2009, 2010). The entire assemblage was not compared; instead, Turner (2013a) divided the site into four cohorts by age ('young' and 'older') and males and females. In older females and young males, there were no significant correlations between caries and isotopic values. In young adult females, Turner found a significant negative association between caries and $\delta^{15}N_{bone}$. In older males there was a significant positive correlation between caries and $\delta^{13}C_{apatite}$. The probable reason for these associations may be a lack of adequate sample size: the two cohorts with significant associations were each comprised of only eight individuals.

An unpublished master's thesis also attempted to quantitatively compare oral

conditions to $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ data (Turner, 2013b). Turner (2013b) tested potential associations between carious lesions, macrowear, and microwear patterns to $\delta^{13}C$ and $\delta^{15}N$ values in a medieval Denmark assemblage ($n = 70$). No significant correlations between isotope values and oral conditions in adults were present in the Danish assemblage.

As a small pilot study, a selection of oral conditions (carious, AMTL, and periodontitis) will be compared to $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values. The 'Atele and Bourewa assemblages provide relatively large sample populations to test the quantitative method of comparing the two methods of understanding paleodiet created by Turner (2013a) and used by Turner (2013b). $\delta^{34}S_{bone}$ will not be analysed in this manner due to the homogenising effect sea spray and/or the local soil environment seem to have on $\delta^{34}S$ values in the Pacific (as addressed in Chapter 3). The results from the two data sets will also be qualitatively compared to test hypothesis 4.

6.0.2 The relationship between paleodietary and paleomobility isotopes

In addition to testing the relationship between the two methods of assessing diet, the potential relationship between paleodietary and paleomobility isotopes within individuals will be explored. Though ancillary to the original aims of this thesis, it is important to determine whether or not the $^{87}Sr/^{86}Sr$ ratio of the samples are potentially being affected by factors other than the underlying geology. Within the Pacific, the geological formations and $^{87}Sr/^{86}Sr$ ratio of seawater basically form two endpoints of values: the lower ratios associated with volcanic geological formations (around 0.704) and the higher ratios (near 0.709) of coralline limestone and modern seawater (Veizer, 1989; McArthur, 1994; Bentley, 2006). Seaspray and/or the consumption of a large proportion of marine foods can alter the $^{87}Sr/^{86}Sr$ ratios in organisms so that the organism's tissue displays $^{87}Sr/^{86}Sr$ ratios closer to 0.7092 (Budd et al., 2000; Whipkey et al., 2000; Bentley et al.,

2007). As marine organisms will display higher $\delta^{13}C$ and $\delta^{15}N$ values than terrestrial organisms, a relationship between $^{87}Sr/^{86}Sr$ ratios and paleodietary isotopic values is possible. In addition, the utility of paleodietary isotope analyses as secondary lines of identifying non-locals will also be discussed. This approach has had success in previous prehistoric Pacific studies (Bentley et al., 2007; Kinaston et al., 2013c) and will be used in this study.

6.1 Methods

6.1.1 Comparing oral indicators of diet and paleodietary isotope values

To test whether the stable isotopic values correlate with oral condition frequencies, comparative methods similar to Turner (2013a) were followed. Oral conditions were collapsed to a present/absent variable as described in the methods section of Chapter 3. Individual percentage frequency of conditions were calculated for 'Atele individuals by calculating the total observed number of an oral condition and dividing by the total number of teeth/alveoli. For example, calculating an individual's caries percentage frequency was as follows:

$$\frac{\text{number of carious teeth}}{\text{total number of teeth}} \times 100\%$$

With this equation, each individual with teeth or alveoli to observe had a percentage frequency between 0 and 100%. Only adults were included in the sample group to avoid complications with breastfeeding and weaning affecting stable isotope values (Katzenberg et al., 1993). Three of the oral conditions measured in this study are compared to isotopic values: caries, AMTL, and periodontitis. Periapical cavities were not compared in this chapter due to their low frequency in the 'Atele assemblage. Calculus and

occlusal edge chipping were not compared due to their more tenuous position as dietary indicators compared to caries, AMTL, and periodontitis, the issues with calculus being lost post-mortem, and the relative dearth of clinical and bioarchaeological studies examining occlusal edge chipping. Pearson's correlation coefficients were measured between condition frequencies and carbon and nitrogen isotopic values from bone collagen. Dentine collagen isotopic values were not correlated with oral condition frequencies, as there is not expected to be a relationship between childhood diet (recorded at a time when permanent teeth are just beginning to erupt) and oral conditions in adults that have been forming over their entire lives.

The two assemblages were not divided by age and/or sex for these tests. Dividing the populations would create too small of cohorts for correlations. Furthermore, determining whether certain groups' oral and isotopic data agree is not the goal of this exploratory research, but to extrapolate whether quantifying the potential relationships between oral and isotopic data provide meaningful information about diet.

6.1.2 Comparing paleodietary isotope values and $^{87}Sr/^{86}Sr$ ratios

The tooth enamel sampled for $^{87}Sr/^{86}Sr$ analysis is not necessarily forming within the same range of time as the dentine sampled from the root for paleodietary isotope analyses. However, for the majority of teeth sampled in this study, the dentine was isolated from the root so that the crown has completed formation within the time range that the dentine was forming (Hillson, 1996). The ages for crown completion and the formation of the tooth roots sections for the teeth most often sampled in this thesis are listed on Table 6.1. With the exception of the first molar, the crown complete mineralisation within or near the time period in which the root section was forming (van Beek, 1983; Hillson, 1996).

A potential issue with the formation timing is that not all of the Bourewa individuals were sampled for $^{87}Sr/^{86}Sr$ analysis following the preferred sampling protocol utilised for

Table 6.1. *Estimation of age of development for crown and root dentine for the most common teeth (all permanent) sampled in this study, in order of sample preference. Age ranges from Hillson (1996), with development range of upper and lower teeth averaged.*

Tooth	Crown formation age range (years)	Tooth root section	Dentine formation age range (years)
2^{nd} molar	7.0–8.0	CEJ–$R_{1/2}$	7.6–10.6
1^{st} premolar	5.0–6.0	CEJ–$R_{1/2}$	6.4–9.3
2^{nd} premolar	6.0–7.0	CEJ–$R_{1/2}$	7.3–10.1
1^{st} molar	2.5–3.0	$R_{1/2}$–A	5.5–8.5

the ‘Atele individuals. As the Bourewa individuals were sampled by another researcher, some of the teeth sampled for $^{87}Sr/^{86}Sr$ analysis were canines (which have much earlier formation times, possibly during breastfeeding) or third molars (which are forming later, during adolescence) (Hillson, 1996). The tooth roots used for childhood paleodietary isotopes were sampled during the course of this research, and so always from the four preferred teeth types (in order of preference: 2^{nd} molars, premolars or 1^{st} molars), even if extra teeth had to be sampled. As such, three individuals in the Bourewa assemblage have $^{87}Sr/^{86}Sr$ ratios sampled from one tooth and childhood paleodietary isotopes sampled from another. Individuals where different teeth were sampled for strontium analysis and for paleodietary isotope analyses (Burials 09, 23, and 31) were excluded from comparisons between $^{87}Sr/^{86}Sr$ ratios and dentine isotope values.

In addition, nine teeth from the Bourewa assemblage were first molars in which the crown and root section formation do not overlap. In the ‘Atele assemblage, only two individuals were represented by first molars, and so formation timing overlap is less of an issue in that assemblage. None of the individuals analysed using first molars were excluded, but any interpretations must be made with the caveat that the formation time in any given individual may not align as perfectly as the preferred sampling protocol would have allowed.

Pearson’s correlation coefficients were measured between $^{87}Sr/^{86}Sr$ ratios and

Table 6.2. *Results of the Pearson correlation coefficients between stable isotope values of bone collagen and percentage frequency of caries, ante-mortem tooth loss, and periodontitis. * marks significance.*

	Caries			**AMTL**			**Periodontitis**		
	n	*r*	*p*	*n*	*r*	*p*	*n*	*r*	*p*
Bourewa									
$\delta^{13}C$	13	0.56	0.045*	16	0.32	0.231	10	0.77	0.010*
$\delta^{15}N$	13	0.51	0.074	16	0.52	0.038*	10	0.61	0.060
'Atele									
$\delta^{13}C$	33	-0.17	0.338	33	-0.08	0.656	31	-0.02	0.920
$\delta^{15}N$	33	0.07	0.701	33	0.34	0.053	31	0.16	0.390

$\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$ values within each assemblage. Pearson's correlation coefficients were also measured between $^{87}Sr/^{86}Sr$ ratios and $\delta^{34}S_{dentine}$ values in the 'Atele assemblage.

6.2 Results

6.2.1 Oral indicators of diet and paleodietary isotopes

Tables 6.2 displays the results of the Pearson correlations. Figures 6.1 through 6.6 display the carbon and nitrogen isotopic values with the percentage frequency of oral conditions within an individual. In the Bourewa assemblage, there was 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 oral conditions, there was nearly a significant positive correlation between AMTL and $\delta^{15}N$, $r(31) = 0.34$, $p = 0.053$.

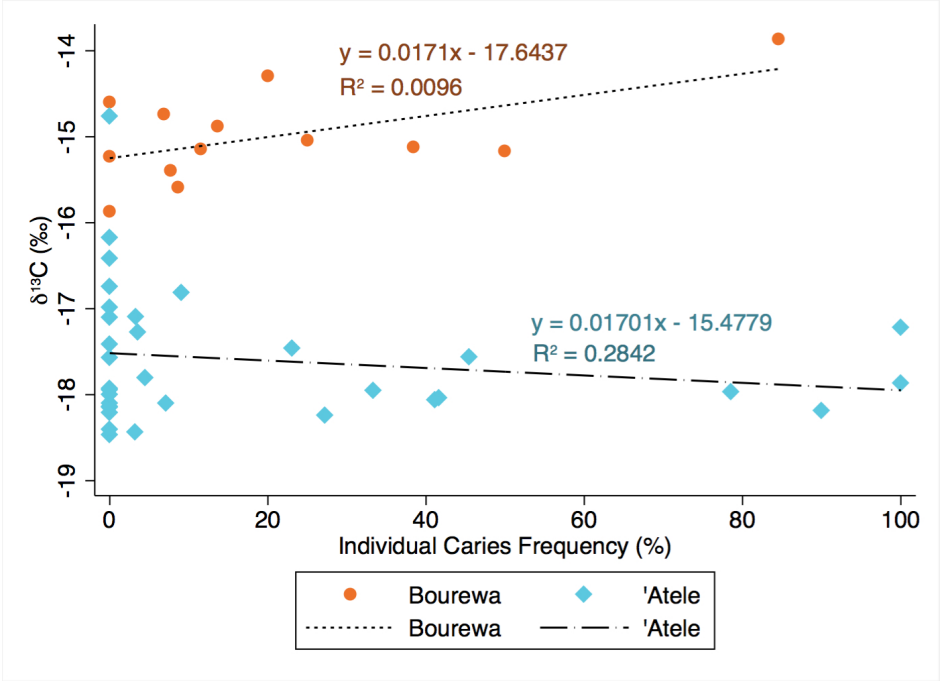


Figure 6.1. *$\delta^{13}C_{bone}$ values and individual caries frequency. Linear regression plot of values (with regression equations) overlaid.*

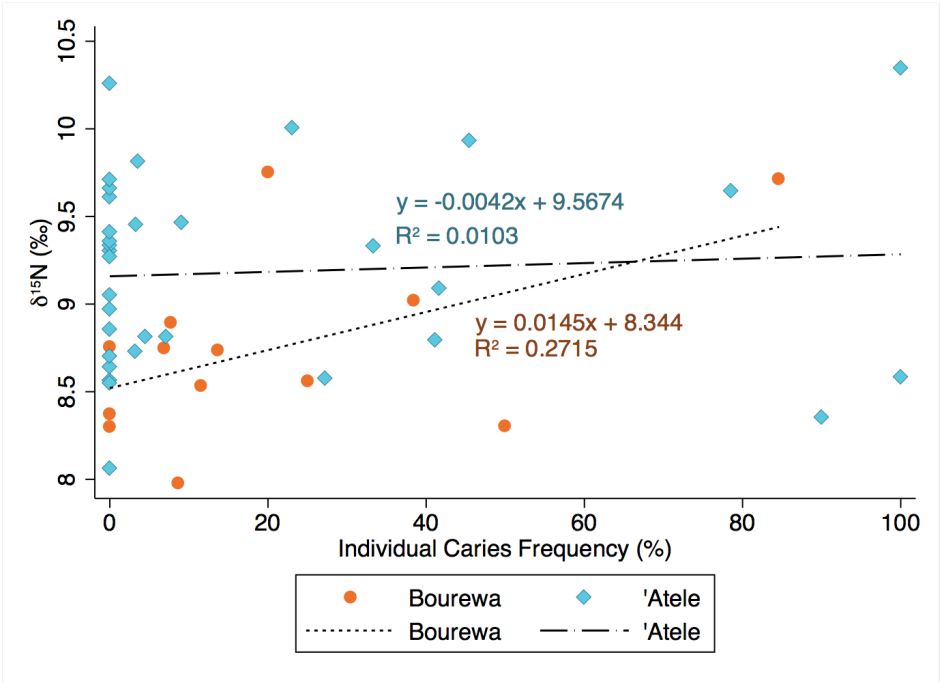


Figure 6.2. *$\delta^{15}N_{bone}$ values and individual caries frequency. Linear regression plot of values (with regression equations) overlaid.*

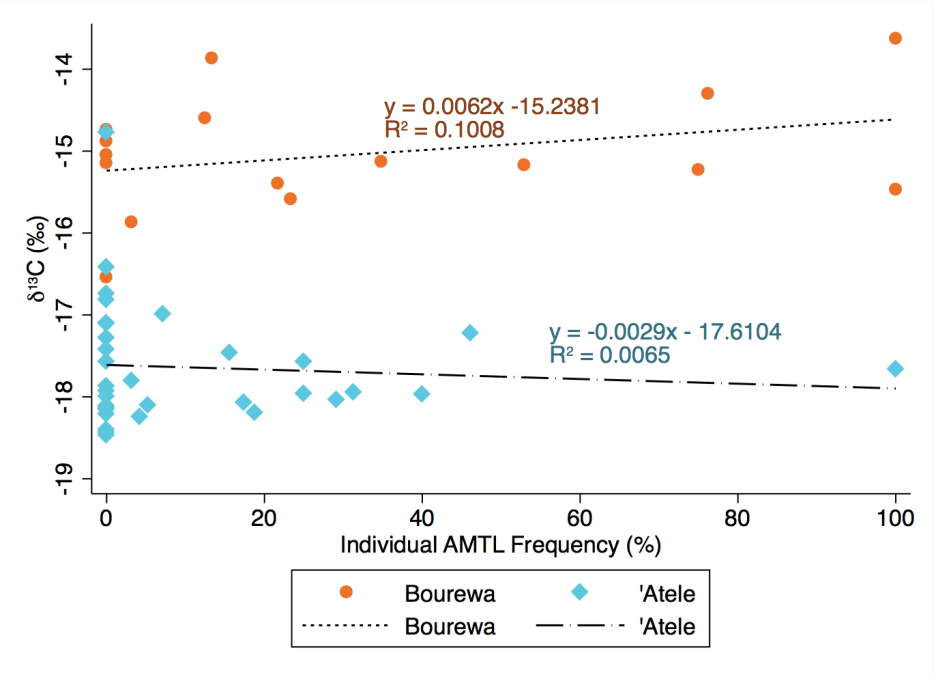


Figure 6.3. *$\delta^{13}C_{bone}$ values and individual AMTL frequency. Linear regression plot of values (with regression equations) overlaid.*

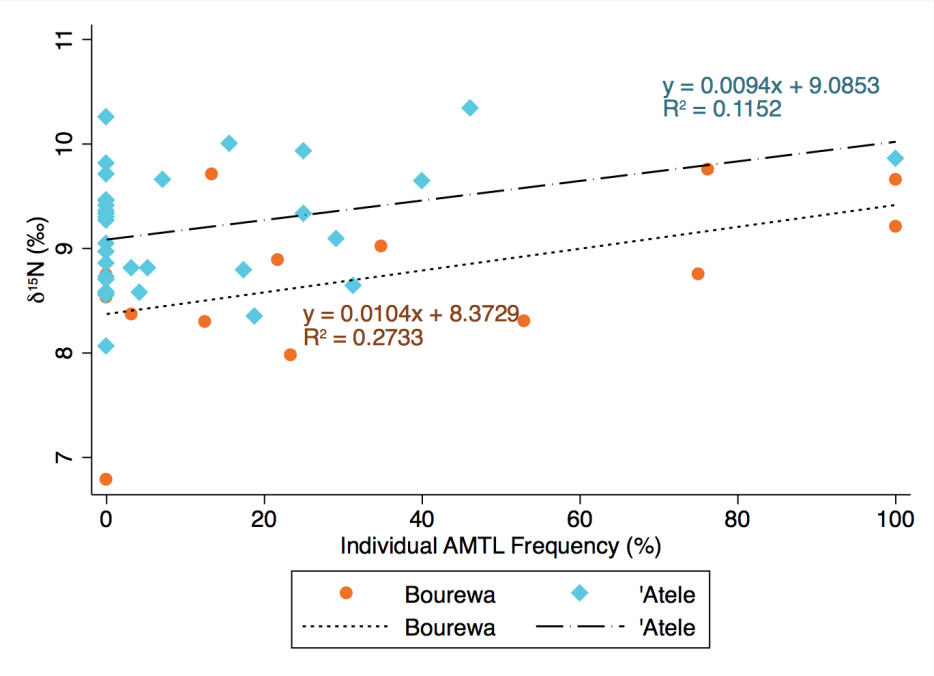


Figure 6.4. *$\delta^{15}N_{bone}$ values and individual AMTL frequency. Linear regression plot of values (with regression equations) overlaid.*

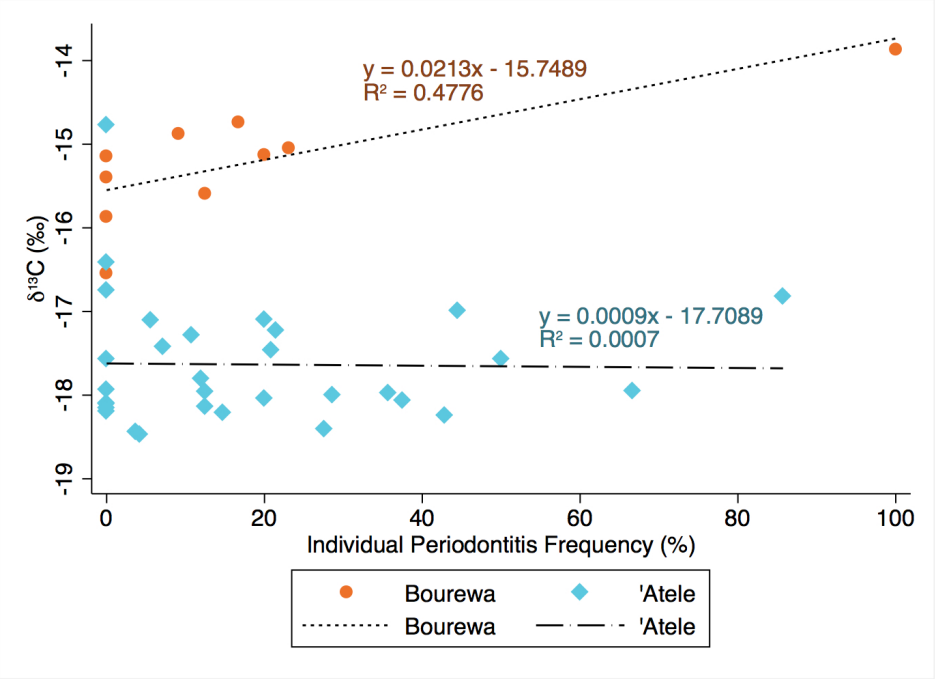


Figure 6.5. *$\delta^{13}C_{bone}$ values and individual periodontitis frequency. Linear regression plot of values (with regression equations) overlaid.*

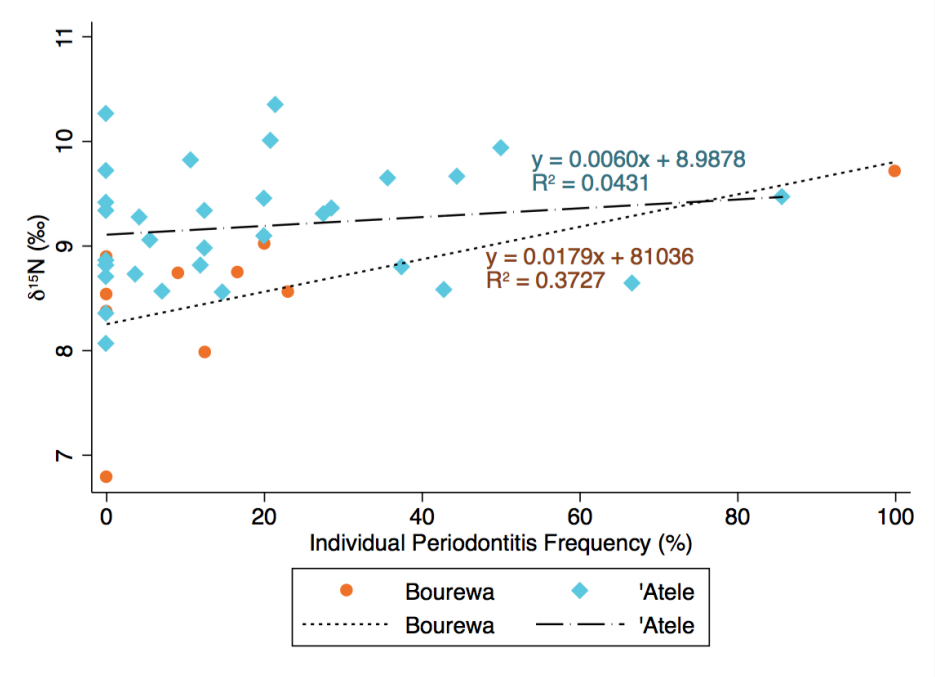


Figure 6.6. *$\delta^{15}N_{bone}$ values and individual periodontitis frequency. Linear regression plot of values (with regression equations) overlaid.*

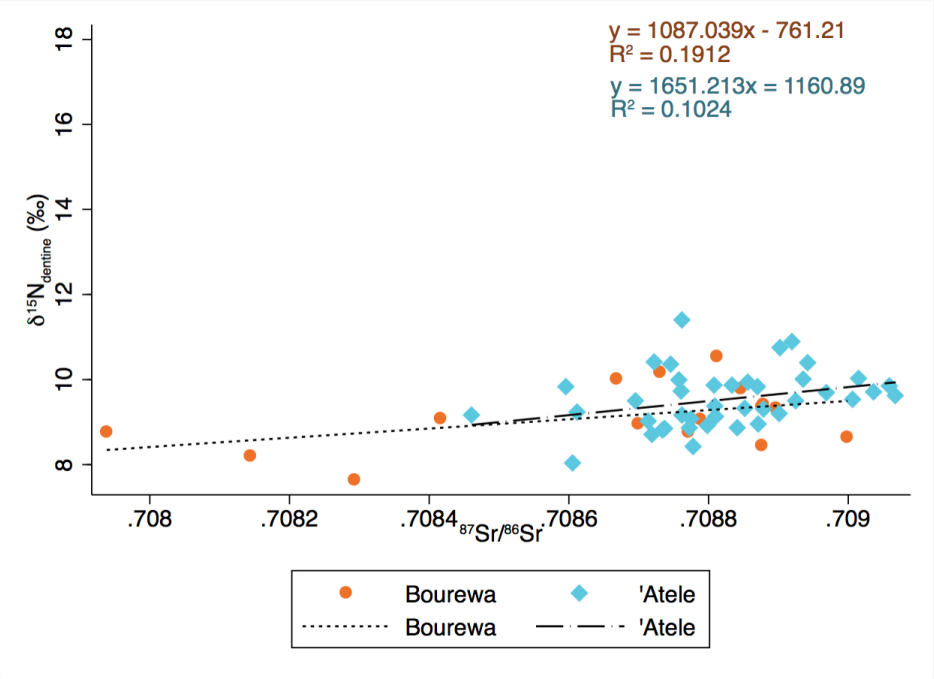


Figure 6.7. *$\delta^{15}N_{dentine}$ and $^{87}Sr/^{86}Sr$ values for Bourewa and 'Atele. Linear regression plot of values (with regression equations) overlaid.*

6.2.2 Paleodietary isotope values and $^{87}Sr/^{86}Sr$ ratios

$\delta^{13}C_{dentine}$ and $^{87}Sr/^{86}Sr$ ratios were strongly correlated in the Bourewa assemblage, $r(12) = 0.63$, $p = 0.020$. $\delta^{13}C_{dentine}$ and $^{87}Sr/^{86}Sr$ values were not correlated in the 'Atele assemblage, $r(33) = 0.13$, $p = 0.438$. Figure 6.8 displays the $\delta^{13}C_{dentine}$ values and $^{87}Sr/^{86}Sr$ ratios for both sites.

$\delta^{15}N_{dentine}$ and $^{87}Sr/^{86}Sr$ were not correlated in Bourewa, $r(12) = 0.48$ $p = 0.095$, though the values were still significantly correlated when the 'Atele assemblage was tested on its own, $r(33) = 0.32$, $p = 0.041$ (Fig. 6.7). In the 'Atele assemblage, $\delta^{34}S_{dentine}$ and $^{87}Sr/^{86}Sr$ values were strongly correlated, $r(25) = 0.45$, $p = 0.020$ (Fig. 6.9).

6.3 Discussion

The analyses presented in this chapter are all ancillary to the mains aims of the thesis. One hypothesis, H_4, was tested in this chapter using correlations: the two methods of

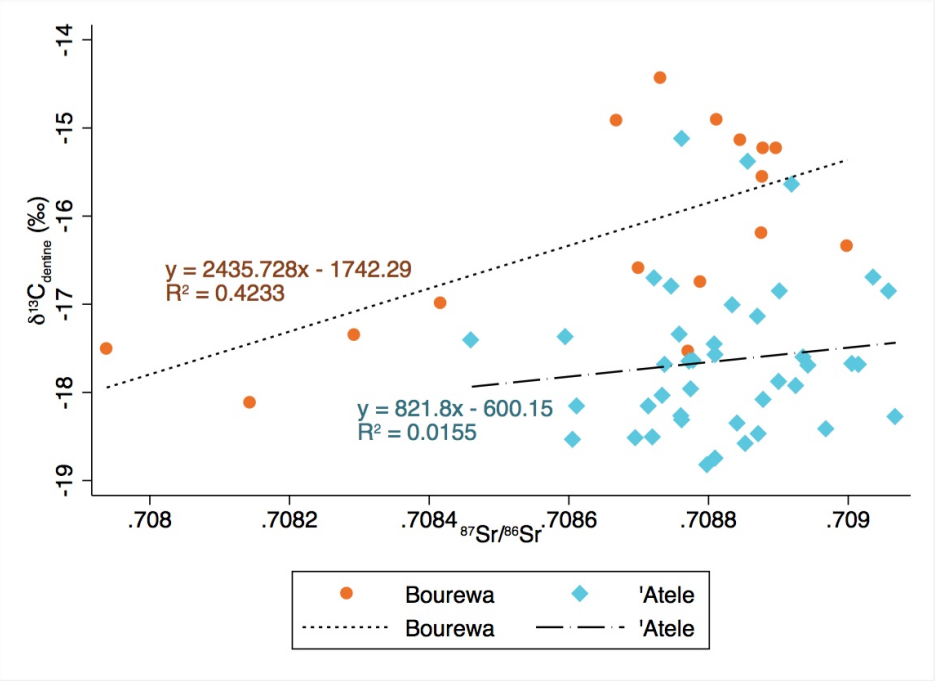


Figure 6.8. *$\delta^{13}C_{dentine}$ and $^{87}Sr/^{86}Sr$ values for Bourewa and 'Atele. Linear regression plot of values (with regression equations) overlaid.*

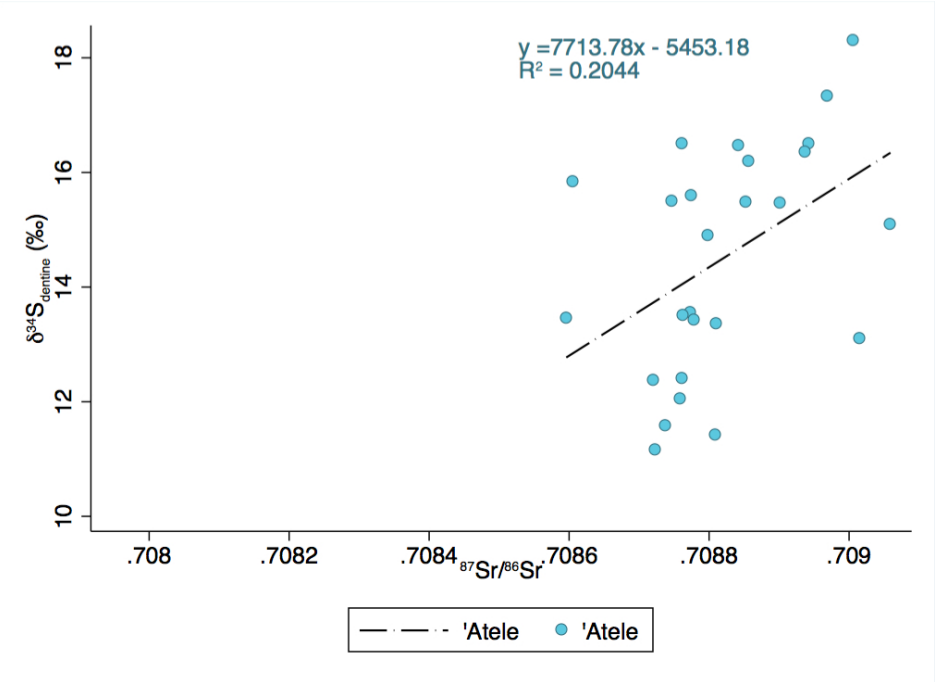


Figure 6.9. *$\delta^{34}S_{dentine}$ and $^{87}Sr/^{86}Sr$ values for 'Atele. Linear regression plot of values (with regression equations) overlaid.*

assessing diet, isotope analyses and oral indicators, will agree.

6.3.1 Relationships between oral indicators of diet and paleodietary isotopes

There were very few significant correlations between oral indicators of diet and isotopic values. There were no significant correlations between oral indicators of diet and isotopic values in the 'Atele assemblage, though the relationship between AMTL and δ^{15}N was nearly significant ($p = 0.053$).

In the Bourewa assemblage, there were significant positive correlations between carious lesions and δ^{13}C, periodontitis and δ^{13}C, and AMTL and δ^{15}N. A closer examination of the graphs for caries and periodontitis reveal an outlier with high carbon values and a higher frequency of caries and periodontitis compared to the rest of the assemblage (Burial 25). Removal of Burial 25 reduces the correlations between the isotopic values and caries and isotopic values and periodontitis to non-significant relationships.

Ante-mortem tooth loss and δ^{15}N values provide the only strong relationship between both sites, though it is recognized that the correlation in the 'Atele assemblage is non-significant. It is interesting that diet-related causes of AMTL (caries, periodontitis, and wear) are not related to δ^{15}N values although AMTL was. One possibility is that the relationship between AMTL and δ^{15}N values is not interconnected with caries and periodontitis but with trauma. Increased δ^{15}N values 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, a relationship between δ^{15}N values and occlusal edge chipping could be expected (but was not tested). 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).

The two methods of assessing diet did not agree when exploring the potential relationship using Pearson's correlation coefficients. The two methods can also be compared in a qualitative manner: are the conclusions about diet drawn from each method in agreement?

Dietary differences between the sites were significant using isotope analyses: 'Atele individuals consumed proportionately more terrestrial foods from a higher trophic level as interpreted by lower $\delta^{13}C_{bone}$ and higher $\delta^{15}N_{bone}$. Using oral indicators of diet collapsed as presence/absence variables, there were no differences between sites. When comparing the two sites in terms of oral condition severity, the 'Atele individuals displayed increased odds of severe carious lesions when adjusted for adult age. A greater reliance on starchy root vegetables compared to the marine foods could leave these individuals more susceptible to carious lesions (Littleton and Frohlich, 1993). Perhaps the difference in proportions of root vegetable consumption is so small as to not appreciably increase the odds of caries in general, but did exacerbate carious lesions once formed by creating an oral environment that promoted bacterial growth. The higher $\delta^{15}N_{bone}$ values of 'Atele suggest more animal protein from a higher trophic level than the Bourewa diet, and increased consumption of animal protein is in conflict with the increased odds of caries.

Deciding whether the two methods agree when comparing burial mounds is more difficult. To-At-1 individuals displayed significantly higher $\delta^{13}C_{bone}$ values than those excavated from To-At-2, suggesting that To-At-1 individuals consumed proportionally more marine foods. The lack of trophic level difference as inferred by the similar $\delta^{15}N_{bone}$ values could be a result of terrestrial C_3 plants and shellfish occupying roughly the same $\delta^{15}N$ range. To-At-1 adults displayed increased odds of more severe caries and more calculus. Periodontitis severity and caries severity do not seem to be related between

burial mounds, as To-At-1 displayed lower odds of periodontal severity (though not quite to a significant degree). Principal axis analysis of wear showed that To-At-2 adults experienced faster rates of wear, which corroborates with the fact that only To-At-2 adults had occlusal attrition facet caries. While the isotopic evidence suggests that To-At-1 individuals consumed more marine foods, the oral evidence is in opposition. Increased odds of more severe caries and decreased rates of wear suggest a softer diet of root crops in To-At-1 individuals. In the case of comparing burial mounds, the two methods do not seem to agree.

There were no differences between the sexes regarding paleodietary isotope values in Bourewa. In the ‘Atele assemblage, females displayed significantly lower $\delta^{15}N_{bone}$ values than males. Regarding oral conditions, Bourewa males had increased odds of chipped teeth and decreased odds of more severe caries compared to Bourewa females. In ‘Atele, males displayed a higher rate of wear, increased odds of severe periodontal disease, and decreased odds of more severe caries. Comparing the sexes in Bourewa is difficult owing to the small sample size, and so I am hesitant to compare the two types of data. In ‘Atele, if the higher trophic level is animal protein, especially from marine animals such as fish, increased rates of wear and decreased odds of more severe caries would agree with isotopic evidence of diet and can be used to complement each other. Ultimately, the two methods of assessing diet do not always agree from a qualitative standpoint.

Both quantitative and qualitative methods of assessing agreement reject Hypothesis 4 (Figure 6.10). Much of this chapter was dedicated to testing this hypothesis. Though not explicitly an aim within this thesis, if the two methods of assessing diet did not agree, then it would be possible that one (or both) were not reliable methods of understanding diet in prehistoric Fiji and Tonga. However, it is important to keep in mind all of the ways in which the two methods differ in reflecting diet in an individual. While isotopic values of bones reflect the last ten or so years of life and isotopic values of teeth reflect a short time period during childhood or adolescence, most of the oral indicators of diet

are cumulative and last the entire lifetime of the individual. Calculus, which can be removed ante- and post-mortem (Lieverse, 1999), and alveolar lesions and periodontal disease, which can remodel (Ogden, 2008), are the only exceptions.

In addition, differences in diet may not fully explain the frequency of oral conditions. Extramasticatory use can cause dental wear, chipping, alveolar lesions and tooth loss (Molnar, 2011). 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 such as diabetes mellitus and eating disorders (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 isotope analyses (e.g. proportions of marine versus 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 isotope analyses.

The method of calculating how affected an individual is by a given oral condition is not without flaws, as it can suffer from some of the same problems any bioarchaeological study is liable to: missing data. An individual with only one observable tooth with calculus has a percentage frequency of 100%, same as an individual with a complete adult dentition covered in calculus. The outlier in the Bourewa assemblage, Burial 25, is a good example of how missing data may affect bioarchaeological research. Burial 25, who was excluded from calculations of caries and periodontitis, had six observable alveoli for periodontitis and 13 teeth for observing carious lesions. With so few remaining alveoli and teeth, it is impossible to know whether he would have displayed such a relatively high percentage frequency of oral conditions if his full dentition had been preserved for observation.

Ultimately, comparing isotopic and oral conditions findings using Pearson's correla-

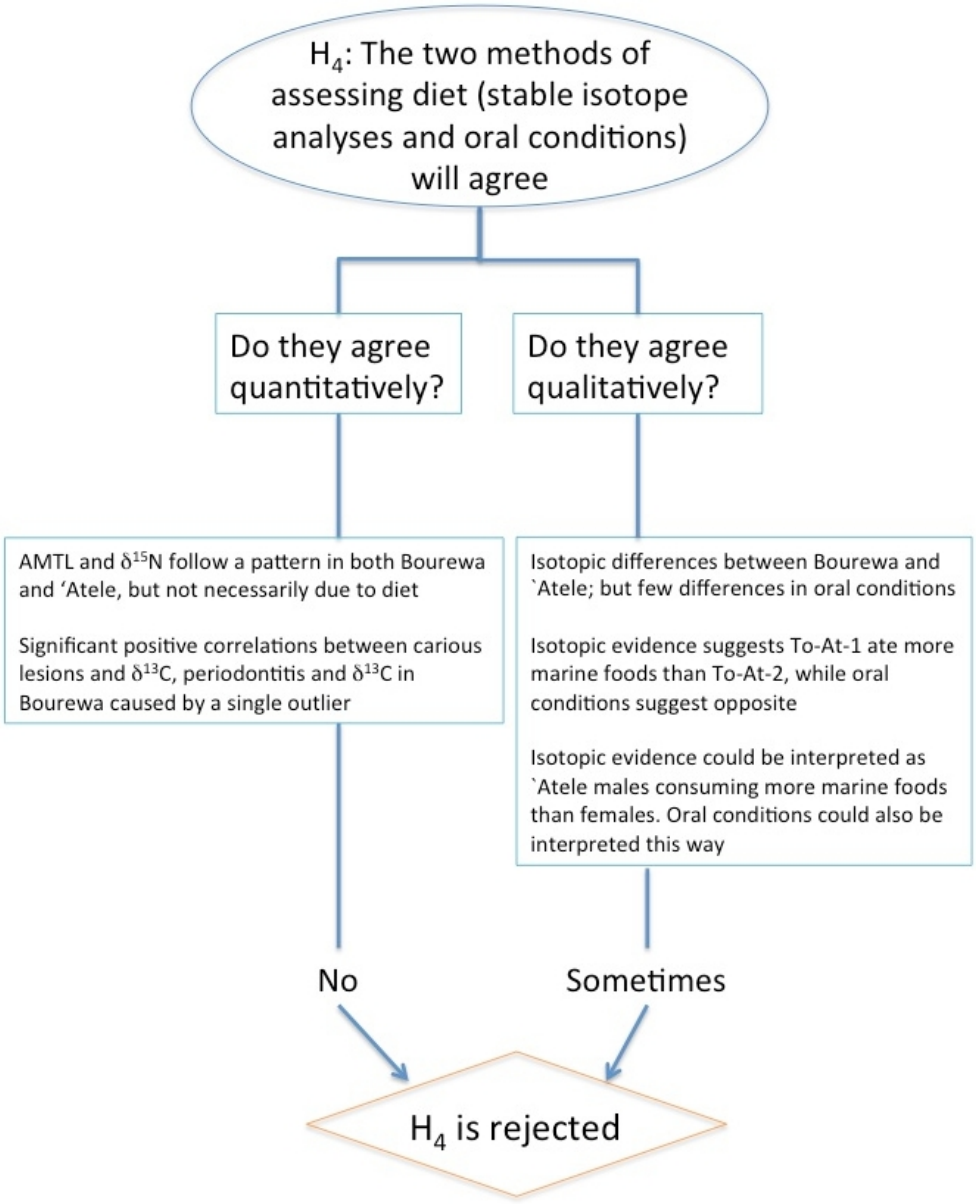


Figure 6.10. *Conceptual summary of Hypothesis 4 findings.*

tion coefficients do not seem to be a meaningful way of understanding the relationships between diet, isotope values, and oral conditions. Unless a more effective means of comparing the two methods quantitatively is found, qualitative interpretations and comparisons are stronger when considering the two methods of assessing paleodiet.

6.3.2 Relationship between paleodietary isotopes and $^{87}Sr/^{86}Sr$ ratios

In the Bourewa assemblage, $\delta^{13}C_{dentine}$ and $^{87}Sr/^{86}Sr$ were significantly correlated, although $\delta^{15}N_{dentine}$ and $^{87}Sr/^{86}Sr$ were not. In the 'Atele assemblage, $\delta^{15}N_{dentine}$ and $^{87}Sr/^{86}Sr$ were correlated, as were $\delta^{34}S_{dentine}$ and $^{87}Sr/^{86}Sr$. $\delta^{13}C_{dentine}$ values were not correlated with $^{87}Sr/^{86}Sr$ ratios in the 'Atele assemblage.

As explained in the introduction of this chapter, examining the relationship between $^{87}Sr/^{86}Sr$ and paleodietary isotopes from dentine collagen may not be appropriate in the Bourewa assemblage, as the teeth sampled for collagen were not always the same teeth sampled for enamel. Burial 09 from the Bourewa assemblage, for example, is represented by a third molar for $^{87}Sr/^{86}Sr$ values, a tooth that does not begin calcification until between 12 –16 years of age (van Beek, 1983), up to 11 years after the age represented by the dentine collagen sampled for that individual (5-10 years of age) (Hillson, 1996).

In addition, strontium in calcified tissue is derived from the whole diet (Spencer et al., 1973; Burton and Price, 1999; Bhagavan, 2002), while carbon, nitrogen, and sulphur in bone collagen are largely derived from protein (Ambrose and Norr, 1993; Fernandes et al., 2012; Podlesak and McWilliams, 2006; Nimni et al., 2007). Despite these potential issues in interpretation, comparing the $^{87}Sr/^{86}Sr$ ratios and dentine collagen paleodietary isotope values still provides an opportunity to understand whether there is a relationship between these values in the population as a whole. As noted in Chapter 5, the possible non-locals in the Bourewa assemblage display lower $^{87}Sr/^{86}Sr$ values than the rest of the assemblage. These non-locals also display lower $\delta^{13}C_{dentine}$ values on the whole. More negative $\delta^{13}C_{dentine}$ values suggest a childhood diet more

reliant on terrestrial foods rather than marine foods (Sharp, 2007; Hoefs, 2009). In the tropical Pacific, higher strontium ratios in tooth enamel can be associated with small islands and coastal sites affected by seaspray and/or limestone bedrock, while lower strontium ratios in tooth enamel may reflect the underlying geology of islands unaffected by saltwater (Bentley et al., 2007) if the islands have volcanic bedrocks, or a mixture of volcanic and limestone bedrocks. The association between $\delta^{13}C_{dentine}$ and $^{87}Sr/^{86}Sr$ in the Bourewa assemblage likely stems from the fact that those individuals who spent their childhood inland also consumed proportionately more terrestrial foods.

The ‘Atele assemblage displays no significant association between $\delta^{13}C_{dentine}$ and $^{87}Sr/^{86}Sr$. While there was one outlier outside 2SD from the $^{87}Sr/^{86}Sr$ mean in the ‘Atele assemblage, her $^{87}Sr/^{86}Sr$ ratios are not as low as the Bourewa assemblage immigrants. She may have spent her childhood on a coralline limestone island or limestone/basalt mix, or in an environment not quite as inland as the Bourewa outliers. Additionally, the ‘Atele assemblage as a whole displays lower $\delta^{13}C_{dentine}$ values than Bourewa. With more terrestrial plants being consumed by the population as a whole, regardless of the childhood residence of an individual, a weaker relationship between $\delta^{13}C_{dentine}$ and $^{87}Sr/^{86}Sr$ is expected in the ‘Atele assemblage compared to Bourewa.

Given the positive correlations between $^{87}Sr/^{86}Sr$ and $\delta^{15}N_{dentine}$ values in the ‘Atele assemblage, there may be a confounding issue of marine-based diets or seaspray affecting $^{87}Sr/^{86}Sr$ values. Seaspray and ocean-derived rainwater both have a $^{86/87}Sr$ value of roughly 0.7092 (Whipkey et al., 2000). Budd et al. (2000) identify that most Sr^{2+} ions in a non-coastal individual are derived from drinking water, but most Sr^{2+} ions in Oceanic individuals are sourced from marine water. Higher $\delta^{15}N_{dentine}$ values suggest a relatively higher proportion of marine foods in individual's childhood diets, which can alter $^{87}Sr/^{86}Sr$ values in enamel to be closer to the value of seawater (Bentley, 2006; Bentley et al., 2007). As plants contain a higher concentration of strontium due to biopurification in higher trophic level organisms (Bhagavan, 2002), the consumption

of seaweeds and seagrasses may be the reason. Although there were problems in this study with finding a relationship between $\delta^{34}S$ isotope values and diet, the positive correlation between $^{87}Sr/^{86}Sr$ and $\delta^{34}S_{dentine}$ may be related to seaspray affecting both the sulphur and strontium isotopic compositions in food and drinking water.

The $^{87}Sr/^{86}Sr$ means of the 'Atele (0.7089) and Bourewa (0.7088) assemblages are very similar to the $^{87}Sr/^{86}Sr$ isotopic signature of modern seawater, 0.7092. It is possible that the positive correlations between these dietary isotopes and strontium may be indicative of seaspray, limestone bedrock, and/or marine-based diets affecting $^{87}Sr/^{86}Sr$ values in the 'Atele and Bourewa assemblages, rendering interpretation of movement difficult as any coastal/ small island individual with a marine or coastal diet will display high $^{87}Sr/^{86}Sr$ values. However, if a marine-based diet were affecting the $^{87}Sr/^{86}Sr$ values, one would expect a positive correlation between $^{87}Sr/^{86}Sr$ and $\delta^{13}C_{dentine}$ values, which is not present in 'Atele. Plants utilise nitrogen, sulphur, and strontium mostly from the soil (Haneklaus et al., 2003; Bentley et al., 2007), but most carbon is metabolised from atmospheric CO_2 (O'Leary, 1988; Prentice et al., 2001). This suggests that seaspray is affecting the isotopic composition of the foods consumed by the individuals from 'Atele rather than a heavily marine-based diet affecting $^{87}Sr/^{86}Sr$ values. Nonetheless, without further proof there is no reason to believe that the isotopic results are so affected by seaspray to be unusable as a means of interpreting mobility, and if all the locals are affected similarly in a given region a non-local may still be visible if they came from a place with different bioavailable $^{87}Sr/^{86}Sr$ ratios.

6.3.3 Identifying the dietary and mobility outliers

The relationship between dietary isotope values and $^{87}Sr/^{86}Sr$ ratios were examined quantitatively using Pearson's correlation coefficients in two populations. However, a qualitative examination is necessary to understanding how mobility and diet interacted during these individuals' lives, as well as explore the potential utility of paleodietary

isotopes to identify non-locals in these two sites.

A single non-local was found in Bourewa using 2SD from the mean as the method for determining outliers. This individual, Burial 23, was a middle-aged female. Given the comparatively high $^{87}Sr/^{86}Sr$ ratio of seawater and the marl/limestone geology of the Rove Peninsula (which would ostensibly have a relatively high $^{87}Sr/^{86}Sr$ ratio), Burial 23 may have spent her childhood inland rather than on the coast, consuming foods and drinking water free of seaspray. Burial 23 may have been a woman raised in the interior who married a coastal man. This conclusion is consistent with modern life in rural Fiji where women generally move to their husband's village after marriage (Nayacakalou, 1955; Becker, 1995; Jones, 2009).

With no bioavailable strontium baseline for the local area, it is difficult to determine with certainty who the other non-locals were in the assemblage. Beyond Burial 23, two other individuals display low $^{87}Sr/^{86}Sr$ ratios (though within two standard deviations of the mean). The other individuals with low $^{87}Sr/^{86}Sr$ ratios are Burial 17, a female of unknown age, and Burial 15, the only subadult (around 13 years of age) in the assemblage. These three individuals have three of the four lowest $\delta^{13}C_{dentine}$ values within the population (Figure 6.11), suggesting a childhood diet of more terrestrial foods than the rest of the group. The fourth individual is Burial 21 (located on Figure 6.11 next to Burial 23), a female adult of unknown age. Her $^{87}Sr/^{86}Sr$ ratio was identical to the population mean, 0.7087. With the exception of Burial 21, did these individuals spend their childhood in another location? Without a bioavailable strontium baseline for Fiji, only Burial 23 would have been considered a non-local using 2SD from the mean as a method of identifying immigrants but childhood diet appears to be a strong line of evidence for identifying migrants in Bourewa.

Figure 6.12 compares the potential non-locals' bone collagen to the rest of the population. The C:N ratios for the samples from Burial 17 were outside acceptable parameters and were excluded from examination. The diet of Burial 23 within the last

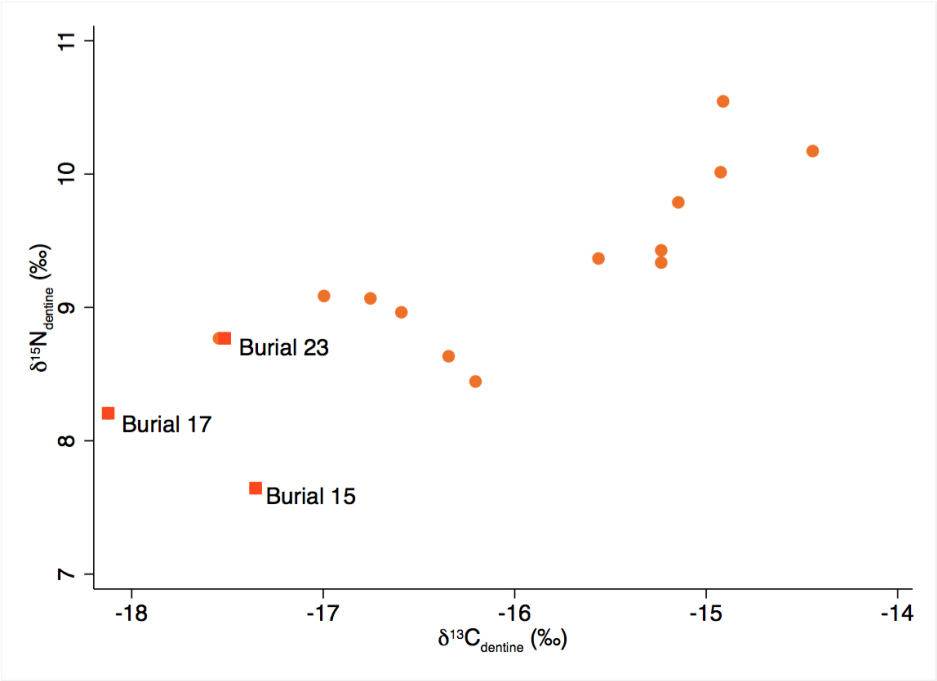


Figure 6.11. *$\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$ values of Bourewa individuals, with the three individuals with the lowest $^{87}Sr/^{86}Sr$ values in the group labelled.*

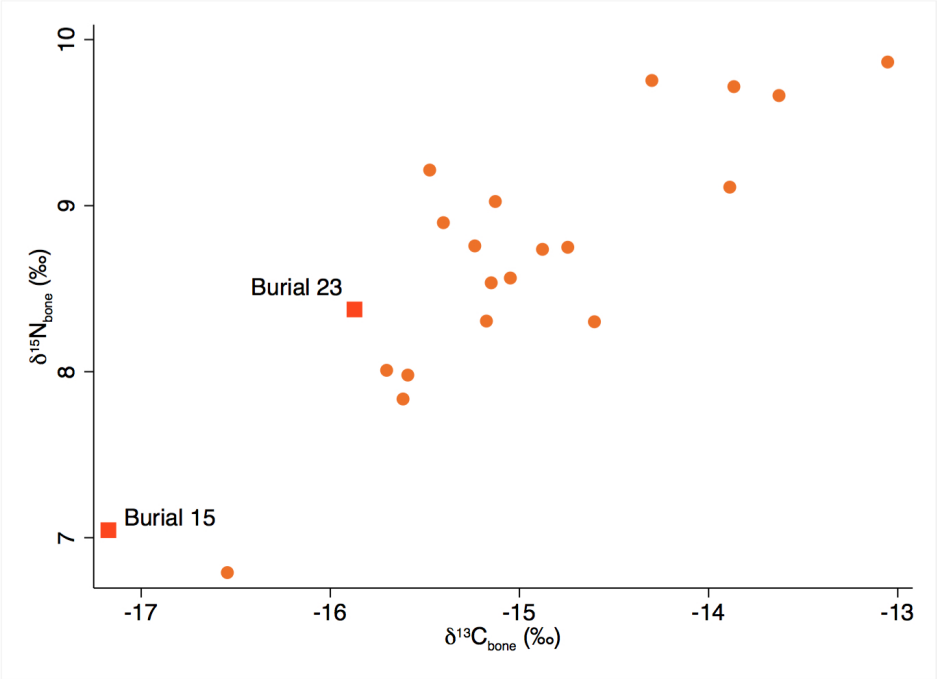


Figure 6.12. *$\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values of Bourewa individuals, with Burial 15 and Burial 23 labelled.*

few years of her life are within the values of the rest of the population. The differences between the dentine and bone stable isotope values imply that she spent her childhood elsewhere, but sometime during or after roughly ten years of age she moved to Bourewa and lived there at least a few years before her death. Burial 15's bone and dentine collagen values are both outliers from the rest of the population. As an adolescent approximately 13 years of age there may be some overlap between these two values. With bone collagen stable isotope values markedly different from the others, Burial 15 probably arrived to Bourewa shortly before death. The individual with the lowest $\delta^{15}N_{bone}$ and the second lowest $\delta^{13}C_{bone}$ values near Burial 15 is Burial 04. An adult of indeterminate sex and age who did not have teeth for isotope analyses, we cannot learn more about Burial 04's childhood diet or residence using this study's methods.

The non-local identified via $^{87}Sr/^{86}Sr$ analysis in 'Atele, To-At-1/09, does not display a childhood diet different from the rest of the population (Figure 6.13). The distinct outlier in $\delta^{15}N_{dentine}$ and $\delta^{13}C_{dentine}$ in the upper-right corner of Figure 6.13, To-At-1/13, is a young adult female. To-At-1/13's enamel sample is one of the two from 'Atele that did not yield $^{87}Sr/^{86}Sr$ ratios and so we cannot know more about her childhood residence, but her childhood diet does suggest a drastically different diet from everyone else.

There was a dietary outlier in the bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for the 'Atele burial mounds. To-At-2/33, a young adult male, displays a $\delta^{13}C_{bone}$ value 1.4‰ higher than the next highest 'Atele sample. This value places him outside 3SD from the 'Atele mean. His childhood diet is also composed of a relatively high proportion of marine foods as seen on Figure 6.13. Two other individuals cluster near To-At-2/33 with regards to childhood isotope values, To-At-1/34 and To-At-1/19. All three of these individuals with high $\delta^{13}C_{dentine}$ values have $^{87}Sr/^{86}Sr$ ratios well within the 'Atele population mean. As with the Bourewa dietary outliers, they may have spent their childhood in another location, but were from an area also affected by seaspray like

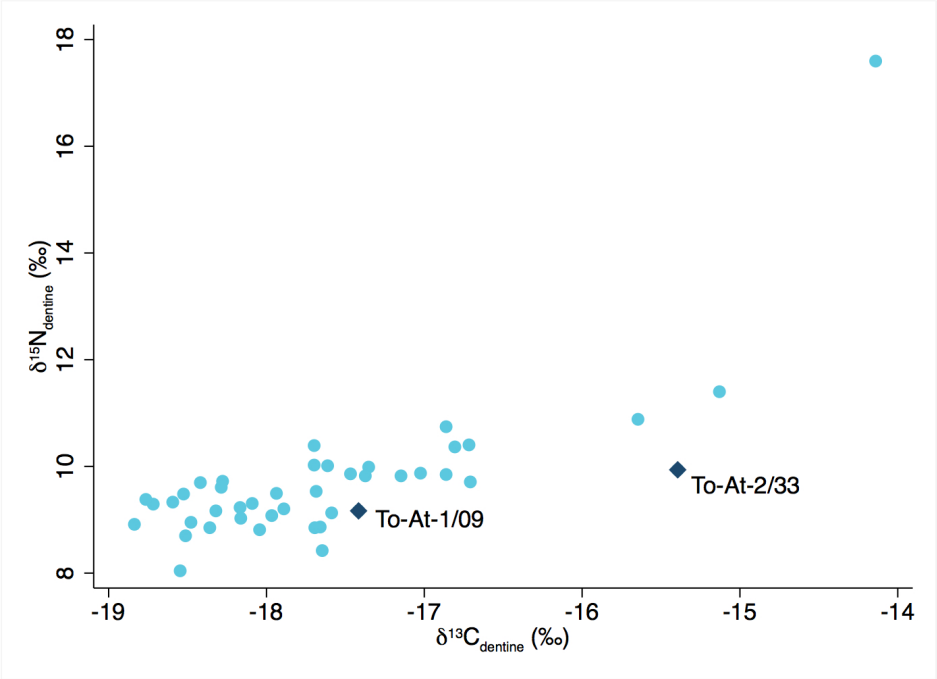


Figure 6.13. *$\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$ values of 'Atele individuals, with the $^{87}Sr/^{86}Sr$ outlier and bone dietary isotopes outlier labelled.*

Tongatapu and so are indistinguishable from locals. To-At-2/33 may also have spent many of the last few years of his life travelling outside of Tongatapu, which is why his bone collagen $\delta^{13}C$ value is so different from the rest of the assemblage. The $^{87}Sr/^{86}Sr$ ratios analysed in this study would not have captured the last few years of his life, and so mobility isotope values cannot confirm or deny this possibility.

A highly mobile lifestyle possibly like To-At-2/33 is similar to the lifestyle hypothesised for the early Maori in New Zealand (Kinaston et al., 2013c). In the Wairau Bar assemblage, many individuals in burial groups 2/3 (the later burials) displayed $^{87}Sr/^{86}Sr$ values within the local mean (as determined from $^{87}Sr/^{86}Sr$ values from prehistoric Wairau Bar dogs). However, highly varied diets as interpreted through paleodietary isotope analyses suggest that these people lived (and ate) in a variety of different locations before being buried at Wairau Bar. As evidenced at Wairau Bar, examining dietary differences are a powerful means of understanding mobility. A scenario parallel to that of Group 2/3 at Wairau Bar may have unfolded for some individuals interred in

the ‘Atele burial mounds. To-At-2/33, with his $\delta^{13}C$ values well outside the population mean, may have been born on Tongatapu, journeyed to other islands, and returned to Tongatapu a few years before his death. Unfortunately, with little material evidence in ‘Atele it is unclear who exactly would undergo these journeys and what sort of power and prestige they received when returning home to Tongatapu.

At Bourewa, individuals identified as outliers from their strontium isotope ratio could be distinguished because of the lower $^{87}Sr/^{86}Sr$ indicative of an inland location on largely volcanic rock. If an immigrant came from a similarly coastal area or small island such as Tongatapu, their $^{87}Sr/^{86}Sr$ ratios would be indistinguishable from locals. Instead, dietary isotopes provide a welcome secondary line of evidence for identifying potential immigrants. While it is conceivable that the differences in diet are due to personal food choices or other sociocultural circumstances, the $\delta^{13}C_{dentine}$ outliers in ‘Atele may be non-locals who display $^{87}Sr/^{86}Sr$ values within the ‘Atele mean. As discussed in Chapter 5, using the 2SD cutoff point is not the most ideal means of determining outliers. In the absence of a bioavailable baseline, and with seaspray potentially affecting coastal areas, the isotopic evidence of childhood diet provides another line of evidence for possibly identifying non-locals.

6.4 Summary

With the exception of the association between $\delta^{15}N_{bone}$ and AMTL, the two methods of assessing diet were not linked together. The fact that the two methods of assessing diet do not readily present a relationship using Pearson’s correlation coefficients is not reason to assume that either are being misinterpreted or presenting misleading information. The two methods present different aspects of dietary information that can be gleaned from archaeologically-derived skeletons, two “pieces of a puzzle.” For Bourewa and ‘Atele, Pearson’s correlation coefficients between oral condition frequencies and paleodietary isotopic values was found to be an ineffective means of comparing the two methods of

exploring paleodiet. Given the lack of interpretable results in previous studies using this method (Turner, 2013a,b), it appears to be a useless means of comparing the two methods in any population. I cannot offer an alternative quantitative method of comparing the two types of dietary data, and so a qualitative comparison remains the strongest.

The two assemblages each displayed different significant associations between paleodietary isotopes and $^{87}Sr/^{86}Sr$ ratios. In the Bourewa assemblage, the relationship between $\delta^{13}C_{dentine}$ values and $^{87}Sr/^{86}Sr$ ratios is likely an effect of the relationship between childhood residence (terrestrial or inland) and the relative proportion of marine foods in the childhood diet. In the 'Atele assemblage, the significant positive correlations between $\delta^{15}N_{dentine}$ and $^{87}Sr/^{86}Sr$ ratios, and $\delta^{34}S_{dentine}$ and $^{87}Sr/^{86}Sr$ ratios are possibly a result of seaspray or ocean-derived rainwater affecting isotopic values of the coastal biosphere, or individuals with largely marine-derived diets displaying isotopic values affected by this diet. In either case, the $^{87}Sr/^{86}Sr$ ratios or paleodietary isotopic values are most likely not affected so much that they must be interpreted for mobility or diet with caution.

The use of paleodietary isotopes as a means of identifying potential non-locals in these sites proved a useful secondary line of evidence. The Bourewa outlier, Burial 23, was also an outlier in terms of childhood diet. Two other individuals with low $^{87}Sr/^{86}Sr$ ratios and diets involving proportionately more terrestrial foods were also potential migrants. The $^{87}Sr/^{86}Sr$ outlier in 'Atele did not display dentine collagen values different from the rest of the population, and the individual who did (To-At-1/13) unfortunately did not have $^{87}Sr/^{86}Sr$ ratios for analysis.

Chapter 7

Conclusion: Diet, Mobility, and the Prehistoric Pacific

The past is never dead. It's not even past.

William Faulkner, *Requiem for a Nun*

This final chapter synthesises the findings presented in the core thesis chapters (Chapters 3 through 6). These findings are interpreted within the general cultural framework of the Pacific Islands outlined in Chapter 1 and the specific ecological and archaeological context for each site described in Chapter 2. Though the hypotheses were addressed in each core chapter as appropriate, the final conclusions regarding these hypotheses will be presented here.

The contents of this thesis present my endeavours to address four aims. The first aim was to understand human mobility in the archaeological sites of 'Atele and Bourewa in order to consider cultural aspects affecting migration such as marriage, political control of human mobility, and inter-island contact. The second aim was to characterise the diet of prehistoric Tongans and Fijians from these sites. The third aim builds from the first two aims. The third aim was to compare inter- and intra-populational differences between and within the two sites to gain a more nuanced understanding of the differences

between late prehistoric Tonga and Fiji and certain subgroups within these sites such as different age categories, sexes, and (within ‘Atele) burial mounds. The final aim, tied to the second aim of characterising diet, was to understand age-at-weaning and weaning food practices in prehistoric Tongan infants and young children. With only one subadult in the Bourewa assemblage, understanding infant and young child diet at this site was not feasible.

7.1 Addressing the hypotheses

These hypotheses and the implications arising from this thesis' findings have been discussed in detail within the core chapters. Here, the hypotheses will be re-stated, the findings summarised, and the final conclusions regarding accepting or rejecting these hypotheses will be highlighted.

H_1: As traditional society in Fiji and Polynesia is patrilocal, a greater proportion of non-locals will be females as determined through $^{87}Sr/^{86}Sr$ analysis

At each site, there was only one non-local as determined by $^{87}Sr/^{86}Sr$ analysis using the two standard deviations from the mean as an indicator of “local-ness” with no bioavailable strontium isotope ratio baseline available. The Bourewa outlier, Burial 23, is a middle-aged female with no evidence of disease or trauma. The ‘Atele non-local, To-At-1/09, is a young adult female with some degenerative joint disease and a few carious lesions.

The fact that To-At-1/09 is female does present an interesting trend, a useful anecdote that might complement the argument that prehistoric Tongan culture was patrilocal and inspire further research into the matter. However, the plural of “anecdote” is not “data.” With no other evidence from this research about how the different sexes moved from place to place, **it is not possible to reject *or* accept H_1** for the ‘Atele burial mounds.

However, the isotopic evidence of childhood diet in Bourewa provides strong evidence of two more non-locals. Although Burial 15 cannot be identified as a male or female due to their young age, Burial 17 is female. Two of the nine individuals of estimated sex are potential non-locals, and both are female. Although sample size is a limiting factor for interpretation in Bourewa, and two outliers are still not enough to confidently accept or reject Hypothesis 1, there is stronger evidence in Bourewa that patrilocality was a strong force affecting movement compared to ‘Atele.

H_2: The Fijians will display greater range of $^{87}Sr/^{86}Sr$ ratios due to Viti Levu's larger island size and greater geological diversity compared to Tongatapu

The Bourewa assemblage do in fact present a greater range of $^{87}Sr/^{86}Sr$ ratios than the ‘Atele assemblage. Viti Levu displays greater geological diversity than Tongatapu, and the volcanic rock formations in part of Viti Levu (with much lower $^{87}Sr/^{86}Sr$ ratios than the coralline limestone of Tongatapu) are probably the reason for the lower values in the Bourewa assemblage. Viti Levu's larger size may also contribute to the lower $^{87}Sr/^{86}Sr$ ratios in the assemblage, allowing humans to live away from the coast and consume foods unaffected by seaspray.

H_2 fails to be rejected.

H_3: Non-locals from each assemblage will display different childhood diets from locals as indicated through isotope analysis and oral indicators of diet

With so few non-locals, it was impossible to compare their prevalence of oral conditions to the locals' prevalence using meaningful inferential statistics. Using isotope analyses, the non-local in Bourewa displays a more terrestrial childhood diet than most within the assemblage (Figure 7.1). As discussed previously, those with even lower $\delta^{13}C_{dentine}$ values within the Bourewa population also display low $^{87}Sr/^{86}Sr$ ratios and are potential non-locals. **Hypothesis 3 is supported for the Bourewa assemblage.**

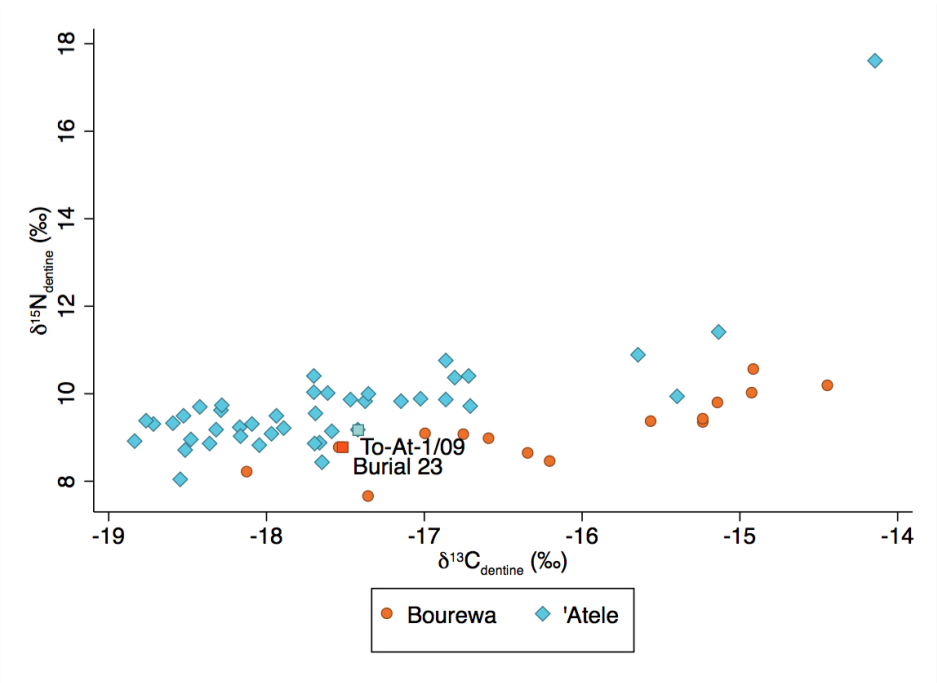


Figure 7.1. *$\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$ values of Bourewa and 'Atele individuals. The non-locals as determined by $^{87}Sr/^{86}Sr$ analysis are labeled.*

The Tongan non-local, however, displays a childhood diet firmly within the assemblage mean. **H_3 is rejected for the 'Atele assemblage.**

This is the first of the hypotheses to require lines of evidence from multiple core chapters. H_3 is a deceptively difficult hypothesis to prove or disprove. On the surface, it appears easy to approach: first, examine the scatter plot of $\delta^{13}C_{dentine}$ and $\delta^{15}N_{dentine}$ and determine if the $^{87}Sr/^{86}Sr$ outliers (Burial 23 from Bourewa and To-At-1/09 from 'Atele) are also dietary outliers. Unfortunately, there are limitations in this approach. Scenarios in which migration and non-local diet might not be detectable by isotope analysis must be considered. The dentine collagen analysed in this study captures childhood diet from a time period roughly between five and ten years of age (Hillson, 1996). If a young child moved to a new place of residence before this age period then their childhood diet would be indistinguishable from locals' diet, even if their $^{87}Sr/^{86}Sr$ values suggest immigration. This is especially plausible if the enamel for $^{87}Sr/^{86}Sr$ analysis were sampled from teeth that formed earlier than five years of age (such as the

first molar sampled in some ‘Atele and Bourewa individuals, or the canine sampled in one Bourewa individual). Of course, it may simply be that To-At-1/09 comes from a childhood residence where the diet was similar to the ‘Atele community.

H_4: The two methods of assessing diet (isotope analysis and oral indicators) will agree

Qualitatively, the two methods of assessing diet did not always agree and the two methods never agreed using the quantitative assessment first used by Turner (2013a). **Both quantitative and qualitative methods of assessing agreement reject Hypothesis 4.** As discussed in Chapter 6, this is not necessarily unexpected and does not leave either of these paleodietary methods inappropriate as tools for understanding prehistoric diet. Instead, each method explores subtly different aspects of diet: the proportions of dietary protein in the case of isotopic values from collagen, and the physical and chemical qualities of food for oral conditions. Environmental factors beyond diet, as well as genetics, must also be considered when interpreting oral condition frequencies especially in regards to carious lesions. Thus far, neither the original studies to use Pearson’s correlation coefficients between oral condition frequencies and isotopic values Turner (2013a,b) nor this thesis have yielded interpretable relationships between oral condition data and isotopic values. While quantitatively comparing the two types of data could have had merit for understanding paleodiet, correlations do not appear to necessarily contribute useful information about diet. Qualitative assessments seem to provide more applicable interpretations than quantitative, especially in an area with isotopically complex food webs such as the tropical Pacific and when the quantitative measures examine $\delta^{13}C$ or $\delta^{15}N$ values singly rather than together.

H_5: Due to the larger island size of Viti Levu, the Bourewa individuals will have a larger terrestrial component in their diet compared to the 'Atele individuals as evidenced by isotope analysis and oral indicators of diet

The significantly higher $\delta^{13}C$ values in the Bourewa assemblage suggests a relatively more marine component in their diet compared to the 'Atele individuals. When collapsing oral conditions to presence/absence variables and including age in the logistic regression model as a means of excluding it as a potential factor, there were no differences between the two sites regarding oral conditions. However, when employing ordered logistic regression to examine patterns of severity of oral conditions, Bourewa individuals displayed decreased odds of severe caries and severe periodontitis and increased odds of more severe occlusal wear. As discussed in Chapter 4, increased wear and decreased odds of caries have been associated with diets containing more marine and freshwater foods, and the periodontal disease may be a result of more severe wear and carious lesions (Littleton and Frohlich, 1993).

Both lines of paleodietary reconstruction agree: **Hypothesis five is rejected**. Despite Viti Levu's larger size, individuals from Bourewa relied more heavily on marine foods rather than terrestrial foods. Environmental restrictions (whether due to climatic fluctuations or long-standing landscape restrictions such as poor soil) may have prevented the Bourewa community from pursuing a heavy reliance on horticulture, and/or the large fringing reef and lagoon on the coast of the Rove Peninsula may have been productive enough that only small gardens kept as supplementary foods were necessary to support the needs of the settlement.

H_6: With no previous studies finding differences between the two burial mounds at 'Atele, there will be no differences regarding diet or movement discerned in this study

There were significant dietary differences between adults in the two burial mounds at 'Atele as evidenced by isotope analyses and oral indicators of diet. While there were no differences between the burial mounds regarding $\delta^{34}S_{bone}$ or $\delta^{15}N_{bone}$, To-At-1 individuals displayed higher $\delta^{13}C_{bone}$ values than those excavated from To-At-2. The $\delta^{13}C_{bone}$ value differences were small (about 1‰), but significant. The potential issues surrounding $\delta^{34}S$ analysis in the Pacific were addressed in Chapter 3, and the lack of trophic level difference as inferred by the similar $\delta^{15}N_{bone}$ values could be a result of terrestrial C_3 plants and shellfish occupying roughly the same $\delta^{15}N$ range. To-At-1 individuals have increased odds of caries severity and more severe wear. To-At-2 individuals are significantly more likely to display chipped teeth than To-At-1 individuals.

The more positive $\delta^{13}C_{bone}$ values, increased caries severity, and decreased odds of chipped teeth in To-At-1 individuals all suggest a greater reliance on horticultural crops. As mentioned previously, the more severe occlusal wear is against expectations as increased wear is suggestive of diets more reliant on marine foods.

There were no differences in diet between To-At-1 and To-At-2 regarding dentine collagen from adults or bone collagen from subadults (though there *were* differences between adult dentine collagen and subadult bone collagen, as discussed for Hypothesis 8). While those interred in the two mounds consumed different diets in adulthood, the childhood diet of To-At-1 and To-At-2 individuals were not significantly different. The underlying cause of dietary differences between mounds, whether temporal in nature or due to social control concerning resource redistribution, affected adult diet but not childhood diet. **Hypothesis 6 is rejected regarding differences in diet.**

Regarding differences in mobility between the mounds, there was only one outlier in the entire assemblage. Beyond this outlier, all individuals displayed similar $^{87}Sr/^{86}Sr$

values. Using isotopic evidence of childhood diet as a way of identifying non-locals also presents no real trend between burial mounds regarding mobility. Thus, **Hypothesis 6 cannot be accepted or rejected regarding movement**.

H_7: Adults will consume more animal protein than subadults (i.e. be on a higher trophic level)

With only one subadult in the Bourewa assemblage, this hypothesis could not be tested in that population. When comparing the bone collagen isotopic values of 'Atele adults and subadults (infants and young children excluded to prevent interference from weaning signals), there were no differences regarding $\delta^{13}C$ or $\delta^{34}S$ values. There were significant differences in $\delta^{15}N_{bone}$ value, with adult $\delta^{15}N_{bone}$values 0.6‰ higher on average. **Hypothesis 7 is supported.**

The reason why 'Atele adults are consuming a higher proportion of animal protein is unclear. Children may have been snacking on non-animal protein between communal meals, eating nuts and tree fruits. Then again, ethnographic accounts record modern Pacific children commonly snacking on lagoon and reef shellfish, which would likely raise $\delta^{15}N$ values (Pollock, 1992; Jones, 2009). This discrepancy may have been associated with inconclusive ethnographic accounts. Children also tend to be more conservative about food preferences than adults (Beauchamp and Mennella, 2011), although these aversions tend to be erased with enculturation (Benton, 2004; Curtis et al., 2011). Another scenario is the portioning of more socially valued flesh foods (Kirch and O'Day, 2003) to older individuals as a means of recognising social status in Tonga (Kaeppler, 1971; Bott, 1981). Ultimately, these differences are between those who survived childhood and those who did not and there may be different environmental factors affecting these two groups. These differences in diet may have also had a serious effect on the subadults health and survival.

H_8: The childhood diet of adults, as inferred through isotope analysis of dentine collagen, will be on a lower trophic level compared to adults within the last few years of their lives as inferred through bone collagen

As with hypothesis 7, it was postulated that subadults diets would be different from adult diets. The purpose of hypothesis 8, however, was to examine the childhood diet of those who survived to adulthood rather than those who died as subadults. This allows the comparison of the survivor's childhood diet to their adult diet within the last few years of their lives. Also unlike hypothesis 7, hypothesis 8 could be tested within both assemblages.

In Bourewa, there were significant differences between bone and dentine $\delta^{13}C$ values: dentine displayed $\delta^{13}C$ values 1.1‰ lower on average. Mean dentine $\delta^{15}N$ values were 0.5‰ higher than bone collagen in the Bourewa assemblage, to a significant degree. Instead of being on a lower trophic level as hypothesised, Bourewa adults appear to have consumed more animal protein during childhood than within the last few years of their lives. The lower $\delta^{13}C$ values suggest a more terrestrial diet during childhood in Bourewa individuals, as well. As mentioned in regards to H_7, children snacking on terrestrial fruits and nuts in between meal times is a plausible scenario if Bourewa adult diets consisted of more marine foods on the same trophic level as terrestrial plants. In the 'Atele assemblage, there were no significant differences between bone and dentine carbon values, but mean $\delta^{15}N_{dentine}$ values were higher than mean $\delta^{15}N_{bone}$ values. The consumption of proportionately more animal protein during childhood, or childhood stress causing an increase in $\delta^{15}N$ values are both possible causes. **Within both sites, hypothesis 8 is rejected.**

H_9: The childhood diet of adults, as inferred through isotope analysis of tooth collagen, will be on a higher trophic level compared to the childhood diet of subadults as inferred through the analysis of bone collagen. In other words, the survivors of childhood (adults) will have consumed more animal protein than non-survivors (subadults)

As with hypothesis 7, hypothesis 9 could only be tested in the 'Atele assemblage due to the paucity of subadult remains in the Bourewa assemblage. In the 'Atele assemblage, there were no differences between adult dentine and subadult bone regarding $\delta^{13}C$ or $\delta^{34}S$ values. There were significant differences between adult $\delta^{15}N_{dentine}$ and subadult $\delta^{15}N_{bone}$ in the 'Atele assemblage, with adult $\delta^{15}N_{dentine}$ displaying a mean 0.6‰ higher than subadult $\delta^{15}N_{bone}$.

There are difficulties with comparing bone collagen and dentine collagen. The time periods captured within dentine collagen from adults and the bone of subadults may be radically different. While the dentine collagen captures a rough time period between five and ten years of age, bone collagen represents the last few years of life (Hedges et al., 2007). Metabolic turnover is much faster in subadults than adults (Smith and Rennie, 2007; Hedges et al., 2007), but the exact rates are not known. Age-specific rates of bone collagen turnover are necessary to understand the time span captured by isotope analysis of human remains. Without that knowledge and without a large enough assemblage to sample only subadults within a five-year time span roughly matching the adult dentine collagen, comparing all subadults who are probably completely weaned was the best way to compare the childhood diet of survivors and non-survivors.

Regardless of the difficulties surrounding comparing survivors and non-survivors, the results imply that **hypothesis 9 is supported**. The 0.6‰ difference in $\delta^{15}N$, while not an entire trophic level, could imply a greater proportion of animal protein consumed in the childhood diet of those who survived into adulthood. This small difference in diet may have been a detriment to nutrition, increasing the risk of poor health, infection,

and death in those who did not survive childhood. The high prevalence of skeletal pathology in the ‘Atele subadults (Buckley, 2000, 2001) corroborates with this finding, though, as Lewis (2007) points out, there are many ways in which a child might die that are not necessarily influenced by culture (accidents, for example).

There is an alternative possibility for the δ^{15}N differences: those who survived adulthood might not have consumed more animal protein, but instead are showing isotopic evidence of physiological stress (Ambrose, 1993; Hobson et al., 1993; Hatch, 2012; Reitsema, 2013). Evidence of stress may indicate a successful response to the environment (Temple and Goodman, 2014), while the lower δ^{15}N levels of the non-survivors implies a lesser ability to adapt (and survive). Adults may have been subject to the same disease/stress the subadults in ‘Atele displayed evidence of, but re-modelled any evidence of childhood disease. This alternative possibility is contingent on the entire population being subjected to biological stresses strong enough to cause a change in their δ^{15}N values, which seems unlikely. Future investigations tying together isotope analyses and non-specific stress indicators (e.g. linear enamel hypoplasia) might determine whether the δ^{15}N differences are due to nutrition or successful stress responses.

H_{10}: Using isotope analysis and oral indicators of diet, males and females will display similar diets due to the practice of communal meals in these islands as evidenced in ethnographic studies

Hypothesis 10 fails to be rejected in the Bourewa assemblage. Other than increased odds of chipping in males, there were no differences in diet as indicated by isotope analyses or oral conditions.

Within ‘Atele, there were no differences in odds of presenting oral conditions when the oral conditions were collapsed to a present/absent variable. When comparing severity of conditions (and accounting for differences between age categories), ‘Atele females had increased odds of caries severity and males had increased periodontal

disease severity. Regarding isotope analyses, ‘Atele males displayed significantly higher $\delta^{15}N_{bone}$ values on average compared to females, 0.5‰ higher on average. Despite the common practice of communal meal-sharing in Tonga (Pollock, 1992), **Hypothesis 10 is rejected for the ‘Atele assemblage.**

These findings imply that, in Bourewa, there were no sex-based dietary differences (at least, not in ways detectable using this study’s methods). Climatic changes that affected Fiji more than Tonga may have created dietary and nutritional pressures that lifted sex-based structural inequalities affecting food access, if these were present in the first place. Sex-based dietary differences in ‘Atele fit within the cultural attitudes about power, rank, and deference within Tongan communities (Kaeppler, 1971; Bott, 1981).

H_{11}: The age of complete weaning for Tongans, as interpreted through trophic level shifts in isotope analysis, will occur within the natural weaning age between 2.5 and 6.0 years

No subadults after two years of age display the elevated $\delta^{15}N$ values expected from breastfeeding. With consideration for collagen turnover, this suggests that infants were generally no longer exclusively breastfed a few months before the age of two years. This implies that the general Tongan age of weaning occurred before the “natural” weaning age proposed by Dettwyler (1995b) and **Hypothesis 11 is rejected**. Instead, the weaning time is close to the weaning age observed ethnohistoric accounts of Polynesian breastfeeding practices of around two years of age (Handy and Pukui, 1952; Gill, 1979; Jansen, 1982).

Consideration must be given that these infants who did not survive infancy may have experienced different breastfeeding experiences to those who did survive. Unfortunately, this is the only means of examining weaning age in this study. This early weaning period is viably a major contributor to infant health and the high rate of infant mortality and disease in the ‘Atele assemblage (Buckley, 2000, 2001) as this difficult period in

childhood life history greatly affects pathogen resistance, nutritional status, and other health factors (Katzenberg et al., 1996; Lewis, 2007; WHO, 2009).

The relatively short period of breastfeeding might also imply increased fertility in the population. High fertility rates during the Chiefdom Period are likely given the archaeological and ethnohistoric accounts of peak population density on the archipelago (Kirch, 1984a; Burley, 1998), and the relatively high child morbidity and mortality compared to other Polynesian populations (Buckley, 2000, 2001) might be a result of increased disease burdens due to higher population density. High infant mortality and morbidity due to early weaning and increased overall fertility are not exclusive.

7.2 Findings ancillary to the main aims and objectives

In almost any research, there will be a few follow-on research opportunities worth pursuing even if they do not contribute to the original aims. In this thesis, there were three main routes of exploration ancillary to the main aims and objectives.

First, sexes, adult age groups, and the ‘Atele burial mounds were compared to determine if there were any differences in childhood diet between certain cohorts. No hypotheses were forwarded regarding the childhood diet of these subgroups, though understanding potential differences in childhood diet between these groups is in line with this thesis’ third aim. There were no differences in childhood diet between males and females in either assemblage. This finding is in agreement with the lack of sex-based dietary differences in Bourewa adults. In ‘Atele, there were no differences in childhood diet between males and females, though there were differences in adult diet. Similarly, though To-At-1 individuals have higher $\delta^{13}C_{bone}$ values on average, there is a lack of differences in childhood diet between the mounds. It is plausible that the cultural pressures affecting adults did not affect children’s food choices in the same manner.

Second, the potential relationship between paleodietary isotope values and $^{87}Sr/^{86}Sr$ ratios were explored. There were significant, positive associations between paleodietary

isotope values and $^{87}Sr/^{86}Sr$ ratios in each of the assemblages, although the associations were different within each site. In the Bourewa assemblage, there was a strong relationship between $\delta^{13}C_{dentine}$ values and $^{87}Sr/^{86}Sr$ ratios, conceivably an effect of the relationship between childhood residence (terrestrial or inland) and the relative proportion of marine foods or foods affected by seaspray in the childhood diet. In the ʻAtele assemblage, the significant correlations between $\delta^{15}N_{dentine}$ and $^{87}Sr/^{86}Sr$ ratios, and $\delta^{34}S_{dentine}$ and $^{87}Sr/^{86}Sr$ ratios were potentially due to seaspray or ocean-derived rainwater affecting the coastal biosphere's isotopic values, or individuals with largely marine-derived diets displaying isotopic values affected by this diet.

The third avenue of ancillary research was borne out of an unexpected opportunity to participate in the excavation of a burial cave on the Cook Islands. Although human remains could not be sampled for destructive analyses due to the community's wishes, I was able to collect modern plants and animals in order to create a dietary baseline. This dietary baseline was compared to the existing collection of tropical Pacific flora and fauna (Kinaston et al., 2014b) in Chapter 3, and found to be similar. The isotopic values of modern plants and animals from the Cook Islands increases the existing dietary baseline for the region.

7.3 Limitations

In the introduction, I described limitations inherent to any bioarchaeological research. These limitations were broadly classified as "controllable" and "uncontrollable." Factors affecting this thesis that could have been controlled include differences in excavation techniques and limitations in project sizes as were discussed briefly in Chapter 2. Though Nunn's repatriation of some of the Bourewa individuals and Davidson's incomplete excavation of human remains at the ʻAtele mounds were both acceptable archaeological practices, they were also limiting factors in examining individual diet and movement. An uncontrollable limitation was the synchronic nature of these sites, preventing the

examination of changes in diet and mobility through time (though it did allow the comparison two contemporaneous sites separated spatially). This especially limited interpreting climate change as a factor affecting diet in Bourewa: without a means of comparing what the community ate previous to the Vuda phase, it is impossible to determine the full effect ENSOs had on subsistence. The discussions in the ends of Chapters three through six addressed several analytical and interpretive limitations specific to the methods used in this thesis. These chapters' discussions included the unquantifiable effect of physiological stress on $\delta^{15}N$ values, potentially homogeneous $^{87}Sr/^{86}Sr$ ratios in coastal and small island environments, and the non-dietary causes behind oral conditions and $\delta^{34}S$ values, among others.

7.4 Avenues of further investigation

There are a few avenues of future research using the assemblages examined in this thesis. As suggested by Shaw et al. (2009) and others, the use of other paleomobility isotopes beyond $^{87}Sr/^{86}Sr$ analysis appears necessary to discern non-locals whose $^{87}Sr/^{86}Sr$ ratios are affected by seawater. Lead isotope analysis, along with trace element analyses, could aid in differentiating between locals and non-locals in an environment affected by sea-spray. The collection of bioavailable lead and strontium isotope values would also be valuable for refining paleomobility studies in Tonga and Fiji.

Regarding paleodietary isotope analyses, the addition of $\delta^{13}C$ analysis of apatite from tooth enamel would yield information about the whole diet of childhood (Balasse et al., 2003; Passey et al., 2005). Rarely conducted in the tropical Pacific, including $\delta^{13}C_{apatite}$ analysis to the Pacific bioarchaeologist's standard toolkit could yield further insight into the non-protein portion of diet. This is especially important when trying to understand a diet largely reliant on high-carbohydrate/low-protein root vegetables.

Tying together diet and childhood nutrition using paleodietary isotope analyses and evidence of stress (e.g. linear enamel hypoplasia) is another intriguing future

investigation. The two analyses have been combined in paleoecological studies (Franz-Odendaal et al., 2003; Frémondeau, 2012) in order to understand how seasonal climatic conditions affected diet and nutrition. Comparing the diet of those who display responses to stress in early life to those without evidence of stress may allow the inference of nutrition (and malnutrition) from paleodietary isotope analyses.

A final potential approach regarding isotope analyses in ‘Atele and Bourewa would be serial sectioning of teeth. Thin (1 mm) incremental sections of dentine capture smaller age ranges (Zazzo et al., 2006; Britton et al., 2011), and examining isotopic values of each tooth section creates a longitudinal diet history in an individual. Compared to the cross-sectional bulk sampling conducted in this study, serial sectioning does not yield as much information about the population as a whole. Instead, serial sections provide detailed longitudinal data about weaning and childhood diet in those who survived childhood. Tooth formation is much more immune to environmental factors and more tightly controlled by genetics than bone development (White and Folkens, 2005; Cardoso, 2007), and intra-tooth isotope analyses are creating higher resolution data as the technique improves (Sandberg et al., 2014; Beaumont et al., 2014). Re-creating the periods of weaning and complete weaning in individuals who survived childhood could be undertaken using isotope analyses of serial sections of dentine. This is the only means of understanding infant and young child feeding practices in Bourewa, and would offer a chance of comparing weaning experiences between survivors and non-survivors of childhood in ‘Atele.

The macroscropic oral conditions that are commonly used in bioarchaeology for understanding diet were recorded in this thesis. However, examining microwear on tooth enamel using powerful microscopes could contribute to understanding the physical properties of the foods eaten within an individual’s last few weeks of life (Ungar et al., 2008; Patnaik et al., 2014). Collecting and analysing microwear data for ‘Atele and Bourewa would allow the comparison of three different means of understanding diet in

skeletal remains: isotope analyses, macroscropic oral conditions, and microwear.

7.5 Final thoughts

This thesis examined multiple aspects of past life on Tonga and Fiji, using isotope analyses and oral conditions to focus on diet and mobility. At first blush, it may appear that this is a broad set of questions to approach within a thesis, and the research would have been better designed with a single subject in sharp focus: only Tonga or Fiji, only diet or mobility.

However, the processes of diet and movement are intertwined in Remote Oceania. Securing food resources can pull people to new lands or push them out of resource-depleted areas. Whenever humans move there are underlying cultural and environmental causes– and consequences. The same forces of social control that could affect resource redistribution could also affect who moved, and where. Collectively, the examination of both diet and mobility contributed to the larger picture of understanding prehistoric life on two Pacific islands.

In Kirch and Green's seminal work on ancestral Polynesian culture (Kirch and Green, 2001), they endeavoured to "triangulate" the core of Polynesian cultures using ethnography, linguistics, and archaeology. Their work in recreating *Hawaiki*, ancestral Polynesia, demonstrated the value of "a holistic and historically grounded anthropology for whom there is no – or only limited – written documentation of their past." (Kirch and Green, 2001, p. 277). This thesis attempted to achieve a similar goal, using multiple bioarchaeological techniques to understand diet and mobility of the people interred in Bourewa and the 'Atele burial mounds. These findings were placed within the wider context of the prehistoric tropical Pacific, and illustrated the challenges and benefits of a biocultural approach to understanding how people lived in the past.

Appendices

Appendix A

General Paleodemographic Data

Table A.1. *Age and sex of Bourewa individuals.*

Burial number	**Age category**	**Estimated age (years)**	**Sex**
03	Young adult	18	Indeterminate
04	Indeterminate adult		Indeterminate
06	Indeterminate adult		Female
09	Middle adult		Male
10	Old adult		Female
13	Indeterminate adult		Indeterminate
14	Old adult		Male
15	Adolescent	13	
16	Indeterminate adult		Female
17	Indeterminate adult		Female
18	Indeterminate		Indeterminate
19	Old adult		Female

Continued on next page

Table A.1 – continued from previous page

Burial number	Age category	Estimated age (years)	Sex
20	Indeterminate adult		Female
21	Indeterminate adult		Female
21(a)	Old adult		Female
22	Young adult		Male
23	Middle adult		Female
24	Old adult		Indeterminate
25	Indeterminate adult		Male
26	Indeterminate adult		Indeterminate
27	Indeterminate		Indeterminate
28	Indeterminate adult		Indeterminate
29	Indeterminate adult		Indeterminate
30	Indeterminate adult		Indeterminate
31	Indeterminate adult		Indeterminate
33	Indeterminate		Indeterminate
34	Indeterminate		Indeterminate
C9X	Indeterminate adult		Indeterminate

Table A.2. *Age and sex of 'Atele individuals.*

Burial number	Age category	Estimated age (years)	Sex
To-At-1/01a	Young Child	1.5	
To-At-1/01b	Infant	0.75	
To-At-1/03	Infant	1	

Continued on next page

Table A.2 – continued from previous page

Burial number	**Age category**	**Estimated age (years)**	**Sex**
To-At-1/04a	Indeterminate adult		Female
To-At-1/04c	Child	4.5	
To-At-1/05	Infant	0.25	
To-At-1/06	Middle adult		Male
To-At-1/07	Middle adult		Male
To-At-1/08	Infant	0.25	
To-At-1/09	Young adult		Female
To-At-1/10	Indeterminate adult		Indeterminate
To-At-1/10a	Child	8	Indeterminate
To-At-1/11	Young adult		Female
To-At-1/12	Middle adult		Female
To-At-1/13	Young adult		Female
To-At-1/13?	Indeterminate adult		Indeterminate
To-At-1/13c	Indeterminate		
To-At-1/13o	Indeterminate adult		Indeterminate
To-At-1/14	Adolescent	13.5	
To-At-1/15	Young Child	1.5	
To-At-1/16	Infant	0	
To-At-1/17	Infant	1	
To-At-1/18	Young Child	2	
To-At-1/19	Young adult		Female
To-At-1/20	Young adult		Male
To-At-1/20a	Indeterminate adult		Indeterminate

Continued on next page

Table A.2 – continued from previous page

Burial number	**Age category**	**Estimated age (years)**	**Sex**
To-At-1/21a(1)	Indeterminate adult		Female
To-At-1/21a(2)	Indeterminate adult		Female
To-At-1/21b	Indeterminate adult		Female
To-At-1/22	Adolescent	16	
To-At-1/23	Young adult		Female
To-At-1/25	Young Child	2	
To-At-1/26	Young adult		Female
To-At-1/26b	Indeterminate adult		Indeterminate
To-At-1/27	Indeterminate adult		Male
To-At-1/29a	Middle adult		Male
To-At-1/29b	Young Child	2	
To-At-1/29c	Infant	0.5	
To-At-1/30	Child	11	
To-At-1/31	Middle adult		Male
To-At-1/32	Infant	0.75	
To-At-1/34	Young adult		Male
To-At-1/35	Infant	1	
To-At-1/36	Young Child	2	
To-At-1/37	Child	4	
To-At-1/4b	Indeterminate		
To-At-2/01a	Young Child	2.5	
To-At-2/01v	Old adult		Female
To-At-2/01d	Young Child		

Continued on next page

Table A.2 – continued from previous page

Burial number	**Age category**	**Estimated age (years)**	**Sex**
To-At-2/01e	Indeterminate adult		Indeterminate
To-At-2/01e(2)	Young adult		Female
To-At-2/02	Infant	0	
To-At-2/03	Child	7	
To-At-2/04	Middle adult		Male
To-At-2/05	Indeterminate adult		Indeterminate
To-At-2/06	Middle adult		Male
To-At-2/07	Infant	1	
To-At-2/08	Indeterminate adult		Male
To-At-2/09	Child	10	
To-At-2/10	Indeterminate adult		Indeterminate
To-At-2/11	Young adult		Female
To-At-2/13	Old adult		Male
To-At-2/13a	Middle adult		Male
To-At-2/13b	Old adult		Female
To-At-2/14	Infant	0.25	
To-At-2/15	Indeterminate adult		Indeterminate
To-At-2/16	Indeterminate adult		Female
To-At-2/17	Infant	1	
To-At-2/18	Old adult		Male
To-At-2/19	Adolescent	16	
To-At-2/1b	Child		
To-At-2/1e(3)	Child	3	

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Table A.2 – continued from previous page

Burial number	**Age category**	**Estimated age (years)**	**Sex**
To-At-2/1e(4)	Adolescent	15	
To-At-2/20a	Indeterminate adult		Female
To-At-2/20b	Indeterminate		
To-At-2/20c	Indeterminate		
To-At-2/21	Young adult		Female
To-At-2/24a	Young adult		Female
To-At-2/24b	Old adult		Female
To-At-2/25	Old adult		Female
To-At-2/27	Young adult		Female
To-At-2/27a	Middle adult		Male
To-At-2/27b	Indeterminate adult		Indeterminate
To-At-2/28	Indeterminate adult		Indeterminate
To-At-2/30	Indeterminate adult		Female
To-At-2/31	Young adult		Male
To-At-2/32	Indeterminate adult		Female
To-At-2/33	Young adult		Male
To-At-2/34	Indeterminate adult		Male
To-At-2/35	Indeterminate adult		Indeterminate
To-At-2/36	Young Child	2	
To-At-2/37	Indeterminate adult		Indeterminate
To-At-2/38	Indeterminate adult		Indeterminate
To-At-2/39	Adolescent	15	
To-At-2/40a	Middle adult		Female

Continued on next page

Table A.2 – continued from previous page

Burial number	**Age category**	**Estimated age (years)**	**Sex**
To-At-2/40b	Middle adult		Female
To-At-2/41a	Old adult		Male
To-At-2/41b	Adolescent	15	
To-At-2/42	Young adult		Female
To-At-2/M	Child	8	
Unnumbered 01	Indeterminate		Indeterminate
Unlabelled 02	Indeterminate		Indeterminate
Unlabelled 03	Indeterminate		Indeterminate
Unlabelled 04	Indeterminate		Indeterminate
Unlabelled 05	Indeterminate		Indeterminate
Unlabelled 06	Indeterminate		Indeterminate
Unlabelled 07	Indeterminate		Indeterminate
Unlabelled 08	Indeterminate		Indeterminate
Unlabelled 09	Indeterminate		Indeterminate
Unlabelled 10	Indeterminate		Indeterminate
Unlabelled 11	Indeterminate		Indeterminate
Unlabelled 12	Indeterminate		Indeterminate
Unlabelled 13	Indeterminate		Indeterminate
Unlabelled 14	Indeterminate		Indeterminate
Unlabelled 15	Indeterminate		Indeterminate
Unlabelled 16	Indeterminate		Indeterminate
Unlabelled 17	Indeterminate		Indeterminate
Unlabelled 18	Indeterminate		Indeterminate

Continued on next page

Table A.2 – continued from previous page

Burial number	**Age category**	**Estimated age (years)**	**Sex**
Unlabelled 41	Indeterminate		Indeterminate
Unlabelled 89.4	Indeterminate		Indeterminate
Unlabelled 89(5)	Indeterminate		Indeterminate
Unlabelled 89a	Indeterminate		Indeterminate
Unlabelled 89b	Indeterminate		Indeterminate
Unlabelled 89c	Indeterminate		Indeterminate
Unlabelled 91	Indeterminate		Indeterminate
Unlabelled 92	Indeterminate		Indeterminate

Appendix B

Human Isotope Data

B.1 Stable isotope data

All $\delta^{13}C$ and $\delta^{15}N$ values averaged from duplicate analyses unless denoted with * next to burial number. For the 'Atele samples, † next to $\delta^{34}S$ values denote that one of the duplicate analyses yielded insufficient sample weight or had collagen quality issues and so only one sample was available. Collagen integrity results in red are outside acceptable parameters and these stable isotope values were not included in analyses.

Table B.1. *Carbon and nitrogen stable isotope bone collagen data for Bourewa individuals.*

Burial number	Bone	$\delta^{13}C$	$\delta^{15}N$	%C	%N	C:N
03*	Long bone	-15.1	8.5	46.4	16.4	3.3
04*	Long bone	-16.5	6.8	44.6	15.1	3.5
06*	Long bone	-15.2	8.8	46.5	15.7	3.5
09	Long bone	-15.6	8.0	42.9	15.5	3.2
10*	Long bone	-15.2	8.3	47.0	16.5	3.3
13	Long bone	-15.7	8.0	44.0	14.9	3.5

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Table B.1 – continued from previous page

Burial number	**Bone**	**$\delta^{13}C$**	**$\delta^{15}N$**	**%C**	**%N**	**C:N**
14	Long bone	-13.6	9.7	46.6	16.2	3.4
15*	Long bone	-17.2	7.0	46.0	15.7	3.4
17	Long bone	-17.7	7.8	43.5	13.1	3.9
18*	Vertebra	-15.5	9.2	47.0	15.9	3.5
19	Long bone	-15.3	8.3	48.0	16.2	3.5
20*	Long bone	-15.4	8.9	46.8	15.5	3.5
21*	Long bone	-14.9	8.7	46.6	16.1	3.4
22*	Long bone	-14.7	8.7	46.7	16.3	3.3
23*	Long bone	-15.9	8.4	46.2	16.6	3.2
24*	Long bone	-14.3	9.8	47.0	15.9	3.5
25*	Long bone	-13.9	9.7	46.8	15.3	3.6
26*	Long bone	-15.0	8.6	44.9	16.3	3.2
27*	Long bone	-15.6	7.8	42.6	15.5	3.2
28*	Long bone	-15.1	9.0	45.7	15.7	3.4
29*	Long bone	-14.6	8.3	47.0	16.9	3.3
33	Long bone	-13.1	9.9	45.9	15.3	3.5
34	Skull fragment	-13.9	9.1	45.5	15.1	3.5

Table B.2. *Carbon, nitrogen, and sulphur stable isotope bone collagen data for the 'Atele burial mound individuals.*

Burial number	Bone	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	%C	%N	%S	C:N	C:S	N:S
To-At-1/01a	rib	-18.4	10.3		41.4	15.1		3.2		
To-At-1/01b	vertebra	-18.6	12.1		43.2	15.5		3.2		

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Table B.2 – continued from previous page

Burial number	Bone	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	%C	%N	%S	C:N	C:S	N:S
To-At-1/04b	long bone	-18.1	8.8		41.9	14.7		3.3		
To-At-1/04c	long bone	-18.1	8.1	†16.5	41.3	14.6	0.24	3.3	459	139
To-At-1/05	vertebra	-17.0	9.5		42.1	15.2		3.2		
To-At-1/06	humerus	-17.6	9.9	14.5	39.8	14.9	0.24	3.1	447	144
To-At-1/07	tibia	-18.2	8.4	†13.2	37.9	13.9	0.25	3.2	410	129
To-At-1/09	scapula	-17.8	8.8	†13.3	39.8	14.3	0.26	3.3	408	126
To-At-1/10	long bone	-18.2	8.9		41.4	14.6		3.3		
To-At-1/10a*	humerus	-17.1	9.2	†15.0	40.8	14.8	0.26	3.2	416	129
To-At-1/11	rib	-17.9	8.7	†15.5	39.3	14.2	0.26	3.2	409	127
To-At-1/12	long bone	-18.0	9.6	†17.2	37.6	13.6	0.25	3.2	396	122
To-At-1/13	long bone	-17.6	8.1	13.2	42.2	15.3	0.23	3.2	488	152
To-At-1/13c	long bone	-17.8	9.3	†11.8	41.6	15.1	0.25	3.2	445	138
To-At-1/14	long bone	-18.2	8.3	13.1	43.1	15.7	0.22	3.2	532	166
To-At-1/15	rib	-17.8	12.0	†18.0	43.2	15.7	0.25	3.2	465	145
To-At-1/16	rib	-18.4	9.2		40.2	†14.8		3.2		
To-At-1/17	long bone	-16.8	11.5		41.3	15.5		3.1		
To-At-1/18	long bone	-17.9	9.6	†16.0	40.8	14.8	0.25	3.2	439	137
To-At-1/19	long bone	-16.7	9.3	†13.1	43.4	15.9	0.21	3.2	558	175
To-At-1/20	humerus	-17.1	9.5	†16.0	37.4	13.8	0.24	3.2	414	131
To-At-1/21a(1)	long bone	-17.0	9.7	†15.5	37.3	13.6	0.26	3.2	378	118
To-At-1/21b	femur	-16.9	9.8	16.7	38.2	13.8	0.23	3.2	451	140
To-At-1/22	long bone	-17.3	8.9	†15.0	40.5	14.5	0.26	3.3	415	127
To-At-1/23	long bone	-17.1	9.0	†14.5	39.6	14.5	0.25	3.2	424	133
To-At-1/25	long bone	-17.1	10.1	†16.4	40.5	14.4	0.21	3.3	512	156
To-At-1/26	ulna	-18.4	8.7		40.0	14.4		3.3		

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Table B.2 – continued from previous page

Burial number	Bone	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	%C	%N	%S	C:N	C:S	N:S
To-At-1/27	long bone	-16.2	9.6	†12.4	40.0	14.2	0.22	3.3	477	145
To-At-1/29a	long bone	-16.4	10.3		42.7	15.7		3.2		
To-At-1/29b	long bone	-16.7	10.2	†14.3	40.0	14.5	0.28	3.2	385	120
To-At-1/29c	vertebra	-17.2	11.6	†13.8	40.7	14.6	0.28	3.3	394	121
To-At-1/03	vertebra	-17.5	11.2		42.1	14.8		3.3		
To-At-1/30	long bone	-17.8	7.7	†15.5	42.6	15.6	0.23	3.2	491	154
To-At-1/31	long bone	-17.7	9.6	†15.6	37.7	13.2	0.29	3.3	353	106
To-At-1/34	long bone	-16.8	9.5		39.9	14.6		3.2		
To-At-1/35	fibula	-18.1	12.5	14.6	43.4	16.0	0.24	3.2	475	150
To-At-1/36	vertebra	-18.1	11.3	†14.6	42.4	15.2	0.24	3.3	482	148
To-At-1/37	metatarsal	-17.7	8.6	†11.9	42.9	15.7	0.21	3.2	538	169
To-At-2/01a	vertebra	-18.8	8.8	16.2	42.1	15.2	0.23	3.2	496	153
To-At-2/01b	vertebra	-17.0	11.9	†14.0	41.6	15.4	0.25	3.2	448	142
To-At-2/01c	vertebra	-17.5	10.0	†13.6	38.7	14.1	0.20	3.2	505	157
To-At-2/01d	long bone	-17.1	11.9		43.8	15.5		3.3		
To-At-2/01e	long bone	-18.1	9.0		39.1	14.2		3.2		
To-At-2/02	rib	-18.2	10.6	15.1	39.6	14.3	0.30	3.2	350	108
To-At-2/03	long bone	-18.0	9.7		41.3	14.7		3.3		
To-At-2/04	fibula	-18.2	9.1	15.7	42.0	15.5	0.27	3.2	421	133
To-At-2/05	metatarsal	-18.0	8.3		42.6	15.5		3.2		
To-At-2/06	scapula	-18.2	8.5	†15.1	40.5	14.5	0.27	3.3	402	123
To-At-2/07*	vertebra	-16.9	11.8	9.5	41.4	15.3	0.24	3.2	466	147
To-At-2/08	tibia	-16.8	10.6	16.1	40.4	14.9	0.24	3.2	443	140
To-At-2/09	vertebra	-18.9	8.7		43.0	15.7		3.2		
To-At-2/10	femur	-18.2	9.4	†14.9	37.5	13.7	0.26	3.2	388	122

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Table B.2 – continued from previous page

Burial number	Bone	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	%C	%N	%S	C:N	C:S	N:S
To-At-2/11	humerus	-18.5	8.4	†16.0	39.9	13.8	0.28	3.4	381	113
To-At-2/13	humerus	-18.1	9.8	† 14.8	41.9	15.1	0.26	3.2	431	133
To-At-2/13a	humerus	-17.3	9.8	†14.8	41.7	14.9	0.23	3.3	476	146
To-At-2/13c	tiba	-18.0	9.3	†13.2	38.6	14.0	0.26	3.2	396	123
To-At-2/14	long bone	-16.4	12.2		40.8	14.9		3.2		
To-At-2/15	fibula	-18.4	8.9	†15.8	39.6	14.3	0.24	3.2	434	134
To-At-2/16	rib	-17.9	8.6	12.3	38.2	13.8	0.23	3.2	437	135
To-At-2/17	long bone	-17.7	11.3		40.4	14.8		3.2		
To-At-2/18	scapula	-17.2	10.3	†14.4	37.3	13.4	0.28	3.3	359	110
To-At-2/19	long bone	-18.5	8.2		40.0	15.0		3.1		
To-At-2/20a	femur	-18.0	8.7	14.6	41.5	15.7	0.24	3.1	467	152
To-At-2/20b	rib	-17.4	9.5	†14.1	39.4	14.3	0.22	3.2	468	146
To-At-2/20c	rib	-17.9	9.3		39.7	14.2		3.3		
To-At-2/21	long bone	-18.1	9.1	† 13.7	42.4	15.2	0.25	3.3	446	137
To-At-2/24a	long bone	-18.1	8.8	14.8	38.1	14.0	0.21	3.2	475	150
To-At-2/24b	long bone	-18.0	9.1	†13.1	40.6	14.8	0.24	3.2	450	141
To-At-2/25	scapula	-17.9	8.6	†13.9	42.5	15.0	0.26	3.3	438	133
To-At-2/27	tibia	-18.2	8.6	†15.4	41.3	15.1	0.20	3.2	538	169
To-At-2/27a	tibia	-17.4	8.6	†9.9	38.3	14.2	0.22	3.1	475	151
To-At-2/30*	tibia	-18.0	9.4	†14.7	41.3	14.6	0.26	3.3	429	130
To-At-2/31	long bone	-18.4	9.3		41.6	14.9		3.2		
To-At-2/32	femur	-18.5	9.3	†16.4	38.6	14.0	0.24	3.2	426	132
To-At-2/33	tibia	-14.8	9.7	†17.2	36.2	13.3	0.28	3.2	340	108
To-At-2/34	long bone	-18.4	9.2	13.7	41.2	15.3	0.23	3.1	470	150
To-At-2/35	long bone	-18.5	9.5	†15.2	41.4	15.1	0.25	3.2	439	138

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Table B.2 – continued from previous page

Burial number	Bone	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	%C	%N	%S	C:N	C:S	N:S
To-At-2/36	femur	-18.8	9.6		41.4	14.8		3.3		
To-At-2/37	tibia	-17.8	9.0	†17.3	37.9	13.8	0.24	3.2	413	129
To-At-2/38	metatarsal	-18.4	9.2	15.8	38.9	14.3	0.22	3.2	463	146
To-At-2/39	metatarsal	-18.3	8.6	17.3	41.9	15.6	0.23	3.1	482	154
To-At-2/40a	rib	-18.1	8.8		43.6	15.7		3.2		
To-At-2/41a	ulna	-17.7	9.9	11.6	41.5	15.2	0.24	3.2	465	146
To-At-2/41b	ulna	-18.0	8.9	†16.1	37.7	13.7	0.24	3.2	414	129
To-At-2/42	rib	-18.1	9.4	†17.8	41.5	14.9	0.26	3.3	431	132
Unlabelled 41	long bone	-17.1	10.4	†17.6	37.6	13.7	0.25	3.2	397	125
Unlabelled 89a	humerus	-17.9	8.9	†13.1	40.0	14.4	0.20	3.2	532	164
Unlabelled 89b	humerus	-18.3	9.0		42.3	15.6		3.2		
Unlabelled 89c	humerus	-17.5	9.8	14.1	42.6	15.6	0.24	3.2	466	146
Unlabelled 89d	humerus	-18.1	9.1	13.4	38.2	13.9	0.23	3.2	436	136
Unlabelled 89e	humerus	-16.9	9.2	†14.6	38.5	14.1	0.23	3.2	457	143
Unlabelled 91	ulna	-17.6	8.5		39.5	14.0		3.3		
Unlabelled 92	fibula	-18.2	8.4	†14.4	43.1	15.9	0.22	3.2	522	165

Table B.3. *Carbon and nitrogen stable isotope dentine collagen data for Bourewa individuals. Tooth specified using FDI notation.*

Burial number	Tooth	$\delta^{13}C$	$\delta^{15}N$	%C	%N	C:N
03	16	-16.2	8.4	42.7	16.0	3.1
06	15	-16.3	8.6	43.3	16.3	3.1
09	15	-17.0	9.1	42.9	15.2	3.3

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Table B.3 – continued from previous page

Burial number	Tooth (FDI)	$\delta^{13}C$	$\delta^{15}N$	%C	%N	C:N
10	24	-16.6	9.0	42.7	15.3	3.3
15	26	-17.4	7.6	43.5	15.4	3.3
17	26	-18.1	8.2	43.6	15.6	3.3
20	26	-14.9	10.5	42.7	15.4	3.2
21	26	-17.5	8.8	44.3	16.1	3.2
22	27	-14.9	10.0	44.6	16.1	3.2
23	35	-17.5	8.8	42.5	15.4	3.2
25	26	-15.1	9.8	44.5	16.1	3.2
26	47	-15.2	9.3	44.8	16.0	3.3
28	16	-14.4	10.2	42.1	15.3	3.2
29	46	-15.2	9.4	42.1	15.4	3.2
30	16	-15.6	9.4	41.9	15.3	3.2
31	26	-16.8	9.1	40.7	14.8	3.2

Table B.4. *Carbon, nitrogen, and sulphur stable isotope dentine collagen data for Bourewa individuals. Tooth specified using FDI notation.*

Burial number	Tooth	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	%C	%N	%S	C:N	C:S	N:S
To-At-1/04a	27	-18.2	9.0		40.3	14.7		3.2		
To-At-1/06	47	-17.7	10.4	†16.5	40.0	14.9	0.27	3.1	398	127
To-At-1/07	17	-18.0	9.1	†15.6	43.0	15.4	0.26	3.3	438	134
To-At-1/09	17	-17.4	9.2		41.9	15.2		3.2		
To-At-1/10	25	-18.5	8.7	†12.4	42.5	15.1	0.25	3.3	457	139
To-At-1/11	45	-17.0	9.9		34.4	12.7		3.2		
To-At-1/12	14	-18.7	9.3	14.5	42.8	15.4	0.27	3.2	425	131

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Table B.4 – continued from previous page

Burial number	Tooth (FDI)	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	%C	%N	%S	C:N	C:S	N:S
To-At-1/13	37	-14.1	17.6	15.2	42.7	15.5	0.29	3.2	393	122
To-At-1/13o	47	-18.0	8.8		42.5	15.4		3.2		
To-At-1/14	17	-18.2	9.2		41.8	15.0		3.3		
To-At-1/19	37	-15.6	10.9		42.1	15.7		3.1		
To-At-1/20	27	-17.7	8.9	†13.6	40.5	15.1	0.26	3.1	423	136
To-At-1/20a	47	-16.8	10.4	†15.5	39.7	14.6	0.26	3.2	408	128
To-At-1/21a(1)	25	-16.7	10.4	†11.2	42.1	15.5	0.26	3.2	440	139
To-At-1/21a(2)	16	-17.1	9.8		41.4	15.2		3.2		
To-At-1/22	25	-18.5	8.9		40.9	15.0		3.2		
To-At-1/23	17	-17.7	9.5	†18.3	43.4	16.1	0.23	3.1	513	163
To-At-1/26	17	-17.7	10.0	†13.1	41.5	15.2	0.26	3.2	419	131
To-At-1/29a	17	-17.4	9.8	†13.5	41.3	15.2	0.24	3.2	464	147
To-At-1/30	27	-17.6	9.1	†13.4	42.3	15.7	0.25	3.1	455	145
To-At-1/34	35	-15.1	11.4	12.4	42.0	15.2	0.25	3.2	457	142
To-At-2/1c	17	-18.3	9.6		41.7	15.2		3.2		
To-At-2/1e	27	-16.7	9.7		40.7	14.9		3.2		
To-At-2/1e(2)	47	-16.9	10.7	†16.9	40.9	15.0	0.55	3.2	199	64
To-At-2/1e(4)	27	-17.6	8.4	†13.4	42.3	15.6	0.26	3.2	438	138
To-At-2/13a	45	-18.8	9.4		43.3	14.9		3.4		
To-At-2/13c	36	-18.3	9.7	†16.5	40.7	14.7	0.25	3.2	432	134
To-At-2/16	17	-17.7	8.8	11.6	42.2	15.3	0.28	3.2	403	125
To-At-2/24a	14	-18.1	9.3		42.7	15.7		3.2		
To-At-2/24b	47	-18.5	9.5		42.2	15.3		3.2		
To-At-2/25	37	-17.9	9.2	15.5	42.3	15.7	0.28	3.1	405	129
To-At-2/27	37	-18.3	9.2	†13.5	43.5	15.8	0.29	3.2	406	127

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Table B.4 – continued from previous page

Burial number	Tooth (FDI)	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	%C	%N	%S	C:N	C:S	N:S
To-At-2/28	17	-16.9	9.8	†15.1	41.5	15.0	0.28	3.2	396	123
To-At-2/30	37	-17.6	10.0	†16.4	42.4	15.6	0.24	3.2	477	150
To-At-2/31	27	-18.4	9.7	†17.3	40.7	15.0	0.26	3.2	414	131
To-At-2/32	47	-17.5	9.9	†11.4	41.7	15.3	0.24	3.2	467	147
To-At-2/33	45	-15.4	9.9	†16.2	42.1	15.5	0.26	3.2	427	135
To-At-2/40a*	35	-17.9	9.5		40.6	14.8		3.2		
To-At-2/40b	27	-17.3	10.0	†12.1	41.5	15.0	0.24	3.2	468	145
To-At-2/41b	15	-18.4	8.8	†16.5	39.6	14.7	0.25	3.2	420	133
To-At-2/42	17	-18.6	9.3	†15.5	41.4	14.9	0.25	3.3	440	135
To-At-2/06	47	-18.5	8.0	†15.8	42.8	15.3	0.26	3.3	440	135
To-At-2/09	17	-18.8	8.9	14.9	43.6	15.9	0.24	3.2	484	152

B.2 Strontium isotope data

Table B.5. *Strontium isotope data for individuals from the Bourewa site.* $^{87}Sr/^{86}Sr$ *ratio correction described in section 5.5.3.*

Burial number	Tooth (FDI)	Corrected $^{87}Sr/^{86}Sr$	Sr concentration (ppm)
03	16	0.70893	87.19
06	15	0.70891	160.33
09	18	0.70809	183.04
10	24	0.70835	119.26
15	26	0.70795	301.99
17	26	0.70776	133.98
20	26	0.70872	207.48
21	26	0.70861	206.80
22	27	0.70862	227.68
23	33	0.70689	234.21
24	26	0.70857	235.96
25	26	0.70865	316.39
26	47	0.70880	254.83
28	16	0.70855	218.51
29	46	0.70881	260.47
30	16	0.70878	226.91
31	48	0.70870	301.04

Table B.6. *Strontium isotope data for individuals from the 'Atele burial mounds. $^{87}Sr/^{86}Sr$ ratio correction described in section 5.5.3.*

Burial number	Tooth (FDI)	Corrected $^{87}Sr/^{86}Sr$	Sr concentration (ppm)
To-At-1/04a	27	0.70872	175.84
To-At-1/06	47	0.70894	276.63
To-At-1/07	17	0.70878	192.94
To-At-1/09	17	0.70846	166.45
To-At-1/10	25	0.70872	205.75
To-At-1/11	45	0.70883	261.21
To-At-1/12	14		0.00
To-At-1/13	37		0.00
To-At-1/13o	47	0.70874	188.10
To-At-1/14	17	0.70861	152.06
To-At-1/19	37	0.70892	229.54
To-At-1/20	27	0.70877	127.86
To-At-1/20.1	47	0.70875	196.19
To-At-1/21a(1)	25	0.70872	241.77
To-At-1/21a(2)	16	0.70887	86.76
To-At-1/22	25	0.70887	122.57
To-At-1/23	17	0.70901	328.58
To-At-1/26	17	0.70902	267.88
To-At-1/29a	17	0.7086	206.62
To-At-1/30	27	0.70881	78.47
To-At-1/34	35	0.70876	244.84
To-At-2/01c	17	0.70907	196.27

Continued on next page

Table B.6 – continued from previous page

Burial number	**Tooth (FDI)**	**Corrected $^{87}Sr/^{86}Sr$**	**Sr concentration (ppm)**
To-At-2/01e	17	0.70904	147.87
To-At-2/01ea(2)	47	0.70890	122.43
To-At-2/01e(4)	27	0.70878	126.93
To-At-2/06	47	0.70861	145.62
To-At-2/09	17	0.70880	209.91
To-At-2/13a	45	0.70881	111.22
To-At-2/13c	36	0.70876	346.04
To-At-2/16	17	0.70874	129.08
To-At-2/24a	14	0.70888	212.80
To-At-2/24b	47	0.70870	208.86
To-At-2/25	37	0.70890	223.89
To-At-2/27	37	0.70876	246.69
To-At-2/28	17	0.70906	190.80
To-At-2/30	37	0.70894	203.88
To-At-2/31	27	0.70897	253.00
To-At-2/32	47	0.70881	299.00
To-At-2/33	45	0.70886	291.76
To-At-2/40a	35	0.70893	178.89
To-At-2/40b	27	0.70876	222.83
To-At-2/41b	15	0.70884	106.07
To-At-2/42	17	0.70885	306.63

Appendix C

Dietary Baseline Stable Isotope Data

Table C.1. *Carbon and nitrogen stable isotope bone collagen data for plant and animal samples collected on Atiu (Cook Islands). The* Pandanus tectorius *sample was too small and could not be analysed.*

Lab #	Scientific name	Common English name	$\delta^{13}C$	$\delta^{15}N$	%C	%N
1	*Turbo marmoratus*	green turban snail	-15.3	5.9	38.4	14.1
2	*Heterocentrotus mammillatus*	pencil urchin	-13.4	4.9	21.3	4.1
3	*Scutellastra flexuosa*	limpet	-10.5	5.2	36.9	13.4
4	*Scutellastra flexuosa*	limpet	-8.4	4.1	41.3	16.2
5	*Patelloida* sp.	limpet	-8.5	1.6	37.5	13.4
6	*Patelloida* sp.	limpet	-7.7	2.9	33.8	11.0
7	*Tridacna maxima*	small giant clam	-13.8	5.4	36.6	13.1
8	*Tridacna maxima*	small giant clam	-13.5	5.4	36.0	12.8
9	*Nerita plicata*	sea snail	-11.4	2.1	29.4	8.2
10	*Nerita plicata*	sea snail	-11.0	2.5	39.9	14.9
11	*Kyphosus cinerascens*	blue sea chub	-13.5	7.1	42.4	17.6
12	*Thunnus albacares*	yellowfish tuna	-12.7	15.0	41.0	17.9

Continued on next page

Table C.1 – continued from previous page

Lab #	Scientific name	Common English name	$\delta^{13}C$	$\delta^{15}N$	%C	%N
13	*Tacca leontopetaloides*	Polynesian arrowroot	-25.6	2.4	40.9	0.9
14	*Pandanus tectorius*	pandanus			0.0	0.0
15	*Musa troglodytorum*	royal banana	-27.7	5.2	44.1	1.6
16	*Dioscorea bulbifera*	yam	-28.8	1.9	41.2	1.1
17	*Artocarpus altilis*	breadfruit	-30.9	1.2	42.4	1.0
18	*Alocasia macrorrhizos*	giant taro	-27.9	2.8	39.5	0.5
19	*Dioscorea* sp.	yam	-28.1	3.2	40.5	1.6
20	*Cordyline fructiosa*	cordyline	-26.2	1.0	41.0	1.4
21	*Cocos nucifera*	coconut	-23.9	4.4	45.1	5.0
22	*Cyrtosperma merkusii*	giant swamp taro	-26.4	3.7	38.9	1.7
23	*Pipturus argenteus*		-25.3	3.9	41.4	2.2
24	*Inocarpus fagifer*	Tahitian chestnut	-24.1	8.0	40.6	0.4
25	*Syzygium malaccense*	Malay apple	-24.2	13.4	42.8	3.8
26	*Saccarum offininarum*	sugar cane	-10.0	4.2	44.6	0.2
28	*Colocasia esculenta*	taro	-26.1	4.7	41.3	0.8

Appendix D

Dental Data Recording Scheme

Presence (from Hillson [2001])

BLANK	Missing post-mortem and jaw with socket missing too.
0	Tooth present, without gross gross caries.
7	Gross gross carious cavity, involving the loss of so much of the tooth that it is not possible to determine whether the lesion was initiated in the crown or root.
8	Gross gross carious cavity, involving the loss of so much of the tooth that it is not possible to determine whether the lesion was initiated in the crown or root, and there is a clear opening into an exposed pulp chamber or root canal.
10	Tooth missing, leaving an empty socket in the jaw without any sign of remodeling.
11	Tooth missing, leaving an empty cavity in which there are signs of remodeling, but the bone is not fully remodeling to a level contour.
12	Tooth missing, with full remodeling of the jaw to leave a level contour.
13	No evidence that the tooth has ever erupted (as a result of young age, impaction or agenesis).
14	Tooth partly erupted (crypt communicating with crest of alveolar process, or tooth not yet in wear).
15	Anomalous eruption, so that the tooth has not reached its normal position in the tooth row.

Tooth formation (from Moorees et al. [1963])

BLANK	Missing for any reason
1	Initial cusp formation
2	Coalescence of cusps
3	Cusp outline complete
4	Crown 1/2 complete
5	Crown 3/4 complete
6	Crown complete
7	Initial root formation
8	Initial cleft formation
9	Root length 1/4
10	Root length 1/2
11	Root length 3/4
12	Root length complete
13	Apex 1/2 closed
14	Apex closed

Calculus, supra- and sub-Gingival (from Buikstra and Ubelaker [1994])

BLANK	Unobservable
0	Absent
1	Initial cusp formation
2	Coalescence of cusps
3	Cusp outline complete

Periapical cavity size

BLANK	Unobservable
0	Absent
1	<3mm
2	>3mm
3	>10mm

Dental wear (from Smith [1984])

BLANK	Missing for any reason
1	Unworn to polished or small facets (no dentine exposure)
2	Moderate cusp removal
3	Full cusp removal and/or moderate dentine patches
4	At least one large dentine exposure on one cusp
5	Two large dentine areas (may be slight coalescence)
6	Dentinal areas coalesced, enamel rim still complete
7	Full dentine exposure, loss of rim on at least one side
8	Severe loss of crown height, crown surface takes on shape of roots.

Dental wear, molars (from Scott [1979])
The molar is oriented as advised by Shykoluk and Lovell (2010).

BLANK	Missing for any reason
1	Wear facets invisible or very small
2	Wear facets large, but large cusps still present and surface features (crenulations, noncarious pits) very evident. It is possible to have pinprick size dentine exposures or dots which should be ignored. This is a quadrant with much enamel.
3	Any cusp in the quadrant area is rounded rather than being clearly defined as in 2. The cusp is becoming obliterated but is not yet worn flat.
4	Quadrant area is worn flat (horizontal) but there is no dentine exposure other than a possible pinprick sized dot.
5	Quadrant is flat, with dentine exposure one-fourth of quadrant or less (be careful not to confuse noncarious pits with dentine)
6	Dentine exposure greater; more than one-fourth of quadrant is involved, but there is still much enamel present. If the quadrant is visualized as having three sides (as in the diagram) the dentine patch is still surrounded on all three sides by a ring of enamel.
7	Enamel is found on only two sides of the quadrant.
8	Enamel on only one side (usually outer rim) but the enamel is thick to medium on this edge.
9	Enamel on only one side as in 8, but the enamel is very thin- just a strip. Part of the edge may be worn through at one or more places.
10	No enamel on any part of quadrant- dentine exposure complete. Wear is extended below the cervicoenamel junction into the root.

Occlusal surface caries (from Hillson [2001])

BLANK	Sites missing for any reason, or fully obscured.
0	Sites present but enamel is translucent and with a smooth surface.
1	White or stained opaque area in enamel of fissure/groove/fossa, with smooth glossy or matte surface.
2	White or stained opaque area, with associated roughening or slight surface destruction.
3	Small cavity, where there is no clear evidence that it penetrates to the dentine.
5	Larger cavity, which clearly penetrates the dentine.
6	Large cavity which was clearly initiated in a fissure/groove/fossa site within the occlusal surface (it does not involve the contact areas), within the floor of which is the open pulp chamber, or open root canals.
7	Gross coronal caries, involving the occlusal crown surface and contact area or pit.
8	Gross coronal caries, defined as in score 7 above, within the floor of which is the open pulp chamber, or open root canals.

Pit caries (from Hillson [2001])

BLANK	Pit site not present or not visible(for any reason).
0	Site or sites present, but enamel is translucent and with a smooth surface.
1	White or stained opaque area in enamel of pit, with smooth glossy or matte surface.
2	White or stained opaque area, with associated roughening or slight surface destruction.
3	Small cavity, where there is no clear evidence that it penetrates to the dentine.
5	Larger cavity, which clearly penetrates the dentine.
6	Large cavity, which was clearly initiated in a pit site, within the floor of which is the open pulp chamber, or open root canals.
7	Gross coronal caries, involving a pit and the occlusal crown surface (Row 2 above).
8	Gross coronal caries, defined as in score seven above, within the floor of which is the open pulp chamber, or open root canals.

Occlusal Attrition Facet Dentine Caries (from Hillson [2001])

BLANK	Worn dentine surface, either not yet exposed, missing or obscured (for whatever reason).
0	Dentine exposed in occlusal attrition facet, but without any stained areas, or cavitation.
4	Stained area of dentine and/or enamel, which may or may not be a carious lesion.
5	Clear cavity in dentine.
6	Pulp chamber, exposed in the attrition facet, which is stained or appears to have been modified by the development of a cavity.
8	Exposed pulp chamber in which there is no sign of either staining or irregular formation of a cavity.

Occlusal attrition facet enamel edge chipping and caries (from Hillson [2001])

BLANK	Worn enamel rim not yet exposed at any point on the perimeter of the occlusal surface, missing or obscured (for whatever reason).
0	Enamel rim of occlusal attrition facet exposed at any point, but intact with no chipping.
1	Chipping which appears to be post-mortem in origin.
2	Chipping which appears to be ante-mortem, but is not affected by caries.
3	Chipping associated with carious lesion.
7	Gross carious lesion, involving the enamel rim of the occlusal facet, but not clearly associated with any chipping.
8	Gross carious lesion, as defined in score 7 above, involving the enamel rim, within the floor of which is the open pulp chamber, or open root canals.

Mesial and distal attrition score (from Hillson [2001])

BLANK	Contact point missing (for whatever reason).
0	No attrition facet around contact point.
1	Approximal attrition facet confined to the enamel.
2	Approximal attrition facet exposing dentine at its centre.
3	Approximal attrition facet exposes dentine all the way down to the cemento-enamel junction.
4	Occlusal attrition has proceeded down into the roots of the teeth, so that there is no longer any contact between neighbouring teeth.

Mesial and distal contact area caries (from Hillson [2001])

BLANK	Contact area missing, or not visible, for any reason.
0	Contact area present, but enamel is translucent and with a smooth surface (and any exposed dentine is unstained and not cavitated).
1	White or stained opaque area in enamel, with smooth glossy or matte surface (or stained patch in dentine).
2	White or stained opaque area of enamel, with associated roughening or slight surface destruction.
3	Small enamel cavity, where there is no clear evidence that it penetrates to the dentine.
4	Discolouration in exposed dentine of an approximal attrition facet.
5	Larger enamel cavity which clearly penetrates the dentine (or clear cavity in dentine of approximal attrition facet).
6	Large cavity, clearly initiated in the contact area or approximal attrition facet, within the floor of which is the open pulp chamber, or open root canals.
7	Gross cavity in the contact area or approximal attrition facet, which involves neighbouring occlusal sites and/or root surface sites
8	Gross cavity, defined as in score seven above, within the floor of which is the open pulp chamber, or open root canals.

Mesial and distal root surface caries (from Hillson [2001])

BLANK	No part of mesial/distal root surface or cemento-enamel junction preserved, or at least not visible if present.
0	Root surface/cemento-enamel junction present and visible, with no evidence of staining or cavitation.
1	Area of darker staining along cement– enamel junction, or on root surface.
5	Shallow cavity (stained or unstained), following the line of the cemento-enamel junction, or confined to the surface of the root.
6	Cavity involving the cemento-enamel junction, or root surface alone, within the floor of which is the open pulp chamber, or open root canals.
7	Gross cavity, including the cemento- enamel junction or root surface, which involves the neighbouring contact area site occlusal sites or occlusal attrition facet sites.
8	Gross cavity, defined as in score seven above, within the floor of which is the open pulp chamber, or open root canals.

Buccal and lingual smooth surface enamel caries (from Hillson [2001])

BLANK	Site not present or not visible (for any reason).
0	Site present, but enamel is translucent and with a smooth surface.
1	White or stained opaque area in enamel, with smooth glossy or matte surface.
2	White or stained opaque area, with associated roughening or slight destruction of the enamel surface.
3	Small enamel cavity, where there is no clear evidence that it penetrates to the dentine.
5	Larger cavity, which clearly penetrates the dentine.
6	Large cavity, which has exposed the open pulp chamber, still without involving the cemento-enamel junction.
7	Gross cavity, which involves neighbouring occlusal sites and/or root surface sites
8	Gross cavity, defined as in score seven above, within the floor of which is the open pulp chamber, or open root canals.

Buccal and lingual root caries (from Hillson [2001])

BLANK	no part of the buccal/labial/lingual root surface or cemento-enamel junction preserved, or at least not visible if present.
0	root surface/ cemento-enamel junction present and visible, with no evidence of staining or cavitation.
1	area of darker staining along cemento-enamel junction or on root surface.
5	shallow cavity (stained or unstained), following the line of the cemento-enamel junction, or confined to the surface of the root.
6	cavity involving the cemento-enamel junction, or root surface alone, within the floor of which is the open pulp chamber, or open root canals.
7	gross cavity, including the cement– enamel junction, or root surface, which involves the neighbouring crown side, occlusal or pit sites, or occlusal attrition facet sites.
8	gross cavity, defined as in score seven above, within the floor of which is the open pulp chamber, or open root canals.

Periodontitis (from Kerr [1991])
The numbering system is changed slightly- a score of "0" now represents healthy, when before it represented absent/unobservable; all other scores moved accordingly. This integrates better with the rest of the scoring system, in which zero represents healthy, unaltered bone.

BLANK	Missing for any reason
0	Septal form characteristic of its region with the cortical surface continuous and virtually uninterrupted by foramina or grooves. Such a situation is considered to represent the "healthy" situation.
1	Septal form characteristic of the region. Cortical surface showing a range from many small foramina and/or grooves to large foramina with prominent grooves or ridges. This category is indicative of inflammation in the overlying soft tissue and corresponds to a clinical diagnosis of gingivitis.
2	Septal form showing a breakdown of contour, the essential distinguishing feature being a sharp and ragged texture to the bone defect. Such a defect is representative of an acute burst of periodontitis
3	Septal form showing breakdown of contour, the distinguishing feature being a porous or smooth honeycomb effect with all defects rounded. This defect is considered to be a previously acute periodontitis which has reverted to a quiescent phase.
4	Presence of a deep intra-bony defect with sides sloping at 45° or more and with a depth of 3 mm or more. This defect is equivalent to a more aggressive periodontitis in either an acute or quiescent phase.

Bibliography

Açil, Y., Mobasseri, A. E., Warnke, P. H., Terheyden, H., Wiltfang, J., and Springer, I. (2005). Detection of mature collagen in human dental enamel. *Calcified Tissue International*, 76(2):121–126.

Addison, D. J. and Sand, C., editors (2008). *Recent Advances in the Archaeology of the Fiji/West-Polynesia Region*. Number 21 in University of Otago Studies in Prehistoric Anthropology. Department of Anthropology, Gender and Sociology, University of Otago, Dunedin, New Zealand.

Al-Jasser, N. M. and Bello, L. L. (2003). Time of eruption of primary dentition in Saudi children. *The Journal of Contemporary Dental Practice*, 4(3):65–75.

Al-Zahrani, M. S., Borawski, E. A., and Bissada, N. F. (2005). Periodontitis and three health-enhancing behaviors: Maintaining normal weight, engaging in recommended level of exercise, and consuming a high-quality diet. *Journal of Periodontology*, 76(8):1362–1366.

Albandar, J. M., Kingman, A., Brown, L. J., and Löe, H. (1998). Gingival inflammation and subgingival calculus as determinants of disease progression in early-onset periodontitis. *Journal of Clinical Periodontology*, 25(3):231–237.

Albin, B., Hjelm, K., Ekberg, J., and Elmståhl, S. (2005). Mortality among 723,948 foreign- and native-born Swedes 1970–1999. *The European Journal of Public Health*, 15(5):511–517.

Alexander, A. (1971). A study of the distribution of supra and subgingival calculus, bacterial plaque and gingival inflammation in the mouths of 400 individuals. *Journal of Periodontology*, 42(1):21–28.

Allen, J., Gosden, C., Jones, R., and White, J. P. (1988). Pleistocene dates for the human occupation of New Ireland, northern Melanesia. *Nature*, 331(6158):707–709.

Allen, J., Gosden, C., and White, J. P. (1989). Human Pleistocene adaptations in the tropical island Pacific: Recent evidence from New Ireland, a greater Australian outlier. *Antiquity*, 63(240):548–561.

Allen, M. S. and Craig, J. A. (2009). Dynamics of Polynesian subsistence: Insights from archaeofauna and stable isotope studies, Aitutaki, Southern Cook Islands. *Pacific Science*, 63(4):477–506.

Allentoft, M. E., Collins, M., Harker, D., Haile, J., Oskam, C. L., Hale, M. L., Campos, P. F., Samaniego, J. A., Gilbert, M. T. P., Willerslev, E., Zhang, G., Scofield, R. P., Holdaway, R. N., and Bunce, M. (2012). The half-life of DNA in bone: measuring decay kinetics in 158 dated fossils. *Proceedings of the Royal Society B: Biological Sciences*, 279(1748):4724–4733.

Ambrose, S. H. (1990). Preparation and characterization of bone and tooth collagen for isotopic analysis. *Journal of Archaeological Science*, 17:431–451.

Ambrose, S. H. (1991). Effects of diet, climate and physiology on nitrogen isotope

abundances in terrestrial foodwebs. *Journal of Archaeological Science*, 18(3):293–317.

Ambrose, S. H. (1993). Isotopic analysis of paleodiets: methodological and interpretive considerations. In Sandford, M. K., editor, *Investigations of ancient human tissue: chemical analysis in anthropology*, chapter 2, pages 59–130. Gordon and Breach, Philadelphia, Pennsylvania.

Ambrose, S. H., Butler, B. M., Hanson, D. B., Hunter-Anderson, R. L., and Krueger, H. W. (1997). Stable isotopic analysis of human diet in the Marianas Archipelago, Western Pacific. *American Journal of Physical Anthropology*, 104(3):343–361.

Ambrose, S. H. and DeNiro, M. J. (1986). The isotopic ecology of East African mammals. *Oecologia*, 69(3):395–406.

Ambrose, S. H. and Norr, L. (1992). On stable isotopic data and prehistoric subsistence in the Soconusco region. *Current Anthropology*, 33(4):401–404.

Ambrose, S. H. and Norr, L. (1993). Experimental evidence for the relationship of the carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate. In Lambert, J. B. and Grupe, G., editors, *Prehistoric Human Bone*, chapter 1, pages 1–37. Springer Berlin Heidelberg.

Ames, K. M. (2002). Going by boat: The forager-collector continuum at sea. In Fitzhugh, B. and Habu, J., editors, *Beyond Foraging and Collecting: Evolutionary Change in Hunter-Gatherer Settlement Systems*, chapter 2, pages 19–52. Kluwer Academic/ Plenum Publishers, New York, New York.

Anderson, A. and Clark, G. (2009). Research on the early prehistory of Fiji. In Clark, G. and Anderson, A., editors, *The Early Prehistory of Fiji*, volume 31 of *Terra Australis*, pages 1–18. ANU press, Canberra, Australia.

Anderson, D. L. and Popovich, F. (1977). Dental reductions and dental caries. *American Journal of Physical Anthropology*, 47(3):381–385.

Anderson, W. (1967). Anderson's journal. In Beaglehole, J. C., editor, *The Journals of Captain James Cook*, volume 2, chapter Appendix I. Cambridge University Press, Cambridge, UK.

Aoyagi, M. (1966). Kinship organisation and behaviour in a contemporary Tongan village. *The Journal of the Polynesian Society*, 75(2):141–176.

Arcini, C. (2005). The Vikings bare their filed teeth. *American Journal of Physical Anthropology*, 128(4):727–733.

Arcini, C., Ahlström, T., and Tagesson, G. (2014). Variations in diet and stature: Are they linked? Bioarchaeology and paleodietary Bayesian mixing models from Linköping, Sweden. *International Journal of Osteoarchaeology*, 24(4):543–556.

Armitage, G. C. (1999). Development of a classification system for periodontal diseases and conditions. *Annals of Periodontology*, 4(1):1–6.

Aswani, S. and Graves, M. W. (1998). The Tongan maritime expansion: A case in the evolutionary ecology of social complexity. *Asian Perspectives: the Journal of Archaeology for Asia and the Pacific*, 37(2):135–164.

Aubry, M., Mafart, B., Donat, B., and Brau, J. J. (2003). Brief communication: Study of noncarious cervical tooth lesions in samples of prehistoric, historic, and modern populations from the South of France. *American Journal of Physical Anthropology*, 121(1):10–14.

Balasse, M., Smith, A. B., Ambrose, S. H., and Leigh, S. R. (2003). Determining sheep birth seasonality by analysis of tooth enamel oxygen isotope ratios: The Late Stone Age site of Kasteelberg (South Africa). *Journal of Archaeological Science*, 30(2):205–215.

Ball, D. (2007). On ergativity and accusativity in Proto-Polynesian and Proto-Central Pacific. *Oceanic Linguistics*, 46(1):128–153.

Balter, V. (2004). Allometric constraints on Sr/Ca and Ba/Ca partitioning in terrestrial mammalian trophic chains. *Oecologia*, 139(1):83–88.

Baradli, A. N. and Enders, C. K. (2010). An introduction to modern missing data analyses. *Journal of School Psychology*, 48:5–37.

Barfield, T., editor (1997). *The dictionary of Anthropology*. Blackwell, Oxford, UK.

Barker, D. J. P., Godfrey, K. M., Gluckman, P. D., Harding, J. E., Owens, J. A., and Robinson, J. S. (1993). Fetal nutrition and cardiovascular disease in adult life. *The Lancet*, 341(8850):938–941.

Barnaud, J. (1975). Alimentation et carie une plante tropicale "cario-protectrice": le taro. *Revue D'Odonto-Stomatologie*, 4(2):169–173.

Barnhart, H. X., Haber, M. J., and Lin, L. I. (2007). An overview on assessing agreement with continuous measurements. *Journal of Biopharmaceutical Statistics*, 17(4):529–569.

Bascones-Martínes, A., Criado-Cámara, E., Bascones-Ilundáin, C., Herrera, S. A., and Bascones-Ilundáin, J. (2011). Etiology of gingivitis. In Panagakos, F. S., editor, *Etiology of Gingivitis, Gingival Diseases - Their Aetiology, Prevention and Treatment*, chapter 4, pages 55–72. InTech.

Bassham, J. A., Benson, A. A., and Calvin, M. (1950). The path of carbon in photosyntheis: VIII. the role of malic acid. *Journal of Biological Chemistry*, 185(2):781–787.

Bath-Balogh, M. and Fehrenbach, M. J. (2006). *Dental Embryology, Histology, and Anatomy*. Elsevier, St. Louis, MO, second edition.

Baussano, I., Mercadante, S., Pareek, M., Lalvani, A., and Bugiani, M. (2013). High rates of *Mycobacterium tuberculosis* among socially marginalized immigrants in low-incidence area, 1991–2010, Italy. *Emerging Infectious Diseases*, 19:1437–45.

Bayard, D. T. (1976). *The cultural relationships of the Polynesian outliers*. Otago University studies in prehistoric anthropology. University of Otago, Department of Anthropology, Dunedin.

Beauchamp, G. K. and Mennella, J. A. (2011). Flavor perception in human infants: Development and functional significance. *Digestion*, 83(Suppl. 1):1–6.

Beaumont, J., Gledhill, A., Lee-Thorp, J., and Montgomery, J. (2013). Childhood diet: A closer examination of the evidence from dental tissues using stable isotope analysis of incremental human dentine. *Archaeometry*, 55(2):277–295.

Beaumont, J., Gledhill, A., and Montgomery, J. (2014). Isotope analysis of incremental human dentine: towards higher temporal resolution. *Bulletin of the International Association for Paleodontology*, 8(2):212–223.

Beaumont, J., Montgomery, J., Buckberry, J., and Jay, M. (2015). Infant mortality and isotopic complexity: New approaches to stress, maternal health, and weaning. *American Journal of Physical Anthropology*, pages n/a–n/a.

Beavan Athfield, N., Green, R. C., Craig, J., McFadgen, B., and Bickler, S. (2008). Influence of marine sources on ^{14}C ages: Isotopic data from Watom Island, Papua New Guinea inhumations and pig teeth in light of new dietary standards. *Journal of the Royal Society of New Zealand*, 38(1):1–23.

Beck, J. D. (1993). The epidemiology of root surface caries: North American studies. *Advances in Dental Research*, 7(1):42–51.

Becker, A. E. (1995). *Body, self, and society: the view from Fiji*. University of Pennsylvania Press, Philadelphia.

Bedford, S. and Sand, C. (2007). Lapita and Western Pacific settlement: pregress, prospects, and persistent problems. In Bedford, S., Sand, C., and Connaughton, S. P., editors, *Oceania explorations: Lapita and Western Pacific settlement*, volume 26 of *Terra Australis*, chapter 1, pages 1–16. ANU, Canberra, Australia.

Bedford, S., Spriggs, M., Buckley, H., Valentin, F., and Regenvanu, R. (2009). The Teouma Lapita site, South Efate, Vanuatu: A summary of three field seasons (2004-2006). In Sheppard, P., Thomas, T., and Summerhayes, G. R., editors, *Lapita: Ancestors and descendants*, New Zealand Archaeological Association Monograph, pages 215–234. New Zealand Archaeological Association, Auckland.

Belcastro, G., Rastelli, E., Mariotti, V., Consiglio, C., Facchini, F., and Bonfiglioli, B. (2007). Continuity or discontinuity of the life-style in central Italy during the Roman Imperial Age-Early Middle Ages transition: diet, health, and behavior. *American Journal of Physical Anthropology*, 132(3):381–394.

Bell, M. and Ward, G. (2000). Comparing temporary mobility with permanent migration. *Tourism Geographies*, 2(1):87–107.

Bellwood, P. (2001). Early agriculturalist population diasporas? farming, languages, and genes. *Annual Review of Anthropology*, 30(1):181–207.

Bellwood, P., Fox, J. J., and Tryon, D. (1995). The Autronesian history: Common origins and diverse transformations. In Bellwood, P., Fox, J. J., and Tryon, D., editors, *The Austronesians: Historical and Comparative Perspectives*, chapter 1, pages 1–16. ANU Press, Canberra, Australia.

Bellwood, P. S. (1975). The prehistory of Oceania. *Current Anthropology*, 16(1):9–28.

Bellwood, P. S. (1979). The Oceanic context. In Jennings, J., editor, *The Prehistory of Polynesia*, chapter 1, pages 6–26. Australia National University Press, Canberra, Australia.

Bellwood, P. S. (1987). *The Polynesians: Prehistory of an island people*. Thames and Hudson, London, UK.

Benfer, R. A. and Edwards, D. S. (1991). The principal axis method for measuring rate and amount of dental attrition: Estimating juvenile or adult tooth wear from unaged adult teeth. In Kelley, M. A. and Larsen, C. S., editors, *Advances in Dental Anthropology*, chapter 18, pages 325–340. Wiley-Liss, Inc., New York, NY.

Bentley, R. A. (2006). Strontium isotopes from the Earth to the archaeological skeleton: A review. *Journal of Archaeological Method and Theory*, 13(3):135–187.

Bentley, R. A., Buckley, H. R., Spriggs, M., Bedford, S., Ottley, C. J., Nowell, G. M., Macpherson, C. G., and Pearson, D. G. (2007). Lapita migrants in the Pacific's oldest cemetery: Isotopic analysis at Teouma, Vanuatu. *American Antiquity*, 72(4):645–656.

Bentley, R. A. and Knipper, C. (2005). Geographical patterns in biologically available strontium, carbon, and oxygen isotope signatures in prehistoric SW Germany. *Archaeometry*, 47(3):629–644.

Bentley, R. A., Krause, R., Price, T. D., and Kaufmann, B. (2003). Human mobility at the early Neolithic settlement of Vaihingen, Germany: Evidence from strontium isotope analysis. *Archaeometry*, 45(3):471–486.

Bentley, R. A., Price, T., and Stephan, E. (2004). Determining the 'local' $^{87}Sr/^{86}Sr$ range for archaeological skeletons: A case study from Neolithic Europe. *Journal of Archaeological Science*, 31(4):365–375.

Benton, D. (2004). Role of parents in the determination of the food preferences of children and the development of obesity. *International Journal of Obesity and Related Metabolic Disorders*, 28(7):858–869.

Berbesque, J. C., Marlowe, F. W., Pawn, I., Thompson, P., Johnson, G., and Mabulla, A. (2012). Sex differences in Hadza dental wear patterns. *Human Nature*, 23(3):270–282.

Berglund, M. and Wieser, M. E. (2011). Isotopic compositions of the elements 2009 (IUPAC technical report). *Pure and Applied Chemistry*, 83(2):397–410.

Bergman, B., Sandh, G., Lin, S., Larsson, J., and Carpenter, E. J. (2013). *Trichodesmium* – a widespread marine cyanobacterium with unusual nitrogen fixation properties. *FEMS Microbiology Reviews*, 37(3):286–302.

Bermudez de Castro, J. M., Arsuaga, J. L., and Perez, P.-J. (1997). Interproximal grooving in the Atapuerca-SH hominid dentitions. *American Journal of Physical Anthropology*, 102(3):369–376.

Berry, T. G., Summitt, J. B., and Sift, E. J. J. (2004). Root caries. *Operative Dentistry*, 29(6):601–607.

Best, E. (1931). Maori agriculture: Cultivated food-plants of the Maori and native methods of agriculture. *The Journal of the Polynesian Society*, 40(157):1–22.

Best, S. (2002). *Lapita: a view from the east*. New Zealand Archaeological Association, Auckland.

Bhagavan, N. (2002). *Mineral Metabolism*. Academic Press, San Diego, CA, 4th edition.

Biddle, N. and Yap, M., editors (2010). *Demographic and Socioeconomic Outcomes Across the Indigenous Australian Lifecourse: Evidence from the 2006 Census*. CAEPR Research Monograph Series. Australia National University, Canberra, Australia.

Bird, A. R., Brown, I. L., and Topping, D. L. (2000). Starches, resistant starches, the gut microflora and human health. *Current Issues in Intestinal Microbiology*, 1(1):25–37.

Blakely, R. L. and Beck, L. (1984). Toothtool use versus dental mutilation: a case study from the prehistoric Southeast. *Midcontinental Journal of Archaeology*, 9(2):269–284.

Blum, J. D., Taliaferro, E. H., Weisse, M. T., and Holmes, R. T. (2000). Changes in Sr/Ca, Ba/Ca and $^{87}Sr/^{86}Sr$ ratios between trophic levels in two forest ecosystems in the Northeastern U.S.A. *Biogeochemistry*, 49(1):87–101.

Bocherens, H., Billiou, D., Mariotti, A., Patou-Mathis, M., Otte, M., Bonjean, D., and Toussaint, M. (1999). Palaeoenvironmental and palaeodietary implications of isotopic biogeochemistry of last interglacial Neanderthal and mammal bones in Scladina Cave (Belgium). *Journal of Archaeological Science*, 26(6):599–607.

Bocherens, H. and Drucker, D. (2003). Trophic level isotopic enrichment of carbon and nitrogen in bone collagen: case studies from recent and ancient terrestrial ecosystems. *International Journal of Osteoarchaeology*, 13(1-2):46–53.

Boecklen, W. J., Yarnes, C. T., Cook, B. A., and James, A. C. (2011). On the use of stable isotopes in trophic ecology. *Annual Review of Ecology, Evolution, and Systematics*, 42(1):411–440.

Böhlke, J. K., de Laeter, J. R., Bièvre, P. D., Hidaka, H., Peiser, H. S., Rosman, K. J. R., and Taylor, P. D. P. (2005). Isotopic compositions of the elements, 2001. *Journal of Physical and Chemical Reference Data*, 34(1):57–67.

Bonafini, M., Pellegrini, M., Ditchfield, P., and Pollard, A. M. (2013). Investigation of the 'canopy effect' in the isotope ecology of temperate woodlands. *Journal of Archaeological Science*, 40(11):3926–3935.

Bonal, D., Sabatier, D., Montpied, P., Tremeaux, D., and Guehl, J. M. (2000). Interspecific variability of $\delta^{13}C$ among trees in rainforests of French Guiana: functional groups and canopy integration. *Oecologia*, 124(3):454–468.

Bonfiglioli, B., Mariotti, V., Facchini, F., Belcastro, M. G., and Condemi, S. (2004). Masticatory and non-masticatory dental modifications in the Epipalaeolithic necropolis of Taforalt (Morocco). *International Journal of Osteoarchaeology*, 14(6):448–456.

Bongaarts, J. and Potter, R. E. (2013). *Fertility, biology, and behavior: An analysis of the proximate determinants*. Academic Press, New York, New York.

Borjas, G. J., Bronars, S. G., and Trejo, S. J. (1992). Self-selection and internal migration in the United States. *Journal of Urban Economics*, 32(2):159–185.

Borrell, A., Cardona, L., Kumarran, R. P., and Aguilar, A. (2011). Trophic ecology of elasmobranchs caught off Gujarat, India, as inferred from stable isotopes. *ICES Journal of Marine Science: Journal du Conseil*, 68(3):547–554.

Bott, E. (1981). Power and rank in the Kingdom of Tonga. *The Journal of Polynesian Society*, 90(1):7–82.

Bott, E. (1982). *Tongan society at the time of Captain Cook's visits: discussions with Her Majesty Queen Salote Tupou*. Number 44 in Memoirs of the Polynesian Society. Polynesian Society, Wellington, New Zealand.

Bowen, G. J., West, J. B., Miller, C. C., Zhao, L., and Zhang, T. (2013). IsoMAP: Isoscapes modeling, analysis and prediction (version 1.0). The IsoMAP Project.

Bowen, W., Amsbaugh, S., Monell-Torrens, S., Brunelle, J., Kuzmiak-Jones, H., and Cole, M. (1980). A method to assess cariogenic potential of foodstuffs. *The Journal of the American Dental Association*, 100(5):677–681.

Boyce, B. F., Zuscik, M. J., and Xing, L. (2013). Biology of bone and cartilage. In Thakker, R. V., Eisman, J. A., Igarashi, T., and Whyte, M. P., editors, *Genetics of Bone Biology and Skeletal Disease*, chapter 1, pages 3–24. Academic Press, San Diego, California.

Brickley, M. and Ives, R. (2008). *The Bioarchaeology of Metabolic Bone Disease*. Academic Press, San Diego.

Britton, K., Grimes, V., Niven, L., Steele, T. E., McPherron, S., Soressi, M., Kelly, T. E., Jaubert, J., Hublin, J.-J., and Richards, M. P. (2011). Strontium isotope evidence for migration in late Pleistocene Rangifer: Implications for Neanderthal hunting strategies at the Middle Palaeolithic site of Jonzac, France. *Journal of Human Evolution*, 61(2):176–185.

Broadmeadow, M. S. J. and Griffiths, H. (1993). Carbon isotope discrimination and the coupling of CO_2 fluxes within forest canopies. In Ehleringer, J. R., Hall, A. E., and Farquhar, G. D., editors, *Stable Isotopes and Plant Carbon-water Relations*, chapter 8, pages 109–129. Academic Press, San Diego.

Brock, F., Geoghegan, V., Thomas, B., Jurkschat, K., and Higham, T. F. G. (2013). Analysis of bone "collagen" extraction products for radiocarbon dating. *Radiocarbon*, 55(2-3):445–463.

Bromfield, K. and Renema, W. (2011). Comparison of $^{87}Sr/^{86}Sr$ isotope and biostratigraphic ages of uplifted fossil reefs in the Indo-Pacific: Indonesia, Papua New Guinea and Fiji. *Australian Journal of Earth Sciences*, 58(1):61–73.

Brook, A. H. (2009). Multilevel complex interactions between genetic, epigenetic and environmental factors in the aetiology of anomalies of dental development. *Archives of Oral Biology*, 54(S1):S3–S17.

Brosnan, J. T. and Brosnan, M. E. (2006). The sulfur-containing amino acids: An overview. *The Journal of nutrition*, 136(6):1636S–1640S.

Brothwell, D. R. (1963). *Digging up bones: the excavation, treatment and study of human skeletal remains*. British Museum (Natural History), London, 1st edition.

Brothwell, D. R. (1989). The relationship of tooth wear to ageing. In İşcan, M. Y., editor, *Age Markers in the Human Skeleton*, pages 303–316. Charles C. Thomas, Springfield, IL.

Brown, T. (1991). Interproximal grooving: Different appearances, different etiologies, reply to Dr. Formicola. *American Journal of Physical Anthropology*, 86(1):86–87.

Brown, T. A., Nelson, D. E., Vogel, J. S., and Southon, J. R. (1988). Improved collagen extraction by modified Longin method. *Radiocarbon*, 30(2):171–177.

Bryant, F. and Loutit, J. (1964). The entry of strontium-90 into human bone. *Proceedings of the Royal Society of London B: Biological Sciences*, 159(976):449–465.

Buchardt, B., Bunch, V., and Helin, P. (2007). Fingernails and diet: Stable isotope signatures of a marine hunting community from modern Uummannaq, North Greenland. *Chemical Geology*, 244(1–2):316–329.

Buckley, H. R. (2000). Subadult health and disease in prehistoric Tonga, Polynesia. *American Journal of Physical Anthropology*, 113(4):481–505.

Buckley, H. R. (2001). *Health and Disease in the Prehistoric Pacific Islands*. PhD thesis, University of Otago.

Buckley, H. R., Kinaston, R., Halcrow, S. E., Foster, A., Spriggs, M., and Bedford, S. (2014). Scurvy in a tropical paradise? evaluating the possibility of infant and adult vitamin C deficiency in the Lapita skeletal sample of Teouma, Vanuatu, Pacific islands. *International Journal of Paleopathology*, 5(0):72–85.

Buckley, H. R., Tayles, N., Halcrow, S. E., Robb, K., and Fyfe, R. (2010). The people of Wairau Bar: a re-examination. *Journal of Pacific Archaeology*, 1(1):1–20.

Budd, P., Gulson, B. L., Montgomery, J., Rainbird, P., Thomas, R. G., and Young, S. M. M. (1996). Pb and Sr isotope composition of human dental enamel: an indicator of Pacific Islander population dynamics. In Galipaud, J.-C. and Lilley, I., editors, *The Western Pacific 5000 to 2000 BP: colonisation and transformations*, pages 301–311. Institut de Recherche pour le Developpement, Port Vila, Vanuatu.

Budd, P., Montgomery, J., Barreiro, B., and Thomas, R. G. (2000). Differential diagenesis of strontium in archaeological human dental tissues. *Applied Geochemistry*, 15(5):687–694.

Buehler, M. J. (2006). Nature designs tough collagen: Explaining the nanostructure of collagen fibrils. *Proceedings of the National Academy of Sciences*, 103(33):12285–12290.

Buikstra, J. E. and Ubelaker, D. H. (1994). *Standards for Data Collection from Human Skeletal Remains*. Arkansas Archaeological Survey Research Series No. 44. Arkansas Archaeological Survey, Fayetteville.

Burger, R. L., Lee-Thorp, J. A., and van der Merwe, N. J. (2003). Rite and crop in the Inca state revisited: an isotopic perspective from Machu Picchu and beyond. In Burger, R. L. and Salazar, L. C., editors, *The 1912 Yale Peruvian Scientific Expedition Collections from Maccu Picchu*, chapter 3, pages 119–137. Yale University Publications in Anthropology, New Haven, CT.

Burley, D. (2005). Mid-sequence archaeology at the Sigatoka Sand Dunes with interpretive implications for Fijian and Oceanic culture history. *Asian Perspectives*, 44(2):320–348.

Burley, D., Barton, A., Dickinson, W. R., Connaughton, S. P., and Taché, K. (2010). Nukuleka as a founder colony for West Polynesian settlement: New insights from recent excavations. *Journal of Pacific Archaeology*, 1(2):128–144.

Burley, D. and Clark, J. T. (2003). The archaeology of Fiji/Western Polynesia in the Post-Lapita era. In Sand, C., editor, *Pacific Archaeology: Assessments*

and Prospects, chapter 17, pages 221–35. Le Cahiers de l'Archeologie en Nouvelle Caledonie, Noumeá, New Caledonia.

Burley, D., Taché, K., Purser, M., and Balenaivalu, R. (2011). An archaeology of salt production in Fiji. *Antiquity*, 85(327):187–200.

Burley, D., Weisler, M. I., and Zhao, J.-x. (2012). High precision U/Th dating of first Polynesian settlement. *PLoS ONE*, 7(11):e48769.

Burley, D. V. (1996). Sport, status, and field monuments in the Polynesian chiefdom of Tonga: The pigeon snaring mounds of northern Ha'apai. *Journal of Field Archaeology*, 23(4):421–435.

Burley, D. V. (1998). Tongan archaeology and the Tongan past, 2850 - 150 B.P. *Journal of World Prehistory*, 12(3):337–392.

Burley, D. V. (2007). Tonga's Lapita beginning and its role in Polynesian origins. In Wood-Ellem, E., editor, *Tonga and the Tongans: heritage and identity*, page 264. E. Wood-Ellem for Tonga Research Association, Melbourne, Australia.

Burley, D. V. (2013). Fijian polygenesis and the Melanesian/Polynesian divide. *Current Anthropology*, 54(4):436–462.

Burley, D. V. and Dickinson, W. R. (2004). Late Lapita occupation and its ceramic assemblage at the Sigatoka Sand Dune Site, Fiji, and their place in Oceanic prehistory. *Archaeology in Oceania*, 39(1):12–25.

Burley, D. V. and Dickinson, W. R. (2010). Among Polynesia's first pots. *Journal of Archaeological Science*, 37(5):1020–1026.

Burley, D. V., Dickinson, W. R., Barton, A., and Jr, R. S. (2001). Lapita on the periphery. new data on old problems in the Kingdom of Tonga. *Archaeology in Oceania*, 36(2):89–104.

Burton, J. (2008). Bone chemistry and trace element analysis. In Katzenberg, M. A. and Saunders, S. R., editors, *Biological Anthropology of the Human Skeleton*, chapter 14, pages 443–460. John Wiley & Sons, Inc., Chichester, UK, second edition.

Burton, J. H. and Price, T. D. (1999). Evaluation of bone strontium as a measure of seafood consumption. *International Journal of Osteoarchaeology*, 9(4):233–236.

Burton, J. H. and Wright, L. E. (1995). Nonlinearity in the relationship between bone Sr/Ca and diet: Paleodietary implications. *American Journal of Physical Anthropology*, 96(3):273–282.

Buzon, M. R. (2012). The bioarchaeological approach to paleopathology. In Grauer, A. L., editor, *A companion to paleopathology*, chapter 4, pages 58–75. Blackwell Publishing Ltd., Chichester, UK, 1st edition.

Campbell, I. C. (1992). *Island Kingdom: Tonga Ancient and Modern*. Canterbury University Press, Christchurch, New Zealand.

Cao, J., Bai, X., Zhao, Y., Liu, J., Zhou, D., Fang, S., Jia, M., and Wu, J. (1996). The relationship of fluorosis and brick tea drinking in Chinese Tibetans. *Environmental Health Perspectives*, 104(12):1340–1343.

Cardoso, H. F. V. (2007). Accuracy of developing tooth length as an estimate

of age in human skeletal remains: The deciduous dentition. *Forensic Science International*, 172(1):17–22.

Carletto, C., Davis, B., Stampini, M., Trento, S., and Zezza, A. (2004). Internal mobility and international migration in Albania. Technical report, The Food and Agriculture Organization of the United Nations.

Carlson, A. K. (1996). Lead isotope analysis of human bone for addressing cultural affinity: a case study from Rocky Mountain House, Alberta. *Journal of Archaeological Science*, 23(4):557–567.

Casey, M. M. and Post, D. M. (2011). The problem of isotopic baseline: Reconstructing the diet and trophic position of fossil animals. *Earth-Science Reviews*, 106(1–2):131–148.

Casu, D., Ceccherelli, G., Sechi, N., Rumolo, P., and Sarà, G. (2009). *Caulerpa racemosa* var. *cylindracea* as a potential source of organic matter for benthic consumers: evidences from a stable isotope analysis. *Aquatic Ecology*, 43(4):1023–1029.

Chadwick, O. A., Derry, L. A., Vitousek, P. M., Huebert, B. J., and Hedin, L. O. (1999). Changing sources of nutrients during four million years of ecosystem development. *Nature*, 397(6719):491–497.

Chai, H., Lee, J. J.-W., Constantino, P. J., Lucas, P. W., and Lawn, B. R. (2009). Remarkable resilience of teeth. *Proceedings of the National Academy of Sciences*, 106(18):7289–7293.

Chattah, N. L.-T. and Smith, P. (2006). Variation in occlusal dental wear of two Chalcolithic populations in the southern Levant. *American Journal of Physical Anthropology*, 130(4):471–479.

Chenery, C. A., Pashley, V., Lamb, A. L., Sloane, H. J., and Evans, J. A. (2012). The oxygen isotope relationship between the phosphate and structural carbonate fractions of human bioapatite. *Rapid Communications in Mass Spectrometry*, 26(3):309–319.

Cheng, R., Yang, H., Shao, M.-y., Hu, T., and Zhou, X.-d. (2009). Dental erosion and severe tooth decay related to soft drinks: a case report and literature review. *Journal of Zhejiang University. Science. B*, 10(5):395–399.

Chiaradia, M., Gallay, A., and Todt, W. (2003). Different contamination styles of prehistoric human teeth at a Swiss necropolis (Sion, Valais) inferred from lead and strontium isotopes. *Applied Geochemistry*, 18(3):353–370.

Child, A. M. (1995a). Microbial taphonomy of archaeological bone. *Studies in Conservation*, 40(1):19–30.

Child, A. M. (1995b). Towards and understanding of the microbial decomposition of archaeological bone in the burial environment. *Journal of Archaeological Science*, 22(2):165–174.

Chisholm, B. S., Nelson, D. E., Hobson, K. A., Schwarcz, H. P., and Knyf, M. (1983). Carbon isotope measurement techniques for bone collagen: Notes for the archaeologist. *Journal of Archaeological Science*, 10(4):355–360.

Chishom, B. S., Nelson, D. E., and Schwarcz, H. P. (1982). Stable-carbon isotope ratios as a measure of marine versus terrestrial protein in ancient diets. *Science*, 216(4550):1131–1132.

Clark, G. and Anderson, A. (2000). The age of the Yanuca Lapita site, Viti Levu,

Fiji. *New Zealand Journal of Archaeology*, 22:15–30.

Clark, G. and Anderson, A. (2001). The pattern of Lapita settlement in Fiji. *Archaeology in Oceania*, 36(2):77–88.

Clark, G. and Anderson, A. (2009). Colonisation and culture change in the early prehistory of Fiji. In Clark, G. and Anderson, A., editors, *The early prehistory of Fiji*, number 31 in Terra Australis, chapter 16, pages 407–437. ANU Press, Canberra, Australia.

Clark, G., Burley, D., and Murray, T. (2008). Monumentality and the development of the Tongan maritime chiefdom. *Antiquity*, 82(318):994–1008.

Clark, G. R., Reepmeyer, C., Melekiola, N., Woodhead, J., Dickinson, W. R., and Martinsson-Wallin, H. (2014). Stone tools from the ancient Tongan state reveal prehistoric interaction centers in the Central Pacific. *Proceedings of the National Academy of Sciences*, 111(29):10491–10496.

Clark, J. T. (1991). Early settlement in the Indo-Pacific. *Journal of Anthropological Archaeology*, 10(1):27–53.

Clarke, N. G. and Hirsch, R. S. (1991). Physiological, pulpal, and periodontal factors influencing alveolar bone. In Kelley, M. A. and Larsen, C. S., editors, *Advances in Dental Anthropology*, chapter 14, pages 241–266. Wiley-Liss, Inc., New York, NY.

Clarkson, J. J. and McLoughlin, J. (2000). Role of fluoride in oral health promotion. *International Dental Journal*, 50(3):119–128.

Clement, A. F., Hillson, S. W., and Aiello, L. C. (2012). Tooth wear, Neanderthal facial morphology and the anterior dental loading hypothesis. *Journal of Human Evolution*, 62(3):367–376.

Cochrane, E. E. and Neff, H. (2006). Investigating compositional diversity among Fijian ceramics with laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS): implications for interaction studies on geologically similar islands. *Journal of Archaeological Science*, 33(3):378–390.

Cohen, M. N. (1994). The osteological paradox reconsidered. *Current Anthropology*, 35(5):629–637.

Cohen, M. N. (1997). Does paleopathology measure community health? a rebuttal of "the osteological paradox" and its implications for world history. In Paine, R. R., editor, *Integrating Archaeological Demography: Multidisciplinary Approaches to Prehistoric Population*. Center for Archaeological Investigations at Southern Illinois University, Carbondale, Illinois.

Collins, M. J. and Galley, P. (1998). Towards an optimal method of archaeological collagen extraction: the influence of pH and grinding. *Ancient Biomolecules*, 2:209–222.

Colonese, A. C., Collins, M., Lucquin, A., Eustace, M., Hancock, Y., de Almeida Rocha Ponzoni, R., Mora, A., Smith, C., DeBlasis, P., Figuti, L., Wesolowski, V., Plens, C. R., Eggers, S., de Farias, D. S. E., Gledhill, A., and Craig, O. E. (2014). Long-term resilience of Late Holocene coastal subsistence system in Southeastern South America. *PLoS ONE*, 9(4):e93854.

Coltrain, J. B. and Janetski, J. C. (2013). The stable and radio-isotope chemistry of southeastern Utah Basketmaker II burials: dietary analysis using the linear mixing model SISUS, age and sex patterning, geolocation and temporal patterning. *Journal of Archaeological Science*, 40(12):4711–4730.

Commendador, A. S., Dudgeon, J. V., Finney, B. P., Fuller, B. T., and Esh, K. S. (2013). A stable isotope (δ^{13}C and δ^{15}N perspective on human diet on Rapa Nui (Easter Island) ca. AD 1400 - 1900. *Am. J. Phys. Anthropol.*, 152(2):173–185.

Cook, J. (1967a). *Journals of Captain James Cook on his voyages of discovery*, volume 2. Cambridge University Press, Cambridge, UK.

Cook, J. (1967b). *Journals of Captain James Cook on his voyages of discovery*, volume 3. Cambridge University Press, Cambridge, UK.

Corbett, T. L. and Dawes, C. (1998). A comparison of the site-specificity of supragingival and subgingival calculus deposition. *Journal of Periodontology*, 69(1):1–8.

Cortés, E. (1999). Standardized diet compositions and trophic levels of sharks. *ICES Journal of Marine Science: Journal du Conseil*, 56(5):707–717.

Cox, M. (2000). Ageing adults from the skeleton. In Cox, M. and Mays, S., editors, *Human Osteology in Archaeology and Forensic Science*, pages 61–81. Greenwich Medical Media, London.

Cox, P. A. and Banack, S. A. (1991). *Islands, plants, and Polynesians: an introduction to Polynesian ethnobotany*. Dioscorides Press, Portland, Oregon.

Craig, O., Ross, R., Andersen, S. H., Milner, N., and Bailey, G. (2006). Focus: sulphur isotope variation in archaeological marine fauna from northern Europe. *Journal of Archaeological Science*, 33(11):1642 – 1646.

Crowther, A. (2005). Starch residues on undecorated Lapita pottery from Anir, New Ireland. *Archaeology in Oceania*, 40(2):62–66.

Currey, J. (2003). The many adaptations of bone. *Journal of Biomechanics*, 36(10):1487–1495.

Currey, J. D. (2002). *Bones: structure and mechanics*. Princeton University Press, Princeton, New Jersey.

Currie, T. E. and Mace, R. (2009). Political complexity predicts the spread of ethnolinguistic groups. *Proceedings of the National Academy of Sciences*, 106(18):7339–7344.

Curtis, V., de Barra, M., and Aunger, R. (2011). Disgust as an adaptive system for disease avoidance behaviour. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366(1563):389–401.

Dahlén, G. (2002). Microbiology and treatment of dental abscesses and periodontal-endodontic lesions. *Periodontology 2000*, 28(1):206–239.

D'Alessandro, W. (2006). Human fluorosis related to volcanic activity: a review. *Environmental Toxicology.*, 10:21–30.

Danenberg, P. J., Hirsch, R. S., Clarke, N. G., Leppard, P. I., and Richards, L. C. (1991). Continuous tooth eruption in Australian aboriginal skulls. *American Journal of Physical Anthropology*, 85(3):305–12.

Danforth, M. E. (1999). Nutrition and politics in prehistory. *Annual Review of Anthropology*, 28(1):1–25.

Darveau, R. P. (2010). Periodontitis: a polymicrobial disruption of host homeostasis. *Nautre Review Microbiology*, 8(7):481–490.

Davidson, J. (1969). Archaeological excavations in two burial mounds at 'Atele, Tongatapu. *Records of the Auckland Institute and Museum*, 6:251–286.

Davidson, J. (1977). Western Polynesia and Fiji: Prehistoric contact, diffusion and differentiation in adjacent archipelagos. *World Archaeology*, 9(1):82–94.

Davidson, J. (1979). Samoa and Tonga. In Jennings, J., editor, *The Prehistory of Polynesia*, pages 82–109. Harvard University Press, Cambridge, Massachusetts.

Davidson, J. (1984). *The prehistory of New Zealand*. Longman Paul, Auckland, New Zealand.

Davidson, J., Hinds, E., Holdaway, S., and Leach, B. F. (1990). Lapita site of Natunuku, Fiji. *New Zealand Journal of Archaeology*, 12:121–155.

Davidson, J. and Leach, F. (2001). The Strandlooper concept and economic naivety. In Clark, G., Anderson, A., and Vunidilo, T., editors, *The archaeology of Lapita dispersal in Oceania*, Terra Australis, chapter 9, pages 115–124. Pandanus Books, Canberra, Australia.

Davies, G. N. (1952). *Dental disease among the Polynesians of Pukapuka or Danger Island*. DDS thesis, University of Otago, Dunedin, New Zealand.

Davies, G. N. (1956). Dental conditions among the Polynesians of Pukapuka (Danger Island) II. the prevalence of periodontal disease. *Journal of Dental Research*, 35(5):734–741.

Dawson, T. E., Mambelli, S., Plamboeck, A. H., Templer, P. H., and Tu, K. P. (2002). Stable isotopes in plant ecology. *Annual Review of Ecology and Systematics*, 33:507–559.

de Laeter, J. R. (1998). Mass spectrometry and geochronology. *Mass Spectrometry Reviews*, 17(2):97–125.

De Menezes, A., Costa, I., and El-Guindy, M. (1984). Clinical manifestations of hypervitaminosis A in human gingiva: a case report. *Journal of Periodontology*, 55(8):474–476.

Dean, M. (2009). Extension rates and growth in tooth height of modern human and fossil hominin canines and molars. *Frontiers of oral biology*, 13:68–73.

Demirci, M., Tuncer, S., and Yuceokur, A. A. (2010). Prevalence of caries on individual tooth surfaces and its distribution by age and gender in university clinic patients. *European Journal of Dentistry*, 4(3):270–9.

Denham, T. (2013). Ancient and historic dispersals of sweet potato in oceania. *Proceedings of the National Academy of Sciences*, 110(6):1982–1983.

Denham, T. and Barton, H. (2006). The emergence of agriculture in New Guinea: A model of continuity from pre-existing foraging practices. In Kennett, D. and Winterhalder, B., editors, *Behavioral Ecology and the Transition to Agriculture*, chapter 11, pages 237–264. University of California Press, Berkley, California.

Denham, T. I. M., Ramsey, C. B., and Specht, J. I. M. (2012). Dating the appearance of Lapita pottery in the Bismarck Archipelago and its dispersal to Remote Oceania. *Archaeology in Oceania*, 47(1):39–46.

Denham, T. P., Haberle, S. G., Lentfer, C., Fullagar, R., Field, J., Therin, M., Porch, N., and Winsborough, B. (2003). Origins of agriculture at Kuk Swamp in the Highlands of New Guinea. *Science*, 301(5630):189–193.

Deniel, C. and Pin, C. (2001). Single-stage method for the simultaneous isolation of lead and strontium from silicate samples for isotopic measurements. *Analytica Chimica Acta*, 426(1):95–103.

DeNiro, M. J. (1985). Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature*, 317(6040):806–809.

DeNiro, M. J. (1987). Stable isotopy and archaeology. *American Scientist*, 75(2):182–191.

DeNiro, M. J. and Epstein, S. (1978). Influence of diet on the distribution of carbon isotopes in animals. *Geochimica et cosmochimica acta*, 42(5):495–506.

DeNiro, M. J. and Epstein, S. (1981). Influence of diet on the distribution of nitrogen isotopes in animals. *Geochimica et Cosmochimica Acta*, 45(3):341–351.

DeStefano, F., Anda, R. F., Kahn, H. S., Williamson, D. F., and Russell, C. M. (1993). Dental disease and risk of coronary heart disease and mortality. *BMJ: British Medical Journal*, 306(6879):688.

Deter, C. A. (2009). Gradients of occlusal wear in hunter-gatherers and agriculturalists. *American Journal of Physical Anthropology*, 138(3):247–54.

Dettwyler, K. A. (1995a). Beauty and the breast: The cultural context of breastfeeding in the United States. In Stuart-Macadam, P. and Dettwyler, K. A., editors, *Breastfeeding: Biocultural Perspectives*, Foundations of Human Behavior, chapter 7, pages 167–216. Aldine de Gruyter, Hawthorne, New York.

Dettwyler, K. A. (1995b). A time to wean: the hominid blueprint for the natural age of weaning in modern human populations. In Stuart-Macadam, P. and Dettwyler, K. A., editors, *Breastfeeding: Biocultural Perspectives*, chapter 2, pages 39–73. Aldine de Gruyter, Hawthorne, New York.

Diamond, J. (2000). Linguistics: Taiwan's gift to the world. *Nature*, 403(6771):709–710.

Diamond, J. (2011). Linguistics: Deep relationships between languages. *Nature*, 476(7360):291–292.

Diamond, J. and Bellwood, P. (2003). Farmers and their languages: The first expansions. *Science*, 300(5619):597–603.

Dias, G. J., Cook, R. B., and Mirhosseini, M. (2011). Influence of food consistency on growth and morphology of the mandibular condyle. *Clinical Anatomy*, 24(5):590–598.

Dias, G. J. and Tayles, N. (1997). 'Abscess cavity,' a misnomer. *International Journal of Osteoarchaeology*, 7(5):548–554.

Dickinson, W. R. (2007). Paleoenvironment of Lapita sites on Fanga 'Uta Lagoon, Tongatapu, Kingdom of Tonga.

In Bedford, S., Sand, C., and Connaughton, S. P., editors, *Oceanic Explorations: Lapita and Western Pacific Settlement*, Terra Australis, chapter 10, pages 177–186. ANU Press, Canberra, Australia.

Dickinson, W. R. and Burley, D. V. (2007). Geoarchaeology of Tonga: Geotectonic and geomorphic controls. *Geoarchaeology*, 22(2):229–259.

Dickinson, W. R. and Shutler, Richard, J. (2000). Implications of petrographic temper analysis for Oceanian prehistory. *Journal of World Prehistory*, 14(3):203–266.

Dickinson, W. R., Shutler, Richard, J., Shortland, R., Burley, D. V., and Dye, T. S. (1996). Sand tempers in indigenous Lapita and Lapitoid Polynesian Plainware and imported protohistoric Fijian pottery of Ha'apai (Tonga) and the question of Lapita tradeware. *Archaeology in Oceania*, 31(2):87–98.

Dietz, W. H. (1998). Childhood weight affects adult morbidity and mortality. *The Journal of Nutrition*, 128(2):411–414.

Dobberstein, R. C., Collins, M. J., Craig, O. E., Taylor, G., Penkman, K. E. H., and Ritz-Timme, S. (2009). Archaeological collagen: Why worry about collagen diagenesis? *Archaeological and Anthropological Sciences*, 1(1):31–42.

Dobney, K., Cucchi, T., and Larson, G. (2008). The pigs of Island Southeast Asia and the Pacific: New evidence for taxonomic status and human-mediated dispersal. *Asian Perspectives: the Journal of Archaeology for Asia and the Pacific*, 47(1):59–74.

Doherty, M. A. H., Blinkhorn, A. S., and Vane, E. S. (2010). Oral health in the Pacific Islands. *International Dental Journal*, 60(2):122–128.

Donohue, M. and Denham, T. (2012). Lapita and Proto-Oceanic: Thinking outside the pot? *The Journal of Pacific History*, 47(4):443–457.

Douglas, M. T., Pietrusewsky, M., and Ikehara-Quebral, R. M. (1997). Skeletal biology of Apurguan: A precontact Chamorro site on Guam. *American Journal of Physical Anthropology*, 104(3):291–313.

Dreizen, S. (1970). Vitamins and dental caries. In Gould, R. F., editor, *Dietary Chemicals vs. Dental Caries*, Advances in Chemistry, chapter 4, pages 33–45. American Chemical Society, Washington D.C.

Dufour, D. L. (2006). Biocultural approaches in human biology. *American Journal of Human Biology*, 18(1):1–9.

Dupras, T. L. and Tocheri, M. W. (2007). Reconstructing infant weaning histories at Roman period Kellis, Egypt using stable isotope analysis of dentition. *American Journal of Physical Anthropology*, 134(1):63–74.

D'Urville, J.-S.-C. D., Ollivier, I., de Biran, A., and Clark, G. (2003). On the islands of the great ocean. *The Journal of Pacific History*, 38(2):163–174.

d'Incau, E., Couture, C., and Maureille, B. (2012). Human tooth wear in the past and the present: Tribological mechanisms, scoring systems, dental and skeletal compensations. *Archives of Oral Biology*, 57(3):214–229.

Edgar, W. M. and Higham, S. M. (1991). Diet as a determinant of caries risk. In Johnson, N. W., editor, *Dental Caries: Markers of high and Low Risk Groups and Individuals*, volume 1 of *Risk Markers for Oral Diseases*. Cambridge University Press, Cambridge.

Edmondson, E. M. S. (1990). Paper D: Food composition and food cariogenicity factors affecting the cariogenic potential of foods. *Caries Research*, 24(Suppl. 1):60–71.

Edward, J. B. and Benfer (1993). The effects of diagenesis on the Paloma skeletal material. In Sandford, M. K., editor, *Investigations of ancient human tissue: chemical analyses in anthropology*, chapter 5, pages 183–268. Gordon and Breach, Langhorne, PA.

Eerkens, J. W., Berget, A. G., and Bartelink, E. J. (2011). Estimating weaning and early childhood diet from serial micro-samples of dentin collagen. *Journal of Archaeological Science*, 38(11):3101–3111.

Ehleringer, J. R. and Cerling, T. E. (2001). Photosynthetic pathways and climate. In Schulze, E.-D., Heimann, M., Harrison, S., Holland, E., Lloyd, J., Prentice, I. C., and Schimel, D., editors, *Global Biogeochemical Cycles in the Climate System*, chapter 1.21, pages 267–277. Academic Press, Waltham, MA.

Elderfield, H. (1986). Strontium isotope stratigraphy. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 57(1):71–90.

Elevitch, C. R., Abbott, I. A., and Leakey, R. R. B. (2006). *Traditional trees of Pacific Islands: their culture, environment, and use*. Permanent Agriculture Resources, Hōlualoa, Hawaii.

Epstein, S., Buchsbaum, R., Lowenstam, H., and Urey, H. C. (1951). Carbonate-water isotopic temperature scale. *Geological Society of America Bulletin*, 62(4):417–426.

Epstein, S., Buchsbaum, R., Lowenstam, H. A., and Urey, H. C. (1953). Revised carbonate-water isotopic temperature scale. *Geological Society of America Bulletin*, 64(11):1315–1326.

Ericson, J. E. (1985). Strontium isotope characterization in the study of prehistoric human ecology. *Journal of Human Evolution*, 14(5):503–514.

Erlandson, J. M. (2001). The archaeology of aquatic adaptations: paradigms for a new millennium. *Journal of Archaeological Research*, 9(4):287–350.

Erlandson, J. M., Graham, M. H., Bourque, B. J., Corbett, D., Estes, J. A., and Steneck, R. S. (2007). The kelp highway hypothesis: Marine ecology, the coastal migration theory, and the peopling of the Americas. *The Journal of Island and Coastal Archaeology*, 2(2):161–174.

Ettinger, B., Burr, D. B., and Ritchie, R. O. (2013). Proposed pathogenesis for atypical femoral fractures: Lessons from materials research. *Bone*, 55(2):495–500.

Evans, D. T. (1973). A preliminary evaluation of tooth tartar among the preconquest Maya of the Tayasal Area, El Peten, Guatemala. *American Antiquity*, 38(4):489–493.

Evans, J., Montgomery, J., and Wildman, G. (2009). Isotope domain mapping of $^{87}Sr/^{86}Sr$ biosphere variation on the Isle of Skye, Scotland. *Journal of the Geological Society*, 166(4):617–631.

Evans, J., Montgomery, J., Wildman, G., and Boulton, N. (2010). Spatial variations in biosphere $^{87}Sr/^{86}Sr$ in Britain. *Journal of the Geological Society*, 167(1):1–4.

Evans, J. A. (1987). *Comparative dental conditions in several prehistoric Oceanic groups*. PhD thesis, University of Otago.

Ewart, A., Collerson, K. D., Regelous, M., Wendt, J. I., and Niu, Y. (1998). Geochemical evolution within the Tonga–Kermadec–Lau arc–back-arc systems: the role of varying mantle wedge composition in space and time. *Journal of Petrology*, 39(3):331–368.

Fain, O. (2005). Musculoskeletal manifestations of scurvy. *Joint Bone Spine*, 72(2):124–128.

Faine, S. and Hercus, C. E. (1951). The nutritional status of Cook Islanders. *British Journal of Nutrition*, 5:327–343.

Faure, G. and Powell, J. L. (1972). *Strontium isotope geology*. Springer-Verlag, Berlin, Germany.

Fawell, J., Bailey, K., Chilton, J., Dahi, E., Fewtrell, L., and Magara, Y. (2006). *Fluoride in Drinking-water*. WHO Drinking-water Quality Series. IWA Publishing, London.

Featherstone, J. D. B. (1999). Prevention and reversal of dental caries: role of low level fluoride. *Community Dentistry and Oral Epidemiology*, 27(1):31–40.

Featherstone, J. D. B. (2000). Caries detection and prevention with laser energy. *Dental Clinics of North America*, 44(4):955–969.

Featherstone, J. D. B. (2004). The continuum of dental caries: Evidence for a dynamic disease process. *Journal of Dental Research*, 83(suppl 1):C39–C42.

Fejerskov, O. (2004). Changing paradigms in concepts on dental caries: Consequences for oral health care. *Caries Research*, 38(3):182–191.

Fenner, J. N., Clark, G., Cressey, A., Valentin, F., Olesen, S. H., and Armstrong, R. (2015). Isotopic uniformity and segregation in Tongan mounds. *Journal of Archaeological Science: Reports*, 2(June 2015):644–653.

Fernandes, R., Nadeau, M.-J., and Grootes, P. (2012). Macronutrient-based model for dietary carbon routing in bone collagen and bioapatite. *Archaeological and Anthropological Sciences*, 4(4):291–301.

Fernández-Mosquera, D., Vila-Taboada, M., and Grandal-d'Anglade, A. (2001). Stable isotopes data ($\delta^{13}C$, $\delta^{15}N$) from the cave bear (*Ursus spelaeus*): a new approach to its palaeoenvironment and dormancy. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 268(1472):1159–1164.

Ferraro, M. and Vieira, A. R. (2010). Explaining gender differences in caries: A multifactorial approach to a multifactorial disease. *International Journal of Dentistry*, 2010.

Ferreira, M. C., Batista, A. M., Ferreira, F. d. O., Ramos-Jorge, M. L., and Marques, L. S. (2014). Pattern of oral–maxillofacial trauma stemming from interpersonal physical violence and determinant factors. *Dental Traumatology*, 30(1):15–21.

Field, J. S. (2004). Environmental and climatic considerations: a hypothesis for

conflict and the emergence of social complexity in Fijian prehistory. *Journal of Anthropological Archaeology*, 23(1):79 – 99.

Field, J. S. (2005). Land tenure, competition and ecology in Fijian prehistory. *Antiquity*, 79(305):586–600.

Field, J. S., Cochrane, E. E., and Greenlee, D. M. (2009). Dietary change in Fijian prehistory: isotopic analyses of human and animal skeletal material. *Journal of Archaeological Science*, 36(7):1547–1556.

Fietzke, J. and Eisenhauer, A. (2006). Determination of temperature-dependent stable strontium isotope ($^{88}Sr/^{86}Sr$) fractionation via bracketing standard MC-ICP-MS. *Geochemistry, Geophysics, Geosystems*, 7(8):Q08009.

Fiji Meteorological Service (2006). The climate of Fiji. Information Sheet no. 35.

Fildes, V. A. (1986). *Breasts, bottles and babies: a history of infant feeding*. Edinburgh University Press, Edinburgh, Scotland.

Fisher, K. and Newton, W. E. (2002). Nitrogen fixation– a general overview. In Leigh, G. J., editor, *Nitrogen Fixation at the Millennium*, chapter 1, pages 1–34. Elsevier Science, Amsterdam, Kindgom of Netherlands.

Flanagan, J. G. (1989). Hierarchy in simple "egalitarian" societies. *Annual Review of Anthropology*, 18:245–266.

Fogel, M. L., Tuross, N., Johnson, B. J., and Miller, G. H. (1997). Biogeochemical record of ancient humans. *Organic Geochemistry*, 27(5–6):275–287.

Folayan, M., Owotade, F., Adejuyigbe, E., Sen, S., Lawal, B., and Ndukwe, K. (2007). The timing of eruption of the primary dentition in Nigerian children. *American Journal of Physical Anthropology*, 134(4):443–448.

Foley, R. A. (2004). The evolutionary ecology of linguistic diversity in human populations. In Jones, M., editor, *Traces of ancestry: studies in honour of Colin Renfrew*, pages 61–71. McDonald Institute, Cambridge, England.

Formicola, V. (1988). Interproximal grooving of teeth: Additional evidence and interpretation. *Current Anthropology*, 29(4):663–671.

Foster, A. V. (2011). *Gendered Divisions of Labour in Southeast Asian and Pacific Island Prehistory*. PhD thesis, University of Otago.

Franz-Odendaal, T. A., Lee-Thorp, J. A., and Chinsamy, A. (2003). Insights from stable light isotopes on enamel defects and weaning in Pliocene herbivores. *Journal of biosciences*, 28(6):765–773.

Frost, E. L. (1979). Fiji. In Jennings, J., editor, *The Prehistory of Polynesia*, chapter 3, pages 61–81. Australian National University Press, Canberra, Australia.

Frostell, G. (1969). Dental plaque pH in relation to intake of carbohydrate products. *Acta Odontologica Scandinavica*, 27(1-2):3–29.

Fry, A. J. and Grenby, T. H. (1972). The effects of reduced sucrose intake on the formation and composition of dental plaque in a group of men in the Antarctic. *Archives of Oral Biology*, 17(5):873–882.

Fry, B., Scalan, R., and Parker, P. (1983). $^{13}C/^{12}C$ ratios in marine food webs of

the Torres Strait, Queensland. *Marine and Freshwater Research*, 34(5):707–715.

Fry, B., Scalan, R. S., Winters, J. K., and Parker, P. L. (1982). Sulphur uptake by salt grasses, mangroves, and seagrasses in anaerobic sediments. *Geochimica et Cosmochimica Acta*, 46(6):1121–1124.

Frémondeau, D. (2012). *Rythmes saisonniers des élevages porcins archéologiques: propositions pour un protocole d'analyse isotopique*. PhD thesis, École doctorale Sciences de la Nature et de l'Homme (Paris).

Fuller, B. T., Fuller, J. L., Harris, D. A., and Hedges, R. E. M. (2006). Detection of breastfeeding and weaning in modern human infants with carbon and nitrogen stable isotope ratios. *American Journal of Physical Anthropology*, 129(2):279–293.

Fuller, B. T., Richards, M. P., and Mays, S. A. (2003). Stable carbon and nitrogen isotope variations in tooth dentine serial sections from Wharram Percy. *Journal of Archaeological Science*, 30(12):1673–1684.

Fure, S. and Zickert, I. (1990). Root surface caries and associated factors. *European Journal of Oral Sciences*, 98(5):391–400.

Gage, T. B., DeWitte, S., and Wood, J. W. (2012). Demography part 1: Mortality and migration. In Stinson, S., Bogin, B., and O'Rourke, D., editors, *Human Biology: An Evolutionary and Biocultural Perspective*, chapter 14, pages 695–756. Wiley-Blackwell, Hoboken, New Jersey, 2nd edition.

Galbany, J. and Perez-Perez, A. (2004). Buccal enamel microwear variability in Cercopithecoidea primates as a reflection of dietary habits in forested and open savanna environments. *Anthropologie*, 42(1):13–19.

Geddes, D. (1994). Diet patterns and caries. *Advances in Dental Research*, 8(2):221–224.

George, A. (2013). *Dental pathology profile of pre-European Maori and Moriori*. PhD thesis, University of Otago, Dunedin, NZ.

Geyh, M. A. (2001). Bomb radiocarbon dating of animal tissues and hair. *Radiocarbon*, 43(2b):723–730.

Giacaman, R. A., Jobet-Vila, P., and Muñoz-Sandoval, C. (2014). Fatty acid effect on sucrose-induced enamel demineralization and cariogenicity of an experimental biofilm–caries model. *Odontology*, pages 1–8.

Gill, J. B. (1984). Sr-Pb-Nd isotopic evidence that both MORB and OIB sources contribute to Oceanic island arc magmas in Fiji. *Earth and Planetary Science Letters*, 68(3):443 – 458.

Gill, W. W. (1979). *Cook Islands custom*. University of the South Pacific, Rarotonga, Cook Islands.

Gillman, M. W. (1995). Mothers, babies, and disease in later life. *BMJ*, 310(6971):68–69.

Goffer, Z. (2007). *Archaeological Chemistry*. Chemical Analysis. Wiley, Hoboken, NJ, 2nd edition.

Goldberg, M., Kulkarni, A. B., Young, M., and Boskey, A. (2011). Dentin: Structure, composition and mineralization: The role of dentin ECM in dentin formation and mineralization. *Frontiers in bioscience*, 3:711–735.

Goodman, A. H. (1993). On the interpretation of health from skeletal remains. *Current Anthropology*, 34(3):281–288.

Goodman, A. H. and Armelagos, G. J. (1988). Childhood stress and decreased longevity in a prehistoric population. *American Anthropologist*, 90:936–944.

Goodman, A. H. and Leatherman, T. L., editors (1998). *Building a New Biocultural Synthesis: Political-Economic Perspectives on Human Biology*. Linking Levels of Analysis. The University of Michigan Press, Ann Arbor, MI.

Gopinath, V. K. and Arzreanne, A. R. (2006). Saliva as a diagnostic tool for assessment of dental caries. *Archives of Orofacial Sciences*, 1(57-59):57–59.

Grandjean, P. and Patterson, C. C. (1988). Ancient skeletons as silent witnesses of lead exposures in the past. *Critical Reviews in Toxicology*, 19(1):11–21.

Gray, R. D. and Jordan, F. M. (2000). Language trees support the express-train sequence of Austronesian expansion. *Nature*, 405(6790):1052–1055.

Green, R. (1963a). Two collections of pottery from Sigatoka, Fiji. *Journal of the Polynesian Society*, 72:261–264.

Green, R. (1995). Linguistic, biological, and cultural origins of the initial inhabitants of Remote Oceania. *New Zealand Journal of Archaeology*, 17:5–27.

Green, R. C. (1963b). A suggested revision of the Fijian sequence. *The Journal of the Polynesian Society*, 72(3):235–253.

Green, R. C. (1967). The immediate origin of the Polynesians. In Highland, G. A., Force, R. W., Howard, A., Kelly, M., and Sinoto, Y. H., editors, *Polynesian Culture History: essays in honor of Kenneth P. Emory*, pages 215–240. Bishop Museum Press, Honolulu, Hawaii.

Green, R. C. (1976). Lapita sites in the Santa Cruz group. In Green, R. C. and Cresswell, M. M., editors, *Southeast Solomon Island Cultural History: A Preliminary Survey*, chapter 16, pages 245–265. Bulletin of the Royal Society of New Zealand, Wellington, New Zealand.

Green, R. C. (1979). Lapita. In Jennings, J., editor, *The Prehistory of Polynesia*, pages 27–60. Harvard University Press, Cambridge, Massachusetts.

Green, R. C. (1991). Near and Remote Oceania- disestablishing "Melanesia" in culture history. In Pawley, A., editor, *Man and a Half: Essays in Pacific Anthropology and Ethnobiology in Honour of Ralph Bulmer*, pages 491–502. The Polynesian Society, Auckland, New Zealand.

Greene, D. L. (1970). Environmental influences on Pleistocene hominid dental evolution. *BioScience*, 20(5):276–279.

Greene, D. L. (1972). Dental anthropology of early Egypt and Nubia. *Journal of Human Evolution*, 1(3):315–324.

Greenhill, S. and Clark, R. (2011). POLLEX-online: The Polynesian lexicon project online. *Oceanic Linguistics*, 50(2):551–559.

Greenwood, M. J. (1975). Research on internal migration in the United States: A survey. *Journal of Economic Literature*, 13(2):397–433.

Griffin, S. O., Griffin, P. M., Swann, J. L., and Zlobin, N. (2004). Estimating rates of new root caries in older adults. *Journal of Dental Research*, 83(8):634–638.

Griffin, S. O., Griffin, P. M., Swann, J. L., and Zlobin, N. (2005). New coronal caries in older adults: Implications for prevention. *Journal of Dental Research*, 84(8):715–720.

Griffin, S. O., Regnier, E., Griffin, P. M., and Huntley, V. (2007). Effectiveness of fluoride in preventing caries in adults. *Journal of Dental Research*, 86(5):410–415.

Gröning, M. (2004). International stable isotope reference materials. In de Groot, P. A., editor, *Handbook of Stable Isotope Analytical Techniques*, chapter 40, pages 874–906. Elsevier, Amsterdam, Kingdom of the Netherlands.

Groube, L. M. (1971). Tonga, Lapita pottery, and Polynesian origins. *The Journal of the Polynesian Society*, 80(3):278–316.

Grueger, B. (2004). Weaning from the breast. *Paediatrics & Child Health*, 9(4):249–253.

Gunn, B. F., Baudouin, L., and Olsen, K. M. (2011). Independent origins of cultivated coconut (*Cocos nucifera L.*) in the Old World Tropics. *PLoS ONE*, 6(6):e21143.

Gurney, B. and Huschart, J. H. (1950). A dietary aspect of calculus. *Journal of Dental Research*, 29(1):63–67.

Gushulak, B. D. and MacPherson, D. W. (2006). The basic principles of migration health: population mobility and gaps in disease prevalence. *Emerging Themes in Epidemiology*, 3(3).

Gustafsson, B. E., Quensel, C.-E., Lanke, L. S., Lundqvist, C., Grahnen, H., Bonow, B. E., and Krasse, B. (1953). The effect of different levels of carbohydrate intake on caries activity in 436 individuals observed for five years. *Acta Odontologica Scandinavica*, 11(3-4):232–364.

Hagerman, D. B. and Faust, R. A. (1955). Use of vanadium pentoxide in combustion method for sulfur in refactory materials. *Analytical Chemistry*, 27(12):1970–1972.

Halcrow, S. E., Harris, N. J., Tayles, N., Ikehara-Quebral, R., and Pietrusewsky, M. (2013). From the mouths of babes: Dental caries in infants and children and the intensification of agriculture in mainland Southeast Asia. *American Journal of Physical Anthropology*, 150(3):409–20.

Halcrow, S. E. and Tayles, N. (2011). The bioarchaeological investigation of children and childhood. In Agarwal, S. C. and Glencross, B. A., editors, *Social Bioarchaeology*, Blackwell Studies in Global Archaeology. Blackwell Publishing, West Sussex, England.

Halcrow, S. E., Tayles, N., and Buckley, H. R. (2007). Age estimation of children from prehistoric Southeast Asia: are the dental formation methods used appropriate? *Journal of Archaeological Science*, 34(7):1158–1168.

Hall, R. L. (1967). Those late corn dates: Isotopic fractionation as a source of error in carbon-14 dates. *Michigan Archaeologist*, 13(4):171–180.

Handy, E. S. C. and Pukui, M. K. (1952). The Polynesian family system in Ka-u, Hawai'i. *The Journal of the Polynesian Society*, 61(3 & 4):243–282.

Haneklaus, S., Bloem, E., and Schnug, E. (2003). The global sulphur cycle and its link to plant environment. In Abrol, Y. P. and Ahmad, A., editors, *Sulphur*

in plants, chapter 1, pages 1–28. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Hardy, K., Blakeney, T., Copeland, L., Kirkham, J., Wrangham, R., and Collins, M. (2009). Starch granules, dental calculus and new perspectives on ancient diet. *Journal of Archaeological Science*, 36(2):248–255.

Harris, D. R. (2007). Agriculture, cultivation and domestication: Exploring the conceptual framework of early food production. In Denham, T., Iriarte, J., and Vrydaghs, L., editors, *Rethinking Agriculture: Archaeological and Ethnoarchaeological Perspectives*, pages 16–35. Left Coast Press, Walnut Creek, California.

Hartman, G. (2011). Are elevated δ^{15}N values in herbivores in hot and arid environments caused by diet or animal physiology? *Functional Ecology*, 25(1):122–131.

Hastorf, C. A. (1988). The use of paleoethnobotanical data in prehistoric studies of crop production, processing, and consumption. In Hastorf, C. A. and Popper, V. S., editors, *Current Paleoethnobotany: Analytical Methods and Cultural Interpretations of Archaeological Plant Remains*, chapter 8, pages 119–144. The University of Chicago Press, Chicago, Illinois.

Hatch, K. (2012). The use and application of stable isotope analysis to the study of starvation, fasting, and nutritional stress in animals. In McCue, M. D., editor, *Comparative Physiology of Fasting, Starvation, and Food Limitation*, chapter 20, pages 337–364. Springer-Verlag Berlin Heidelberg, Heidelberg Germany.

Hatch, K. A., Crawford, M. A., Kunz, A. W., Thomsen, S. R., Eggett, D. L., Nelson, S. T., and Roeder, B. L. (2006). An objective means of diagnosing anorexia nervosa and bulimia nervosa using $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios in hair. *Rapid communications in mass spectrometry*, 20(22):3367–3373.

Hatch, M. D. and Slack, C. R. (1966). Photosynthesis by sugar-cane leaves. a new carboxylation reaction and the pathway of sugar formation. *Biochemical Journal*, 101(1):103–111.

Heaton, T. H. E. (1999). Spatial, species, and temporal variations in the $^{13}C/^{12}C$ ratios of C_3 plants: Implications for palaeodiet studies. *Journal of Archaeological Science*, 26(6):637–649.

Hedges, R. E. M. (2002). Bone diagenesis: an overview of processes. *Archaeometry*, 44(3):319–328.

Hedges, R. E. M. (2004). Isotopes and red herrings: comments on Milner et al. and Lidén et al. *Antiquity*, 78(299):34–37.

Hedges, R. E. M., Clement, J. G., Thomas, C. D. L., and O'Connell, T. C. (2007). Collagen turnover in the adult femoral mid-shaft: Modeled from anthropogenic radiocarbon tracer measurements. *American Journal of Physical Anthropology*, 133(2):808–816.

Hedges, R. E. M. and Reynard, L. M. (2007). Nitrogen isotopes and the trophic level of humans in archaeology. *Journal of Archaeological Science*, 34(8):1240–1251.

Helu, F. (1995). Brother/sister and gender relations in ancient and modern Tonga. *Journal de la Société des océanistes*, 100(100-101):191–200.

Henry, A. G., Brooks, A. S., and Piperno, D. R. (2011). Microfossils in calculus demonstrate consumption of plants and cooked foods in Neanderthal diets (Shanidar III, Iraq; Spy I and II, Belgium). *Proceedings of the National Academy of Sciences of the United States of America*, 108(2):486–491.

Hesslein, R. H., Capel, M. J., Fox, D. E., and Hallard, K. A. (1991). Stable isotopes of sulfur, carbon, and nitrogen as indicators of trophic level and fish migration in the Lower Mackenzie River Basin, Canada. *Canadian Journal of Fisheries and Aquatic Sciences*, 48(11):2258–2265.

Hezel, F. X. (2001). *The New Shape of Old Island Cultures: A Half Century of Social Change in Micronesia*. University of Hawai'i Press, Honolulu, Hawai'i.

Hillson, S. (1996). *Dental Anthropology*. Cambridge University Press, Cambridge, UK.

Hillson, S. (2001). Recording dental caries in archaeological human remains. *International Journal of Osteoarchaeology*, 11(4):249–289.

Hillson, S. (2006). *Teeth*. Manuals in Archaeology. Cambridge University Press, Cambridge, UK, second edition.

Hillson, S. (2008). Dental pathology. In Katzenberg, M. A. and Saunders, S. R., editors, *Biological Anthropology of the Human Skeleton*, chapter 10, pages 301–340. John Wiley and Sons, Inc., Hoboken, NJ, 2nd edition.

Hillson, S. W. (1979). Diet and dental disease. *World Archaeology*, 11(2):147–162.

Hillson, S. W. (2000). Dental pathology. In Katzenberg, M. A. and Saunders, S. R., editors, *Biological Anthropology of the Human Skeleton*, chapter 9, pages 249–286. Wiley-Liss, New York, NY.

Hinton, R. J. (1981). Form and patterning of anterior tooth wear among aboriginal human groups. *American Journal of Physical Anthropology*, 54(4):555–564.

Hobson, K. A., Alisauskas, R. T., and Clark, R. G. (1993). Stable-nitrogen isotope enrichment in avian tissues due to fasting and nutritional stress: implications for isotopic analyses of diet. *Condor*, 95:388–394.

Hodell, D. A., Mead, G. A., and Mueller, P. A. (1990). Variation in the strontium isotopic composition of seawater (8 Ma to present): Implications for chemical weathering rates and dissolved fluxes to the oceans. *Chemical Geology: Isotope Geoscience section*, 80(4):291–307.

Hoefs, J. (2009). *Stable Isotope Geochemistry*. Springer-Verlag, Berlin, Germany, 6th edition.

Hooton, E. (1930). The Indians of Pecos Pueblo, a study of their skeletal remains. Technical report, Yale University Press, Andover, MA.

Hoppe, K. A., Koch, P. L., and Furutani, T. T. (2003). Assessing the preservation of biogenic strontium in fossil bones and tooth enamel. *International Journal of Osteoarchaeology*, 13(1-2):20–28.

Horrocks, M. and Bedford, S. (2005). Microfossil analysis of Lapita deposits in Vanuatu reveals introduced *Araceae* (aroids). *Archaeology in Oceania*, 40(2):67–74.

Horrocks, M., Nieuwoudt, M. K., Kinaston, R., Buckley, H., and Bedford, S. (2013). Microfossil and Fourier Transform Infrared analyses of Lapita and post-Lapita

human dental calculus from Vanuatu, Southwest Pacific. *Journal of the Royal Society of New Zealand*, 44(1):17–33.

Horrocks, M. and Nunn, P. D. (2007). Evidence for introduced taro (*Colocasia esculenta*) and lesser yam (*Dioscorea esculenta*) in Lapita-era (c. 3050–2500 cal. BP) deposits from Bourewa, southwest Viti Levu Island, Fiji. *Journal of Archaeological Science*, 34(5):739–748.

Howell, D. C. (2008). The analysis of missing data. In Outhwaite, W. and Turner, S., editors, *Handbook of Social Science Methodology*, chapter 11, pages 208–224. Sage, London, UK.

Howells, W. W. (1973). *The Pacific Islanders*. Reed, Sydney, Australia.

Howie, P. W. (2002). Protective effect of breastfeeding against infection in the first and second six months of life. In *Integrating Population Outcomes, Biological Mechanisms and Research Methods in the Study of Human Milk and Lactation*, Advances in Experimental Medicine and Biology, chapter 16, pages 141–147. Springer Science+Business Media New York, New York, New York.

Hrdlička, A. (1940). *Ritual ablation of front teeth in Siberia and America*, volume 99, no. 3 of *Smithsonian miscellanous collections*. The Smithsonian Institute, Washington, DC.

Huebert, J. M., Allen, M. S., and Wallace, R. T. (2010). Polynesian earth ovens and their fuels: Wood charcoal remains from Anaho Valley, Nuku Hiva, Marquesas Islands. *The Journal of the Polynesian Society*, 119(1):61–97.

Hughes, R. G. and Lawrence, M. A. (2005). Globalization, food and health in Pacific Island countries. *Asia Pacific journal of clinical nutrition*, 14(4):298–306.

Humphrey, L. T. (2010). Weaning behaviour in human evolution. *Seminars in Cell & Developmental Biology*, 21(4):453–461.

Hung, S., Chen, Y., Wan, H., Liu, T., Chen, Y., and Ling, L. (2000). Effects of areca nut extracts on the functions of human neutrophils *in vitro*. *Journal of Periodontal Research*, 35(4):186–193.

Hunt, T. L. (1986). Conceptual and substantive issues in Fijian prehistory. In Kirch, P. V., editor, *Island Societies: archaeological approaches to evolution and transformation*, New Directions in Archaeology, chapter 3, pages 20–31. Cambridge University Press, Cambridge, England.

Hunt, T. L. (1987). Patterns of human interaction and evolutionary divergence in the Fiji Islands. *The Journal of the Polynesian Society*, 96(3):299–334.

Iida, H., Auinger, P., Billings, R. J., and Weitzman, M. (2007). Association between infant breastfeeding and early childhood caries in the United States. *Pediatrics*, 120(4):e944–e952.

Ikehara-Quebral, R. and Douglas, M. T. (1997). Cultural alteration of human teeth in the Mariana Islands. *American Journal of Physical Anthropology*, 104(3):381–391.

Indriati, E. and Buikstra, J. E. (2001). Coca chewing in prehistoric coastal Peru: Dental evidence. *American Journal of Physical Anthropology*, 114(3):242–257.

Inoue, N. (1993). *Culture of Food and Oral Health in Maori*. Therapeia Publishing Co., Tokyo, Japan.

Iwasaki, M., Manz, M. C., Taylor, G. W., Yoshihara, A., and Miyazaki, H. (2012). Relations of serum ascorbic acid and alpha-tocopherol to periodontal disease. *Journal of Dental Research*, 91(2):167–172.

Jackes, M. (1993). On paradox and osteology. *Current Anthropology*, 34(4):434–439.

Jansen, A. A. J. (1982). Malnutrition and child feeding practices in the Kingdom of Tonga. *Journal of Tropical Pediatrics*, 28(4):202–208.

Jardine, T. D., Kidd, K. A., and Fisk, A. T. (2006). Applications, considerations, and sources of uncertainty when using stable isotope analysis in ecotoxicology. *Environmental Science and Technology*, 40(24):7501–7511.

Jarić, J. (2004). *Use of Pb and Sr Isotopes in Human Teeth as an Indicator of Pacific Islander Population Dynamics*. PhD thesis, University of Western Sydney.

Jay, M., Fuller, B. T., Richards, M. P., Knüsel, C. J., and King, S. S. (2008). Iron Age breastfeeding practices in Britain: Isotopic evidence from Wetwang Slack, East Yorkshire. *American Journal of Physical Anthropology*, 136(3):327–337.

Jelliffe, D. B. (1967). Parallel food classifications in developing and industrialized countries. *The American Journal of Clinical Nutrition*, 20(3):279–281.

Jelliffe, D. B. (1968). *Infant Nutrition in the Subtropics and Tropics*, volume 29 of *World Health Organization Monograph Series*. World Health Organization, Geneva, Switzerland, 2nd edition.

Jenkins, G. N. (1979). Salivary effects on plaque pH. In Kleinburg, I., Ellison, S. A., and Mandel, I. D., editors, *Saliva and Dental Caries*, pages 307–322. Information Retrieval, Inc., New York City, London.

Jenkins, W. M. and Kinane, D. F. (1989). The 'high risk' group in periodontitis. *British Dental Journal*, 167(5):168–171.

Jiang, X., Ye, M., Jiang, X., Liu, G., Feng, S., Cui, L., and Zou, H. (2007). Method development of efficient protein extraction in bone tissue for proteome analysis. *Journal of Proteome Research*, 6(6):2287–2294.

Jinam, T. A., Hong, L.-C., Phipps, M. E., Stoneking, M., Ameen, M., Edo, J., and Saitou, N. (2012). Evolutionary history of continental Southeast Asians: "early train" hypothesis based on genetic analysis of mitochondrial and autosomal DNA data. *Molecular Biology and Evolution*, 29(11):3513–3527.

Johnson, C. M., Lipman, P. W., and Czamanske, G. K. (1990). H, O, Sr, Nd, and Pb isotope geochemistry of the Latir volcanic field and cogenetic intrusions, New Mexico, and relations between evolution of a continental magmatic center and modifications of the lithosphere. *Contributions to Mineralogy and Petrology*, 104(1):99–124.

Jones, A. M., O'Connell, T. C., Young, E. D., Scott, K., Buckingham, C. M., Iacumin, P., and Brasier, M. D. (2001). Biogeochemical data from well preserved 200 ka collagen and skeletal remains. *Earth and Planetary Science Letters*, 193(1–2):143–149.

Jones, S. (2009). *Food and Gender in Fiji:*

Ethnoarchaeological explorations. Lexington Books, Lanham, MD.

Jones, S. and Quinn, R. L. (2009). Prehistoric Fijian diet and subsistence: integration of faunal, ethnographic, and stable isotopic evidence from the Lau Island Group. *Journal of Archaeological Science*, 36(12):2742–2754.

Jørkov, M. L. S., Heinemeier, J., and Lynnerup, N. (2007). Evaluating bone collagen extraction methods for stable isotope analysis in dietary studies. *Journal of Archaeological Science*, 34(11):1824–1829.

Joshipura, K., Rimm, E., Douglass, C., Trichopoulos, D., Ascherio, A., and Willett, W. (1996). Poor oral health and coronary heart disease. *Journal of Dental Research*, 75(9):1631–1636.

Juhl, M. (1983). Localization of carious lesions in occlusal pits and fissures of human premolars. *European Journal of Oral Sciences*, 91(4):251–255.

Junk, G. and Svec, H. J. (1958). The absolute abundance of the nitrogen isotopes in the atmosphere and compressed gas from various sources. *Geochimica et Cosmochimica Acta*, 14(3):234–243.

Kaeppler, A. L. (1971). Rank in Tonga. *Ethnology*, 10(2):174–193.

Kaeppler, A. L. (1978). Exchange patterns in goods and spouses: Fiji, Tonga and Samoa. *Mankind*, 11(3):246–252.

Kaifu, Y. (1999). Changes in the pattern of tooth wear from prehistoric to recent periods in Japan. *American Journal of Physical Anthropology*, 109(4):485–499.

Kalita, S. J. (2008). Nanostructured biomaterials. In Seal, S., editor, *Functional Nanostructures: Processing, Characterization, and Applications*, chapter 4, pages 168–219. Springer Science+Business Media New York, New York, New York.

Karn, K. W., Shockett, H. P., Moffitt, W. C., and Gray, J. L. (1984). Topographic classification of deformities of the alveolar process. *Journal of Periodontology*, 55(6):336–340.

Katzenberg, M. A. (2012). The ecological approach: understanding past diet and the relationship between diet and disease. In Grauer, A. L., editor, *A companion to paleopathology*, chapter 6, pages 97–113. Wiley-Blackwell, Chichester, UK.

Katzenberg, M. A., Herring, D. A., and Saunders, S. R. (1996). Weaning and infant mortality: Evaluating the skeletal evidence. *American Journal of Physical Anthropology*, 101:177–199.

Katzenberg, M. A. and Lovell, N. C. (1999). Stable isotope variation in pathological bone. *International Journal of Osteoarchaeology*, 9(5):316–324.

Katzenberg, M. A., Saunders, S. R., and Fitzgerald, W. R. (1993). Age differences in stable carbon and nitrogen isotope ratios in a population of prehistoric maize horticulturists. *American Journal of Physical Anthropology*, 90(3):267–281.

Katzenberg, M. A. and Weber, A. (1999). Stable isotope ecology and palaeodiet in the Lake Baikal region of Siberia. *Journal of Archaeological Science*, 26(6):651–659.

Kayser, M., Brauer, S., Cordaux, R., Casto, A., Lao, O., Zhivotovsky, L. A., Moyse-Faurie, C., Rutledge, R. B., Schiefenhoevel, W., Gil, D., Lin, A. A., Underhill, P. A., Oefner, P. J., Trent, R. J., and

Stoneking, M. (2006). Melanesian and Asian origins of Polynesians: mtDNA and Y chromosome gradients across the Pacific. *Molecular Biology and Evolution*, 23(11):2234–2244.

Kayser, M., Brauer, S., Weiss, G., Underhill, P. A., Roewer, L., Schiefenhövel, W., and Stoneking, M. (2000). Melanesian origin of Polynesian Y chromosomes. *Current Biology*, 10(20):1237–1246.

Keegan, W. F. (1989). Stable isotope analysis of prehistoric diet. In Işcan, M. Y. and Kennedy, K. A., editors, *Reconstruction of Life from the Skeleton*, pages 223–236. Alan R. Liss, New York, NY.

Keeling, C. D. (1979). The Suess effect: ^{13}Carbon-^{14}Carbon interrelations. *Environment International*, 2(4–6):229–300.

Keene, H. (1986). Dental caries prevalence in early Polynesians from the Hawaiian Islands. *Journal of Dental Research*, 65(6):935–938.

Keene, H. J. and Keene, A. (1985). Dental caries prevalence in early Hawaiian children. *Pediatric Dentistry*, 7:271–277.

Keeney, D. R. and Hatfield, J. L. (2001). The nitrogen cycle, historical perspective, and current and potential future concerns. In Follett, R. F. and Hatfield, J. L., editors, *Nitrogen in the Environment: Sources, Problems and Management*, chapter 1, pages 3–16. Elsevier Science, Amsterdam, Kingdom of the Netherlands.

Kelly, J. F. (2000). Stable isotopes of carbon and nitrogen in the study of avian and mammalian trophic ecology. *Canadian Journal of Zoology*, 78(1):1–27.

Kendall, E. J., Montgomery, J., Evans, J. A., Stantis, C., and Mueller, V. (2013). Mobility, mortality, and the Middle Ages: Identification of migrant individuals in a 14$^{\text{th}}$ century Black Death cemetery population. *American Journal of Physical Anthropology*, 150(2):210–222.

Kennedy, B. V. and Krouse, H. R. (1990). Isotope fractionation by plants and animals: implications for nutrition research. *Canadian Journal of Physiology and Pharmacology*, 68(7):960–972.

Kennett, D., Anderson, A., and Winterhalder, B. (2006). The ideal free distribution, food production, and the colonization of Oceania. In Kennett, D. and Winterhalder, B., editors, *Behavioral Ecology and the Transition to Agriculture*, chapter 12, pages 265–288. University of California Press, Berkley, CA.

Kerr, N. W. (1991). Prevalence and natural history of periodontal disease in Scotland –the mediaeval period (900–1600 A.D.). *Journal of Periodontal Research*, 26(4):346–354.

Kerr, N. W. (1998). Prevalence and natural history of periodontal disease in prehistoric scots (pre–900 AD). *Journal of Periodontal Research*, 33(3):131–137.

Kieser, J. (2012). Biomechanics of bone and bony trauma. In Kieser, J., Taylor, M., and Carr, D., editors, *Forensic Biomechanics*, chapter 3, pages 35–69. Wiley, Chichester, UK.

Kieser, J. A., Dennison, K. J., Kaidonis, J. A., Huang, D., Herbison, P. G. P., and Tayles, N. G. (2001). Patterns of dental wear in the early Maori dentition. *International Journal of Osteoarchaeology*, 11(3):206–217.

Kiljunen, M., Grey, J., Sinisalo, T., Harrod, C., Immonen, H., and Jones, R. I. (2006).

A revised model for lipid-normalizing $\delta^{13}C$ values from aquatic organisms, with implications for isotope mixing models. *Journal of Applied Ecology*, 43(6):1213–1222.

Kinaston, R. (2010). *Prehistoric Diet and Health in the Western Pacific Islands*. PhD thesis, University of Otago.

Kinaston, R., Bedford, S., Richards, M., Hawkins, S., Gray, A., Jaouen, K., Valentin, F., and Buckley, H. (2014a). Diet and human mobility from the Lapita to the Early Historic Period on Uripiv Island, Northeast Malakula, Vanuatu. *PLoS ONE*, 9(8):e104071.

Kinaston, R., Buckley, H., Gray, A., Shaw, B., and Mandui, H. (2013a). Exploring subsistence and cultural complexes on the south coast of Papua New Guinea using palaeodietary analyses. *Journal of Archaeological Science*, 40(2):904 – 913.

Kinaston, R., Buckley, H., Valentin, F., Bedford, S., Spriggs, M., Hawkins, S., and Herrscher, E. (2014b). Lapita diet in Remote Oceania: New stable isotope evidence from the 3000-year-old Teouma site, Efate Island, Vanuatu. *PLoS ONE*, 9(3):e90376.

Kinaston, R. and Buckley, H. R. (2013). The stable isotope analysis of prehistoric human diet Pacific islands with an emphasis on Lapita. In Summerhayes, G. Buckley, H., editor, *Pacific archaeology: documenting the past 50,000 years: papers from the 2011 Lapita Pacific Archaeology Conference*, number 25 in University of Otago studies in archaeology, chapter 7, pages 91–106. University of Otago Press, Dunedin, New Zealand.

Kinaston, R. L., Buckley, H. R., and Gray, A. (2013b). Diet and social status on Taumako, a Polynesian outlier in the Southeastern Solomon Islands. *American Journal of Physical Anthropology*, 151(4):589–603.

Kinaston, R. L., Buckley, H. R., Halcrow, S. E., Spriggs, M. J. T., Bedford, S., Neal, K., and Gray, A. (2009). Investigating foetal and perinatal mortality in prehistoric skeletal samples: a case study from a 3000-year-old Pacific Island cemetery site. *Journal of Archaeological Science*, 36(12):2780–2787.

Kinaston, R. L., Walter, R. K., Jacomb, C., Brooks, E., Tayles, N., Halcrow, S. E., Stirling, C., Reid, M., Gray, A. R., Spinks, J., Shaw, B., Fyfe, R., and Buckley, H. R. (2013c). The first New Zealanders: Patterns of diet and mobility revealed through isotope analysis. *PLoS ONE*, 8(5):e64580.

King, C. A. (2008). *Stable isotopic analysis of carbon and nitrogen as an indicator of paleodietary change among pre-state metal age societies in northeast Thailand*. Number 1788 in BAR International Series. British Archaeological Reports, Oxford, UK.

Kirch, P. V. (1978). The Lapitoid Period in West Polynesia: Excavations and survey in Niuatoputapu, Tonga. *Journal of Field Archaeology*, 5(1):1–13.

Kirch, P. V. (1979). Subsistence and ecology. In Jennings, J., editor, *The Prehistory of Polynesia*, pages 286–307. Harvard University Press, Cambridge, Massachusetts.

Kirch, P. V. (1984a). *Evolution of the Polynesian Chiefdoms*. New Studies in Archaeology. Cambridge University Press, Cambridge, England.

Kirch, P. V. (1984b). The Polynesian outliers: Continuity, change, and replacement. *The Journal of Pacific History*, 19(4):224–238.

Kirch, P. V. (1989). Second millennium B.C. arboriculture in Melanesia: Archaeological evidence from the Mussau Islands. *Economic Botany*, 43(2):225–240.

Kirch, P. V. (1997). *The Lapita peoples: Ancestors of the Oceanic world*. The Peoples of South-East Asia and the Pacific. Blackwell Publishers, Cambridge, Massachusetts.

Kirch, P. V. (2000). *On the Road of the Winds: An Archaeological History of the Pacific Islands before European Contact*. University of California Press, Berkeley and Los Angeles.

Kirch, P. V. and Dye, T. S. (1979). Ethnoarchaeology and the development of Polynesian fishing strategies. *The Journal of the Polynesian Society*, 88(1):53–76.

Kirch, P. V. and Green, R. C. (2001). *Hawaiki, Ancestral Polynesia: An Essay in Historical Anthropology*. Cambridge University Press, Cambridge, UK.

Kirch, P. V. and Hunt, T. L. (1997). *Historical ecology in the Pacific Islands: prehistoric environmental and landscape change*. Yale University Press, New Haven.

Kirch, P. V. and O'Day, S. J. (2003). New archaeological insights into food and status: A case study from pre-contact Hawaii. *World Archaeology*, 34(3):484–497.

Knudson, K. J., Williams, H. M., Buikstra, J. E., Tomczak, P. D., Gordon, G. W., and Anbar, A. D. (2010). Introducing $\delta^{88/86}$Sr analysis in archaeology: a demonstration of the utility of strontium isotope fractionation in paleodietary studies. *Journal of Archaeological Science*, 37(9):2352–2364.

König, K. G. (1963). Dental morphology in relation to caries resistance with special reference to fissures as susceptible areas. *Journal of Dental Research*, 42(1):461–476.

Konigsberg, L. W. and Frankenberg, S. R. (1994). Paleodemography: "not quite dead". *Evolutionary Anthropology: Issues, News, and Reviews*, 3(3):92–105.

Körner, C., Farquhar, G. D., and Roksandic, Z. (1988). A global survey of carbon isotope discrimination in plants from high altitude. *Oecologia*, 74(4):623–632.

Koulourides, T., Bodden, R., Keller, S., Manson-Hing, L., Lastra, J., and Housch, T. (1976). Cariogenicity of nine sugars tested with an intraoral device in man. *Caries Research*, 10(6):427–441.

Kramer, M. S., Vanilovich, I., Matush, L., Bogdanovich, N., Zhang, X., Shishko, G., Muller-Bolla, M., and Platt, R. W. (2007). The effect of prolonged and exclusive breast-feeding on dental caries in early school-age children. *Caries Research*, 41(6):484–488.

Krigbaum, J. (2005). Reconstructing human subsistence in the West Mouth (Niah Cave, Sarawak) burial series using stable isotopes of carbon. *Asian Perspectives*, 44(1):73–89.

Krueger, H. W. and Sullivan, C. H. (1984). Models for carbon isotope fractionation between diet and bone. In Turnlund,

J. R. and Johnson, P. E., editors, *Stable Isotopes in Nutrition*, chapter 15, pages 205–220. American Chemical Society, Washington, D.C.

Laffoon, J. E., Davies, G. R., Hoogland, M. L., and Hofman, C. L. (2012). Spatial variation of biologically available strontium isotopes ($^{87}Sr/^{86}Sr$) in an archipelagic setting: a case study from the Caribbean. *Journal of Archaeological Science*, 39(7):2371–2384.

Lalla, E., Cheng, B., Lal, S., Kaplan, S., Softness, B., Greenberg, E., Goland, R. S., and Lamster, I. B. (2007). Diabetes mellitus promotes periodontal destruction in children. *Journal of Clinical Periodontology*, 34(4):294–298.

Lambert, J. B., Szpunar, C. B., and Buikstra, J. E. (1979). Chemical analysis of excavated human bone from Middle and Late Woodland sites. *Archaeometry*, 21(2):115–129.

Lamster, I. B., Lalla, E., Borgnakke, W. S., and Taylor, G. W. (2008). The relationship between oral health and diabetes mellitus. *The Journal of the American Dental Association*, 139(suppl 5):19S–24S.

Landis, J. R. and Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 33(1):159–174.

Larsen, C. S. (1994). In the wake of Columbus: Native population biology in the postcontact Americas. *American Journal of Physical Anthropology*, 37(S19):109–154.

Larsen, C. S. (1995). Biological changes in human populations with agriculture. *Annual Review of Anthropology*, 24(1):185–213.

Larsen, C. S. (2002). Bioarchaeology: The lives and lifestyles of past people. *Journal of Archaeological Research*, 10(2):119–166.

Larson, G., Cucchi, T., Fujita, M., Matisoo-Smith, E., Robins, J., Anderson, A., Rolett, B., Spriggs, M., Dolman, G., Kim, T.-H., Thuy, N. T. D., Randi, E., Doherty, M., Due, R. A., Bollt, R., Djubiantono, T., Griffin, B., Intoh, M., Keane, E., Kirch, P., Li, K.-T., Morwood, M., Pedriña, L. M., Piper, P. J., Rabett, R. J., Shooter, P., Van den Bergh, G., West, E., Wickler, S., Yuan, J., Cooper, A., and Dobney, K. (2007). Phylogeny and ancient DNA of *Sus* provides insights into neolithic expansion in Island Southeast Asia and Oceania. *Proceedings of the National Academy of Sciences*, 104(12):4834–4839.

Layman, C. A., Araujo, M. S., Boucek, R., Hammerschlag-Peyer, C. M., Harrison, E., Jud, Z. R., Matich, P., Rosenblatt, A. E., Vaudo, J. J., Yeager, L. A., Post, D. M., and Bearhop, S. (2012). Applying stable isotopes to examine food-web structure: an overview of analytical tools. *Biological Reviews*, 87(3):545–562.

Leach, B. F. and Davidson, J. (2000). Fishing: a neglected aspect of Oceanic economy. In Anderson, A. and Murray, T., editors, *Australian Archaeologist: Collected papers in honour of Jim Allen*, chapter 30, pages 412–426. Coombs Academic Publishing, Canberra, Austalia.

Leach, B. F. and Davidson, J. (2008). *Archaeology on Taumako: A Polynesian Outlier in the Eastern Solomon Islands*. New Zealand Journal of Archaeology.

Leach, B. F., Quinn, C., Morrison, J., and Lyon, G. (2003). The use of multiple isotope signatures in reconstruct-

ing prehistoric human diet from archaeological bone from the Pacific and New Zealand. *New Zealand Journal of Archaeology*, 23:31–98.

Leach, H. (1997). The terminology of agricultural origins and food production systems—a horticultural perspective. *Antiquity*, 71(271):135–148.

Leach, H. (2003). Did East Polynesians have a concept of luxury foods? *World Archaeology*, 34(3):442–457.

Leach, H. and Green, R. C. (1989). New information for the Ferry Berth site, Mulifanua, western Samoa. *The Journal of the Polynesian Society*, 98(3):319–29.

Lee, J. J. W., Constantino, P. J., Lucas, P. W., and Lawn, B. R. (2011). Fracture in teeth—a diagnostic for inferring bite force and tooth function. *Biological Reviews*, 86(4):959–974.

Lee-Thorp, J. A. (2008). On isotopes and old bones. *Archaeometry*, 50(6):925–950.

Lee-Thorp, J. A., Sealy, J. C., and van der Merwe, N. J. (1989). Stable carbon isotope ratio differences between bone collagen and bone apatite, and their relationship to diet. *Journal of Archaeological Science*, 16(6):585 – 599.

Leigh, R. W. (1928). Dental pathology of aboriginal California. *University of California Publications in American Archaeology and Ethnology*, 23(10):399–440.

Levins, R. and Lewontin, R. (1985). *The Dialectical Biologist*. Harvard University Press, Cambridge, MA.

Levy, R. (1988). Self and identity. In Pollock, N. J. and Crocombe, R. G., editors, *French Polynesia: A Book of Selected Readings*, chapter 2, pages 8–28. University of the South Pacific, Suva, Fiji.

Levy, S. M. (2003). An update on fluorides and fluorosis. *Journal of the Canadian Dental Association*, 69(5):286–291.

Lewis, M. E. (2007). *The bioarchaeology of children*. Cambridge Studies in Biological and Evolutionary Anthropology. Cambridge University Press, Cambridge, UK.

Li, X., Kolltveit, K. M., Tronstad, L., and Olsen, I. (2000). Systemic diseases caused by oral infection. *Clinical Microbiology Reviews*, 13(4):547–558.

Libby, W. F. (1946). Atmospheric helium three and radiocarbon from cosmic radiation. *Physical Review*, 69(11-12):671–672.

Lieber, M. (1999). Tale telling on a Polynesian Atoll. In MacDonald, M. R., editor, *Traditional Storytelling Today: An international sourcebook*, chapter 34, pages 176–180. Routledge, New York, NY.

Lieverse, A. R. (1999). Diet and the aetiology of dental calculus. *International Journal of Osteoarchaeology*, 9(4):219–232.

Linde, A. and Goldberg, M. (1993). Dentinogenesis. *Critical Reviews in Oral Biology & Medicine*, 4(5):679–728.

Ling, L. J., Hung, S. L., Tseng, S. C., Chen, Y. T., Chi, L. Y., Wu, K. M., and Lai, Y. L. (2001). Association between betel quid chewing, periodontal status and periodontal pathogens. *Oral Microbiology and Immunology*, 16(6):364–369.

Lingstrom, P., van Houte, J., and Kashket, S. (2000). Food starches and dental caries. *Critical Reviews in Oral Biology & Medicine*, 11(3):366–380.

Littleton, J. and Frohlich, B. (1993). Fish-eaters and farmers: Dental pathology in the Arabian Gulf. *American Journal of Physical Anthropology*, 92(4):427–447.

Löe, H., Ånerud, A., and Boysen, H. (1992). The natural history of periodontal disease in man: prevalence, severity, and extent of gingival recession. *Journal of periodontology*, 63(6):489–95.

Löe, H., Theilade, E., and Jensen, S. B. (1965). Experimental gingivitis in man. *Journal of Periodontology*, 36(3):177–187.

Longin, R. (1971). New method of collagen extraction for radiocarbon dating. *Nature*, 230(5291):241–242.

Lovejoy, C. O. (1985). Dental wear in the Libben population: Its functional pattern and role in the determination of adult skeletal age at death. *American Journal of Physical Anthropology*, 68(1):47–56.

Lovell, N. C. (1997). Trauma analysis in paleopathology. *Yearbook of Physical Anthropology*, 40:139–170.

Lukacs, J. R. (1989). Dental paleopathology: Methods for reconstructing health status and dietary patterns in prehistory. In İşcan, M. Y. and Kennedy, K. A., editors, *Reconstructing Life from the Skeleton*, pages 261–286. Liss, New York, NY.

Lukacs, J. R. (1992). Dental paleopathology and agricultural intensification in South Asia: New evidence from Bronze Age Harappa. *American Journal of Physical Anthropology*, 87(2):133–150.

Lukacs, J. R. (1995). The 'caries correction factor': A new method of calibrating dental caries rates to compensate for antemortem loss of teeth. *International Journal of Osteoarchaeology*, 5(2):151–156.

Lukacs, J. R. (2007). Dental trauma and antemortem tooth loss in prehistoric Canary Islanders: prevalence and contributing factors. *International Journal of Osteoarchaeology*, 17(2):157–173.

Lukacs, J. R. (2008). Fertility and agriculture accentuate sex differences in dental caries rates. *Current Anthropology*, 49(5):901–914.

Lukacs, J. R. (2012). Oral health in past populations: Context, concepts and controversies. In Grauer, A. L., editor, *A Companion to Paleopathology*. Wiley-Blackwell, West Sussex, UK.

Lukacs, J. R. and Largaespada, L. (2006). Explaining sex differences in dental caries prevalence: Saliva, hormones, and "life-history" etiologies. *American Journal of Human Biology*, 18:540–555.

Lukacs, J. R. and Thompson, L. M. (2006). Dental caries prevalence by sex in prehistory: magnitude and meaning. In Irish, J. D. and Nelson, G. C., editors, *Technique and Application in Dental Anthropology*, Cambridge studies in Biological and Evolutionary Anthropology. Cambridge University Press, Cambridge, UK.

Lum, J. K., McIntyre, J. K., Greger, D. L., Huffman, K. W., and Vilar, M. G. (2006). Recent Southeast Asian domestication and Lapita dispersal of sacred male pseudohermaphroditic "tuskers" and hairless pigs of Vanuatu. *Proceedings of the National Academy of Sciences*, 103(46):17190–17195.

Luoma, H., Turtola, L., Kuokka, I., and Kaartinen, A. (1970). Plaque pH during and after ingestion of solid sugar. *Journal of Dental Research*, 49(1):79–85.

Ma, P. H. and Teaford, M. F. (2010). Diet reconstruction in antebellum Baltimore: Insights from dental microwear analysis. *American Journal of Physical Anthropology*, 141(4):571–582.

MacDonald, N. S., Ezmirlian, F., Spain, P., and McArthur, C. (1951). The ultimate site of skeletal deposition of strontium and lead. *Journal of Biological Chemistry*, 189(1):387–99.

Mace, R. and Currie, T. E. (2012). The evolution of ethnolinguistic diversity. *Advances in Complex Systems*, 15(01n02):1150006.

Maffi, L. (2008). Biocultural diversity and sustainability. In Pretty, J., Ball, A., Benton, T., Guivant, J., Lee, D. R., Orr, D., Pfeffer, M., and Ward, H., editors, *The SAGE Handbook of Environement and Society*, chapter 18, pages 267–277. SAGE Publications, New York, NY.

Mahoney, P. (2014). Dental fast track: Prenatal enamel growth, incisor eruption, and weaning in human infants. *American Journal of Physical Anthropology*, 156(3):407–421.

Malinowski, B. (2012). *Malinowski Collected Works*, volume VII. Routledge, New York, New York.

Mandel, I. D. and Gaffar, A. (1986). Calculus revisited. *Journal of Clinical Periodontology*, 13(4):249–257.

Manji, F., Fejerskov, O., Baelum, V., Luan, W.-M., and Chen, X. (1991). The epidemiological features of dental caries in African and Chinese populations: implications for risk assessment. In Johnson, N. W., editor, *Dental Caries: Markers of High and Low Risk Groups and Individuals*, volume 1 of *Risk markers for Oral Diseases*. Cambridge University Press, Cambridge, UK.

Mariner, W. and Martin, J. (1827). *An account of the natives of the Tonga Islands in the South Pacific Ocean: with an original grammar and vocabulary of their language*. Constable and Hurst Chance, Edinburgh, Scotland, 3rd edition.

Marlowe, F. (2001). Male contribution to diet and female reproductive success among foragers. *Current Anthropology*, 42(5):755–760.

Marsh, P. D. (2006). Dental diseases: are these examples of ecological catastrophes? *International Journal of Dental Hygiene*, 4:3–10.

Marshall, J. D., Brooks, J. R., and Lajtha, K. (2007). Sources of variation in the stable isotopic composition of plants. In Michener, R. and Lajtha, K., editors, *Stable Isotopes in Ecology and Environmental Science*, chapter 2, pages 22–60. Blackwell Publishing Ltd, Malden, MA, 2nd edition.

Marshall, T. A., Broffitt, B., Eichenberger-Gilmore, J., Warren, J. J., Cunningham, M. A., and Levy, S. M. (2005). The roles of meal, snack, and daily total food and beverage exposures on caries experience in young children. *Journal of Public Health Dentistry*, 65(3):166–173.

Marshall, Y., Crosby, A., Matararaba, S., and Wood, S. (2000). *Sigatoka: the shifting sands of Fijian prehistory*. Oxbow Books, Oxford, England.

Masotti, S., Onisto, N., Marzi, M., and Gualdi-Russo, E. (2013). Dento-alveolar features and diet in an Etruscan population (6th–3rd c. B.C.) from northeast Italy. *Archives of Oral Biology*, 58(4):416–426.

Masters, P. M. (1987). Preferential preservation of noncollagenous protein during bone diagenesis: Implications for chronometric and stable isotopic measurements. *Geochimica et Cosmochimica Acta*, 51(12):3209–3214.

Matisoo-Smith, E. (2007). Lapita: a genetic perspective. In Chiu, S. and Sand, C., editors, *From Southeast Asia to the Pacific: Archaeological Perspectives on the Austronesian expansion and the Lapita Cultural Complex*, chapter 8, pages 243–268. Center for Archaeological Studies Research Center for Humanities and Social Sciences, Academia Sinica, Taipei, Taiwan.

Matisoo-Smith, E., Roberts, R. M., Irwin, G. J., Allen, J. S., Penny, D., and Lambert, D. M. (1998). Patterns of prehistoric human mobility in Polynesia indicated by mtDNA from the Pacific rat. *Proceedings of the National Academy of Sciences*, 95(25):15145–15150.

Matisoo-Smith, E. and Robins, J. H. (2004). Origins and dispersals of Pacific peoples: Evidence from mtDNA phylogenies of the Pacific rat. *Proceedings of the National Academy of Sciences of the United States of America*, 101(24):9167–9172.

Mays, S. (1995). The relationship between Harris lines and other aspects of skeletal development in adults and juveniles. *Journal of Archaeological Science*, 22(4):511–520.

McArthur, J. (1994). Recent trends in strontium isotope stratigraphy. *Terra nova*, 6(4):331–358.

McCaa, R. (2002). Reconstructing health profiles from skeletal remains. In *The Backbone of History: Health and Nutrition in the Western Hemisphere*, chapter 2, pages 94–126. Cambridge University Press, Cambridge, UK.

McCrea, J. (1950). On the isotopic chemistry of carbonates and a paleotemperature scale. *The Journal of Chemical Physics*, 18(6):849–857.

McCutchan, J. H., Lewis, W. M., Kendall, C., and McGrath, C. C. (2003). Variation in trophic shift for stable isotope ratios of carbon, nitrogen, and sulfur. *Oikos*, 102(2):378–390.

McKern, W. (1929). *Archaeology of Tonga*, volume 60. Bernice P. Bishop Museum Bulletin, Honolulu, Hawai‘i.

Meier-Augenstein, W. (2010). *Stable Isotope Forensics: An Introduction to the Forensic Application of Stable Isotope Analysis*. John Wiley and Sons, Inc., Chichester, UK.

Meyer-Rochow, V. (2009). Food taboos: their origins and purposes. *Journal of Ethnobiology and Ethnomedicine*, 5(1):18.

Michael, J. A., Townsend, G. C., Greenwood, L. F., and Kaidonis, J. A. (2009). Abfraction: separating fact from fiction. *Australian Dental Journal*, 54(1):2–8.

Mickleburgh, H. L. (2014). Dental wear and pathology in the precolonial Caribbean: Evidence for dietary change in the ceramic age. *International Journal of Osteoarchaeology*, Early View:n/a–n/a.

Miles, A. (1963). Dentition in the estimation of age. *Journal of Dental Research*, 42(1):255–263.

Miles, A. E. W. (1962). Assessment of the ages of a population of anglo-saxons from their dentitions. *Proceedings of the Royal Society of Medicine*, 55(10):881–6.

Milner, G. R. and Larsen, C. S. (1991). Teeth as artifacts of human behavior: intentional mutilation and accidental modification. In Kelly, M. A. and Larsen, C. S., editors, *Advances in Dental Anthropology*, chapter 20, pages 357–378. Wiley-Liss, New York, NY.

Minagawa, M. and Wada, E. (1984). Stepwise enrichment of ^{15}N along food chains: Further evidence and the relation between δ^{15}N and animal age. *Geochimica et Cosmochimica Acta*, 48(5):1135–1140.

Mobley, C. C. (2003). Nutrition and dental caries. *Dental Clinics of North America*, 47(2):319–336.

Mohebbi, S. Z., Virtanen, J. I., Vahid-Golpayegani, M., and Vehkalahti, M. M. (2008). Feeding habits as determinants of early childhood caries in a population where prolonged breastfeeding is the norm. *Community Dentistry and Oral Epidemiology*, 36(4):363–369.

Molnar, P. (2011). Extramasticatory dental wear reflecting habitual behavior and health in past populations. *Clinical Oral Investigations*, 15(5):681–689.

Molnar, S. (1971). Human tooth wear, tooth function and cultural variability. *American Journal of Physical Anthropology*, 34(2):175–189.

Montgomery, J., Evans, J., Chenery, S. R., Pashley, V., and Killgrove, K. (2010). "Gleaming, white and deadly": using lead to track human exposure and geographic origins in the Roman period in Britain. *Journal of Roman Archaeology*, Supp. 78:199–226.

Montgomery, J., Evans, J. A., Powlesland, D., and Roberts, C. A. (2005). Continuity or colonization in Anglo-Saxon England? isotope evidence for mobility, subsistence practice, and status at West Heslerton. *American Journal of Physical Anthropology*, 126(2):123–138.

Moore, J. W. and Semmens, B. X. (2008). Incorporating uncertainty and prior information into stable isotope mixing models. *Ecology Letters*, 11(5):470–480.

Moore, K. M., Murray, M. L., and Schoeninger, M. J. (1989). Dietary reconstruction from bones treated with preservatives. *Journal of Archaeological Science*, 16(4):437–446.

Morens, D. M., Folkers, G. K., and Fauci, A. S. (2004). The challenge of emerging and re-emerging infectious diseases. *Nature*, 430(6996):242–249.

Morens, D. M., Folkers, G. K., and Fauci, A. S. (2008). Emerging infections: a perpetual challenge. *The Lancet Infectious Diseases*, 8(11):710–719.

Morton, H. (1996). *Becoming Tongan: an ethnography of childhood*. University of Hawai'i Press, Honolulu.

Müldner, G. and Richards, M. P. (2007). Diet and diversity at later medieval Fishergate: The isotopic evidence. *American Journal of Physical Anthropology*, 134(2):162–174.

Mummery, J. R. (1870). On the relations which dental caries, as discovered among the ancient inhabitants of Britain and amongst existing aboriginal races, may be supposed to hold to their food and social conditions. *Transactions of the Odontological Society of Great Britain*, 2 (new series):7–24, 27–80.

Munblatt, M. (1933). A critical study of the incidence of dental caries in children.

The Dental Cosmos, a monthly record of dental science, 75(6):592–609.

Mundorff-Shrestha, S., Featherstone, J., Eisenberg, A., Cowles, E., Curzon, M., Espeland, M., and Shields, C. (1994). Cariogenic potential of foods. *Caries Research*, 28(2):106–115.

Murray, J. J., editor (1986). *Appropriate use of fluorides for human health*. World Health Organization, Geneva, Switzerland.

Nakahara, Y., Sano, T., Kodama, Y., Ozaki, K., and Matsuura, T. (2013). The effect of food hardness on the development of dental caries in alloxan-induced diabetic rats. *Journal of Diabetes Research*, 2013:1–6.

Nanci, A. (2013). *Ten Cate's Oral Histology: Development, Structure, and Function*. Elsevier, St. Louis, MO, 8th edition.

Narasinga Rao, B. S., Siddiqui, A. H., and Srikantia, S. G. (1968). A study of calcium^{45} turnover in skeletal fluorosis. *Metabolism*, 17(4):366–369.

Nayacakalou, R. R. (1955). The Fijian system of kinship and marriage. *The Journal of the Polynesian Society*, 64(1):44–55.

Nehlich, O., Borić, D., Stefanović, S., and Richards, M. P. (2010). Sulphur isotope evidence for freshwater fish consumption: a case study from the Danube Gorges, SE Europe. *Journal of Archaeological Science*, 37(5):1131–1139.

Nehlich, O., Fuller, B. T., Jay, M., Mora, A., Nicholson, R. A., Smith, C. I., and Richards, M. P. (2011). Application of sulphur isotope ratios to examine weaning patterns and freshwater fish consumption in Roman Oxfordshire, UK. *Geochimica et Cosmochimica Acta*, 75(17):4963–4977.

Nehlich, O. and Richards, M. (2009). Establishing collagen quality criteria for sulphur isotope analysis of archaeological bone collagen. *Archaeological and Anthropological Sciences*, 1(1):59–75.

New, M., Lister, D., Hulme, M., and Makin, I. (2002). A high-resolution data set of surface climate over global land areas. *Climate Research*, 21:1–25.

Nimni, M., Han, B., and Cordoba, F. (2007). Are we getting enough sulfur in our diet? *Nutrition & Metabolism*, 4(1):1–24.

Niyibizi, C. and Eyre, D. R. (1994). Structural characteristics of cross-linking sites in type V collagen of bone. *European Journal of Biochemistry*, 224(3):943–950.

Nizel, A. E. (1970). Amino acids, proteins, and dental caries. In Gould, R. F., editor, *Dietary Chemicals vs. Dental Caries*. American Chemical Society, Washington D.C.

Novak, S. A. (2000). Battle-related trauma. In Fiorato, V., Boylston, A., and Knüsel, C. J., editors, *Blood red roses: The archaeology of a mass grave from the Battle of Towton AD 1461*, pages 90–102. Oxbow, Oxford, UK.

Nriagu, J., Rees, C., Mekhtiyeva, V., Lein, A., Fritz, P., Drimmie, R., Pankina, R., Robinson, R., and Krouse, H. (1991). Hydrosphere. In Krouse, H. R. and Grinenko, V. A., editors, *Stable isotopes: natural and anthropogenic sulphur in the environment.*, chapter 6, pages 177–265. John Wiley & Sons, Chichester, UK.

Nunn, P. D. (1993). Beyond the naive lands: Human history and environmental change in the Pacific Basin. In Waddell, E. and Nunn, P. D., editors, *The Margin Fades: Geographical Itineraries in a World of Islands*, chapter 2, pages 5–28. Institute of Pacific Studies, Suva, Fiji.

Nunn, P. D. (1998). *Pacific Island Landscapes: Landscape and Geological Development of Southwest Pacific Islands, especially Fiji, Samoa and Tonga.* Institute of Pacific Studies, The University of the South Pacific, Suva, Fiji.

Nunn, P. D. (2007). Echoes from a distance: research into the Lapita occupation of the Rove Peninsula, southwest Viti Levu, Fiji. In Bedford, S., Sand, C., and Connaughton, S. P., editors, *Oceanic Explorations: Lapita and Western Pacific Settlement*, volume 26 of *Terra Australis*, chapter Chapter 9, pages 163–76. ANU Press, Cannberra, Australia.

Nunn, P. D. (2009). Geographical influences on settlement-location choices by initial colonizers: a case study of the Fiji Islands. *Geographical Research*, 47(3):306–319.

Nunn, P. D. (2012). Disruption of coastal societies in the Pacific Islands from rapid sea-level fall about AD 1300: new evidence from northern Viti Levu Island, Fiji. *Journal of Coastal Conservation*, 16(2):199–209.

Nunn, P. D., Kumar, R., and Matararaba, S. (2003). Recent research relating to Lapita settlement in Fiji. In Sand, C., editor, *Pacific Archaeology: Assessments and Prospects*, chapter 12, pages 183–186. Le Cahiers de l'Archeologie en Nouvelle Caledonie, Noumeá, New Caledonia.

Nunn, P. D., Kumar, R., Matararaba, S., Ishimura, T., Seeto, J., Rayawa, S., Kuruyawa, S., Nasila, A., Oloni, B., Ram, A. R., Saunivalu, P., Singh, P., and Tegu, E. (2004a). Early Lapita settlement site at Bourewa, Southwest Viti Levu Island, Fiji. *Archaeology in Oceania*, 39(3):139–143.

Nunn, P. D., Matararaba, S., Ishimura, T., Kumar, R., and Nakoro, E. (2004b). Reconstructing the Lapita-era geography of northern Fiji: a newly-discovered Lapita site on Yadua island and its implications. *New Zealand Journal of Archaeology*, 26:41–55.

Nunn, P. D. and Petchey, F. (2013). Bayesian re-evaluation of Lapita settlement in Fiji: radiocarbon analysis of the Lapita occupation at Bourewa and nearby sites on the Rove Peninsula, Viti Levu Island. *Journal of Pacific Archaeology*, 4(2):21–34.

O'Brien, M. J. and Wood, W. R. (1998). *The prehistory of Missouri.* University of Missouri Press, Columbia, MO.

O'Connell, J. F. and Allen, J. (2004). Dating the colonization of Sahul (Pleistocene Australia–New Guinea): a review of recent research. *Journal of Archaeological Science*, 31(6):835–853.

O'Connell, T. C., Hedges, R. E. M., Healey, M. A., and Simpson, A. H. R. W. (2001). Isotopic comparison of hair, nail and bone: Modern analyses. *Journal of Archaeological Science*, 28(11):1247–1255.

Ogden, A. R. (2008). Advances in the palaeopathology of teeth and jaws. In Pinhasi, R. and Mays, S., editors, *Advances in Human Palaeopathology*, chapter 13, pages 283–308. John Wiley & Sons, Ltd, West Sussex, England.

Ohtsuka, R. (1985). *The Oriomo Papuans: Gathering versus Horticulture in an Ecological Context*, chapter 45, pages 343–348. Printsman Press Faridabad, New Delhi, India.

O'Leary, M. H. (1988). Carbon isotopes in photosynthesis. *Bioscience*, 38(5):328–336.

Oliver, D. L. (1989). *Oceania: the native cultures of Australia and the Pacific Islands*, volume 1. University of Hawai'i Press, Honolulu, Hawai'i.

Olsen, K. C., White, C. D., Longstaffe, F. J., von Heyking, K., McGlynn, G., Grupe, G., and Rühli, F. J. (2014). Intraskeletal isotopic compositions (^{13}C, ^{15}N) of bone collagen: Nonpathological and pathological variation. *American Journal of Physical Anthropology*, 153(4):598–604.

Ono, R. (2003). Prehistoric Austronesian fishing strategies: a comparison between Island Southeast Asia and the Lapita Cultural Complex. In Sand, C., editor, *Pacific archaeology: assessments and prospects*, chapter 14, pages 191–201. Le Cahiers de l'Archeologie en Nouvelle Caledonie, Noumeá, New Caledonia.

Orbell, G. E. (1983). *Soils of the Kingdom of Tonga: an introduction*. New Zealand Soil Bureau, Dept. of Scientific and Industrial Research, Wellington, N.Z.

Ortner, D. J. (1991). Theoretical and methodological issues in paleopathology. In Ortner, D. J. and Aufderheide, A. C., editors, *Human Paleopathology: Current Syntheses and Future Options*, chapter 1, pages 5–11. Smithsonian Institution Press, Washington, DC.

Ortner, D. J. (2003). *Identification of Pathological Conditions in Human Skeletal Remains*. Smithsonian Institution Press, Washington, DC, 2nd edition.

Oskarsson, M. C. R., Kl utsch, C. F. C., Boonyaprakob, U., Wilton, A., Tanabe, Y., and Savolainen, P. (2012). Mitochondrial DNA data indicate an introduction through Mainland Southeast Asia for Australian dingoes and Polynesian domestic dogs. *Proceedings of the Royal Society B: Biological Sciences*, 279(1730):967–974.

Overman, N. C. and Parrish, D. L. (2001). Stable isotope composition of walleye: ^{15}N accumulation with age and area-specific differences in δ^{13}C. *Canadian Journal of Fisheries and Aquatic Sciences*, 58(6):1253–1260.

Owsley, D. W. and Miles, A.-M. (1985). Carious lesions in permanent dentitions of protohistoric Easter Islanders. *The Journal of the Polynesian Society*, 94(4):415–422.

Oxenham, M. F. and Domett, K. (2011). Paleohealth at Man Bac. In Oxenham, M. F., Matsumura, H., and Kim Dung, N., editors, *Man Bac: The Excavation of a Neolithic site in Northern Vietnam*, number 33 in Terra Australis, chapter 7, pages 77–93. ANU Press, Canberra, Australia.

Oxenham, M. F. and Matsumura, H. (2008). Oral and physiological paleohealth in cold adapted peoples: Northeast Asia, Hokkaido. *American Journal of Physical Anthropology*, 135(1):64–74.

Palazzo, B., Iafisco, M., Laforgia, M., Margiotta, N., Natile, G., Bianchi, C. Walsh, D., Mann, S., and Roveri, N. (2007). Biomimetic hydroxyapatite–drug

nanocrystals as potential bone substitutes with antitumor drug delivery properties. *Advanced Functional Materials*, 17(13):2180–2188.

Panter-Brick, C., Layton, R. H., and Rowley-Conwy, P. (2001). Lines of enquiry. In *Hunter-Gatherers: An Interdisciplinary Perspective*, chapter 1, pages 1–11. Cambridge University Press, Cambridge, UK.

Park, J.-B., Lee, J.-E., Kim, K., Yoo, J.-T., Kim, Y., Kook, Y.-A., and Ko, Y. (2014). The thickness of alveolar bone at the mandibular canine and premolar teeth in normal occlusion. *Journal of Craniofacial Surgery*, 25(3):1115–1119.

Parker, E. J., Jamieson, L. M., Broughton, J., Albino, J., Lawrence, H. P., and Roberts-Thomson, K. (2010). The oral health of Indigenous children: A review of four nations. *Journal of Paediatrics and Child Health*, 46(9):483–486.

Parry, J. T. (1987). *The Sigatoka Valley: Pathway into Prehistory*. Number 9 in Bulletin of the Fiji Museum. Fiji Museum, Suva, Fiji.

Passey, B. H., Robinson, T. F., Ayliffe, L. K., Cerling, T. E., Sponheimer, M., Dearing, M. D., Roeder, B. L., and Ehleringer, J. R. (2005). Carbon isotope fractionation between diet, breath CO_2, and bioapatite in different mammals. *Journal of Archaeological Science*, 32(10):1459–1470.

Patir, A., Seymen, F., Yildirim, M., Deeley, K., Cooper, M. E., Marazita, M. L., and Vieira, A. R. (2008). Enamel formation genes are associated with high caries experience in Turkish children. *Caries Research*, 42(5):394–400.

Patnaik, R., Cerling, T. E., Uno, K. T., and Fleagle, J. G. (2014). Diet and habitat of Siwalik primates *Indopithecus*, *Sivaladapis* and *Theropithecus*. *Annales Zoologici Fennici*, 51(1-2):123–142.

Patrick, J. J. R. (1895). Examination of prehistoric crania. *The Dental Cosmos, a monthly record of dental science*, 37(1):1–24.

Pattanaporn, K. and Navia, J. M. (1998). The relationship of dental calculus to caries, gingivitis, and selected salivary factors in 11- to 13-year-old children in Chiang Mai, Thailand. *Journal of Periodontology*, 69(9):955–61.

Pawley, A. (2007). Why do Polynesian island groups have one language and Melanesian island groups have many? patterns of interaction and diversification in the Austronesian colonization of remote Oceania. In *Paper presented at the Workshop on Migration*, Ile de Porquerolles, France.

Pawley, A. and Green, R. (1973). Dating the dispersal of the Oceanic languages. *Oceanic Linguistics*, 12(1/2):1–67.

Pearl, F. B. (2004). The chronology of mountain settlements on Tutuila, American Samoa. *The Journal of the Polynesian Society*, 113(4):331–348.

Pearl, R. (1930). Some aspects of the biology of human populations. In Cowdry, E. V., editor, *Human biology and racial welfare*, chapter 22, pages 515–552. Paul B. Hoeber, Oc., New York, NY.

Perkins, M. J., McDonald, R. A., van Veen, F. J. F., Kelly, S. D., Rees, G., and Bearhop, S. (2014). Application of nitrogen and carbon stable isotopes (δ^{15}N and δ^{13}C) to quantify food chain

length and trophic structure. *PLoS ONE*, 9(3):e93281.

Petchey, F., Anderson, A., Hogg, A., and Zondervan, A. (2008). The marine reservoir effect in the southern ocean: An evaluation of extant and new ΔR values and their application to archaeological chronologies. *Journal of the Royal Society of New Zealand*, 38(4):243–262.

Petchey, F. and Clark, G. (2011). Tongatapu hardwater: Investigation into the ^{14}C marine reservoir offset in lagoon, reef and open ocean environments of a limestone island. *Quaternary Geochronology*, 6(6):539–549.

Petchey, F., Spriggs, M., Bedford, S., Valentin, F., and Buckley, H. (2014). Radiocarbon dating of burials from the Teouma Lapita cemetery, Efate, Vanuatu. *Journal of Archaeological Science*, 50:227–242.

Petchey, F., Spriggs, M., Leach, F., Seed, M., Sand, C., Pietrusewsky, M., and Anderson, K. (2011). Testing the human factor: radiocarbon dating the first peoples of the South Pacific. *Journal of Archaeological Science*, 38(1):29–44.

Petersen, P. E. (2003). The world oral health report 2003: continuous improvement of oral health in the 21st century – the approach of the WHO global oral health programme. *Community Dentistry and Oral Epidemiology*, 31:3–24.

Peterson, B. J. and Fry, B. (1987). Stable isotopes in ecosystem studies. *Annual review of ecology and systematics*, 18:293–320.

Peterson, B. J., Howarth, R. W., and Garritt, R. H. (1985). Multiple stable isotopes used to trace the flow of organic matter in estuarine food webs. *Science*, 227(4692):1361–1363.

Phaff, B. (2012). Human dietary and mobility patterns of a prehistoric populations from Sigatoka, Fiji: A reconstruction using stable isotope analysis. Master's thesis, University of British Columbia, Vancouver, BC, Canada.

Phillips, D., Newsome, S., and Gregg, J. (2005). Combining sources in stable isotope mixing models: alternative methods. *Oecologia*, 144(4):520–527.

Pickerill, H. P. (1912a). *The prevention of dental caries and oral sepsis*. Bailliáere, Tindall and Cox, London, UK.

Pickerill, H. P. (1912b). Some pathological conditions found in the teeth and jaws of Maori skulls in New Zealand. *Proceedings of the Royal Society of Medicine*, 5(Odontology Section):155–65.

Pierce, E. I. F. (1991). Salivary inorganic and physical factors in the aetiology of dental caries, and their role in prediction. In Johnson, N. W., editor, *Dental Caries: Markers of High and Low Risk Groups and Individuals*, Risk Markers for Oral Diseases. Cambridge University Press, Cambridge, UK.

Pietrusewsky, M. (1969). An osteological study of cranial and infracranial remains from Tonga. *Records of the Auckland Institute and Museum*, 6:287–402.

Pietrusewsky, M. and Douglas, M. T. (1993). Tooth ablation in old Hawai'i. *The Journal of the Polynesian Society*, 102(3):255–272.

Pietrusewsky, M., Douglas, M. T., and Ikehara-Quebral, R. M. (1997). An assessment of health and disease in the prehistoric inhabitants of the Mariana

Islands. *American Journal of Physical Anthropology*, 104(3):315–342.

Pimm, S. L. and Lawton, J. H. (1978). On feeding on more than one trophic level. *Nature*, 275(5680):542–544.

Pinhasi, R. and Bourbou, C. (2008). How representative are human skeletal assemblages for population analysis? In *Advances in Human Palaeopathology*, chapter 2, pages 31–44. John Wiley & Sons, Ltd, Chichester, England.

Pinhasi, R., Shaw, P., White, B., and Ogden, A. R. (2006). Morbidity, rickets and long-bone growth in post-medieval Britain—a cross-population analysis. *Annals of Human Biology*, 33(3):372–389.

Podlesak, D. W. and McWilliams, S. R. (2006). Metabolic routing of dietary nutrients in birds: Effects of diet quality and macronutrient composition revealed using stable isotopes. *Physiological and Biochemical Zoology*, 79(3):534–549.

Polis, G. A. (1991). Complex trophic interactions in deserts: An empirical critique of food-web theory. *The American Naturalist*, 138(1):123–155.

Pollock, N. J. (1986). Food classification in three Pacific societies: Fiji, Hawaii, and Tahiti. *Ethnology*, 25(2):107–117.

Pollock, N. J. (1992). *These Roots Remain: Food Habits in Islands of Central and Eastern Pacific Since Western Contact*. Institute for Polynesian Studies, Honolulu, Hawai'i.

Potter, R. G. (1975). Changes of natural fertility and contraceptive equivalents. *Social Forces*, 54(1):36–51.

Poulson, J. (1968). Archaeological excavations on Tongatapu. In Yawata, I & Sinoto, Y. H., editor, *Prehistoric Culture in Oceania: A Symposium*, pages 85–92. Bishop Museum Press, Honolulu, Hawai'i.

Poulson, J. (1987). *Early Tongan prehistory: the Lapita period on Tongatapu and its relationships*, volume 12 of *Terra Australis*. Dept. of Prehistory, Research School of Pacific Studies, Australian National University, Canberra, Australia.

Poulson, S. R., Kuzminsky, S. C., Scott, G. R., Standen, V. G., Arriaza, B., Muñoz, I., and Dorio, L. (2013). Paleodiet in northern Chile through the holocene: extremely heavy δ^{15}N values in dental calculus suggest a guano-derived signature? *Journal of Archaeological Science*, 40(12):4576 – 4585.

Powell, L. V., Mancl, L. A., and Senft, G. D. (1991). Exploration of prediction models for caries risk assessment of the geriatric population. *Community Dentistry and Oral Epidemiology*, 19(5):291–295.

Power, M., Guiguer, K. R. R. A., and Barton, D. R. (2003). Effects of temperature on isotopic enrichment in *Daphnia magna*: implications for aquatic food-web studies. *Rapid Communications in Mass Spectrometry*, 17(14):1619–1625.

Pregill, G. K. and Dye, T. (1989). Prehistoric extinction of Giant Iguanas in Tonga. *Copeia*, 1989(2):505–508.

Pregill, G. K. and Steadman, D. W. (2004). South pacific iguanas: Human impacts and a new species. *Journal of Herpetology*, 38(1):15–21. doi: 10.1670/73-03A.

Pregill, G. K. and Worthy, T. H. (2003). A new iguanid lizard (Squamata, Iguanidae) from the Late Quaternary of Fiji, Southwest Pacific. *Herpetologica*, 59(1):57–67.

Prentice, I. C., Farquhar, G., Fasham, M., Goulden, M., Heimann, M., Jaramillo, V., Kheshgi, H., LeQuéré, C., Scholes, R., and Wallace, D. W. (2001). The carbon cycle and atmospheric carbon dioxide. In Houghton, J., Ding, Y., Griggs, D., Noguer, M., Van Der Linden, P., and Xiaosu, D., editors, *Climate Change 2001: The Scientific Basis*, chapter 3, pages 183–237. Cambridge University Press, Cambridge, UK.

Price, T., Burton, J., and Bentley, R. (2002). The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. *Archaeometry*, 44(1):117–135.

Price, T. D., Blitz, J., Burton, J., and Ezzo, J. A. (1992). Diagenesis in prehistoric bone: Problems and solutions. *Journal of Archaeological Science*, 19(5):513–529.

Privat, K. L., O'Connell, T. C., and Hedges, R. E. M. (2007). The distinction between freshwater- and terrestrial-based diets: methodological concerns and archaeological applications of sulphur stable isotope analysis. *Journal of Archaeological Science*, 34(8):1197–1204.

Prowse, T. L., Saunders, S. R., Schwarcz, H. P., Garnsey, P., Macchiarelli, R., and Bondioli, L. (2008). Isotopic and dental evidence for infant and young child feeding practices in an imperial Roman skeletal sample. *American Journal of Physical Anthropology*, 137(3):294–308.

Prowse, T. L., Schwarcz, H. P., Garnsey, P., Knyf, M., Macchiarelli, R., and Bondioli, L. (2007). Isotopic evidence for age-related immigration to imperial Rome. *American Journal of Physical Anthropology*, 132(4):510–519.

Puech, P.-F., Serratrice, C., and Leek, F. F. (1983). Tooth wear as observed in ancient Egyptian skulls. *Journal of Human Evolution*, 12(7):617–629.

Pérez-Harguindeguy, N., Díaz, S., Garnier, E., Lavorel, S., Poorter, H., Jaureguiberry, P., Bret-Harte, M. S., Cornwell, W. K., Craine, J. M., Gurvich, D. E., Urcelay, C., Veneklaas, E. J., Reich, P. B., Poorter, L., Wright, I. J., Ray, P., Enrico, L., Pausas, J. G., de Vos, A. C., Buchmann, N., Funes, G., Quétier, F., Hodgson, J. G., Thompson, K., Morgan, H. D., ter Steege, H., van der Heijden, M. G. A., Sack, L., Blonder, B., Poschlod, P., Vaieretti, M. V., Conti, G., Staver, A. C., Aquino, S., and Cornelissen, J. H. C. (2013). New handbook for standardised measurement of plant functional traits worldwide. *Australian Journal of Botany*, 61(3):167–234.

Radosevich, S. C. (1993). The six deadly sins of trace element analysis: A case of wishful thinking in science. In Sandford, M. K., editor, *Investigations of ancient human tissue: chemical analyses in anthropology*, chapter 6, pages 269–332. Gordon and Breach, Langhorne, PA.

Raines, C. A. (2006). Transgenic approaches to manipulate the environmental responses of the C_3 carbon fixation cycle. *Plant, Cell & Environment*, 29(3):331–339.

Ramsey, C. B. (2009). Bayesian analysis of radiocarbon dates. *Radiocarbon*, 51(1):337–360.

Ranson, S. L. and Thomas, M. (1960). Crassulacean acid metabolism. *Annual Review of Plant Physiology*, 11(1):81–110.

Reardon, E. J. and Wang, Y. (2000). A limestone reactor for fluoride removal from wastewaters. *Environmental Science & Technology*, 34(15):3247–3253.

Reddy, G. S. and Narasinga Rao, B. S. (1971). Effect of dietary calcium, vitamin C and protein in development of experimental skeletal fluorosis. II. calcium turnover with ^{45}Ca; calcium and phosphorus balances. *Metabolism*, 20(7):650–656.

Reddy, M. S., Geurs, N. C., Jeffcoat, R. L., Proskin, H., and Jeffcoat, M. K. (2000). Periodontal disease progression. *Journal of Periodontology*, 71(10):1583–1590.

Rees, C., Jenkins, W., and Monster, J. (1978). The sulphur isotopic composition of ocean water sulphate. *Geochimica et Cosmochimica Acta*, 42(4):377–381.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M., and van der Plicht, J. (2013). Intcal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *2013*, 55(4):1869–1887.

Reitsema, L. J. (2013). Beyond diet reconstruction: Stable isotope applications to human physiology, health, and nutrition. *American Journal of Human Biology*, 25(4):445–456.

Reynard, L. M. and Tuross, N. (2015). The known, the unknown and the unknowable: weaning times from archaeological bones using nitrogen isotope ratios. *Journal of Archaeological Science*, 53(0):618–625.

Rho, J. Y., Ashman, R. B., and Turner, C. H. (1993). Young's modulus of trabecular and cortical bone material: Ultrasonic and microtensile measurements. *Journal of Biomechanics*, 26(2):111–119.

Richards, L. C. (1984). Principal axis analysis of dental attrition data from two Australian Aboriginal populations. *American Journal of Physical Anthropology*, 65(1):5–13.

Richards, M. and Hedges, R. (1999). Stable isotope evidence for similarities in the types of marine foods used by Late Mesolithic humans at sites along the Atlantic coast of Europe. *Journal of Archaeological Science*, 26(6):717–722.

Richards, M. P., Fuller, B. T., and Hedges, R. E. M. (2001). Sulphur isotopic variation in ancient bone collagen from Europe: implications for human palaeodiet, residence mobility, and modern pollutant studies. *Earth and Planetary Science Letters*, 191(34):185–190.

Richards, M. P., Fuller, B. T., Sponheimer, M., Robinson, T., and Ayliffe, L. (2003). Sulphur isotopes in palaeodietary studies: a review and results from a controlled feeding experiment. *International Journal of Osteoarchaeology*, 13(1-2):37–45.

Richards, M. P., Mays, S., and Fuller, B. T. (2002). Stable carbon and nitrogen isotope values of bone and teeth reflect weaning age at the Medieval Wharram Percy site, Yorkshire, UK. *American Journal of Physical Anthropology*, 119(3):205–210.

Richards, M. P., West, E., Rolett, B., and Dobney, K. (2009). Isotope analysis of human and animal diets from the Hanamiai archaeological site (French Polynesia). *Archaeology in Oceania*, 44(1):29–37.

Richardson, B. (1881). On the constitutional and local origins of caries of the teeth. *Transactions of the Odontological Society of Great Britain*, 14:6–36.

Riordan, J. and Wambach, K. (2010). *Breastfeeding and human lactation*. Jones & Bartlett Learning, Sudbury, MA.

Ritter, A. V. (2006). Eating disorders and oral health. *Journal of Esthetic and Restorative Dentistry*, 18(2):114–114.

Ritz-Timme, S., Cattaneo, C., Collins, M. J., Waite, E. R., Schütz, H. W., Kaatsch, H. J., and Borrman, H. I. M. (2000). Age estimation: The state of the art in relation to the specific demands of forensic practise. *International Journal of Legal Medicine*, 113(3):129–136.

Rivera, J. (1965). Human bone metabolism inferred from fall-out investigations. *Nature*, 207(5004):1330–1332.

Robb, K. F., Buckley, H. R., Spriggs, M., and Bedford, S. (2012). Cortical index of three prehistoric human Pacific Island samples. *International Journal of Osteoarchaeology*, 22(3):284–293.

Roberts, C. and Manchester, K. (2010). *The archaeology of disease*. The History Press, Gloucestershire, UK, 3rd edition.

Robertson, K. L., Rowland, N. E., and Krigbaum, J. (2014). Effects of caloric restriction on nitrogen and carbon stable isotope ratios in adult rat bone. *Rapid Communications in Mass Spectrometry*, 28(19):2065–2074.

Robinson, J. T. (1954). Prehominid dentition and hominid evolution. *Evolution*, 8(4):324–334.

Rodda, P. (1967). Outline of the geology of Viti Levu. *New Zealand Journal of Geology and Geophysics*, 10(5):1260–1273.

Roff, J. (2013). *Marine Conservation Ecology*. Taylor & Francis, Abingdon, UK.

Rogers, G. (1977). 'The father's sister is black': A consideration of female rank and powers in Tonga. *The Journal of the Polynesian Society*, 86(2):157–182.

Roschger, P., Paschalis, E., Fratzl, P., and Klaushofer, K. (2008). Bone mineralization density distribution in health and disease. *Bone*, 42(3):456–466.

Roullier, C., Benoit, L., McKey, D. B., and Lebot, V. (2013). Historical collections reveal patterns of diffusion of sweet potato in Oceania obscured by modern plant movements and recombination. *Proceedings of the National Academy of Sciences*, 110(6):2205–2210.

Rugg-Gunn, A. J. and Nunn, J. H. (1999). *Nutrition, diet, and oral health*. Oxford University Press, Oxford, UK.

Ruhlen, M. (1994). *On the origin of languages: studies in linguistic taxonomy*. Stanford University Press, Stanford, California.

Rundel, P. W., Ehleringer, J. R., and Nagy, K. A. (1989). *Stable isotopes in ecological research*. Ecological Studies 68. Springer-Verlag, New York, NY.

Rundel, P. W., Ehleringer, J. R., and Nagy, K. A., editors (1992). *Stable Isotopes in Ecological Research*. Springer-Verlag, New York City.

Sage, R. F. (1999). Why C_4 photosynthesis? In Sage, R. F. and Monson, R. K., editors, *C_4 Plant Biology*, pages 3–16. Academic Press, San Diego, CA.

Salazar-García, D. C., Richards, M. P., Nehlich, O., and Henry, A. G. (2014). Dental calculus is not equivalent to bone collagen for isotope analysis: a comparison between carbon and nitrogen stable isotope analysis of bulk dental calculus, bone and dentine collagen from same individuals from the Medieval site of El Raval (Alicante, Spain). *Journal of Archaeological Science*, 47(0):70–77.

Salinger, M., Basher, R., Fitzharris, B., Hay, J., Jones, P., MacVeigh, J., and Schmidely-Leleu, I. (1995). Climate trends in the South-west Pacific. *International Journal of Climatology*, 15(3):285–302.

Sand, C. (2007). The eastern frontier: Lapita ceramics in the Fiji-West Polynesia region. In Chiu, S. and Sand, C., editors, *From Southeast Asia to the Pacific: Archaeological Perspectives on the Austronesian expansion and the Lapita Cultural Complex*, chapter 7, pages 214–242. Center for Archaeological Studies Research Center for Humanities and Social Sciences, Academia Sinica, Taipei, Taiwan.

Sandberg, G. E., Sundberg, H. E., Fjellstrom, C. A., and Wikblad, K. F. (2000). Type 2 diabetes and oral health: A comparison between diabetic and non-diabetic subjects. *Diabetes Research and Clinical Practice*, 50(1):27–34.

Sandberg, P. A., Sponheimer, M., LeeThorp, J., and Van Gerven, D. (2014). Intratooth stable isotope analysis of dentine: A step toward addressing selective mortality in the reconstruction of life history in the archaeological record. *American Journal of Physical Anthropology*, 155(2):281–293.

Sandford, M. K. (1993). Understanding the biogenic-diagenetic continuum: interpreting elemental concentration of archaeological bone. In Sandford, M. K., editor, *Investigations of ancient human tissue: chemical analyses in anthropology*, chapter 1, pages 1–57. Gordon and Breach, Langhorne, PA.

Savara, B. S. and Steen, J. C. (1978). Timing and sequence of eruption of permanent teeth in a longitudinal sample of children from Oregon. *Journal of the American Dental Association*, 97(2):209–214. J Am Dent Assoc.

Schatz, D., Alfter, G., and Göz, G. (2001). Fracture resistance of human incisors and premolars: morphological and pathoanatomical factors. *Dental Traumatology*, 17(4):167–173.

Scheuer, L. and Black, S. (2000). *Developmental Juvenile Osteology*. Academic Press, San Diego, CA.

Schoeninger, M. J. and DeNiro, M. J. (1984). Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. *Geochimica et Cosmochimica Acta*, 48(4):625–639.

Schoeninger, M. J., DeNiro, M. J., and Tauber, H. (1983). Stable nitrogen isotope ratios of bone collagen reflect marine and terrestrial components of prehistoric human diet. *Science*, 220(4604):1381–1383.

Schoeninger, M. J. and Moore, K. (1992). Bone stable isotope studies in archaeology. *Journal of World Prehistory*, 6(2):247–296.

Schoeninger, M. J., Moore, K. M., Murray, M. L., and Kingston, J. D. (1989). Detection of bone preservation in archaeological and fossil samples. *Applied Geochemistry*, 4(3):281–292.

Schroeder, H., O'Connell, T. C., Evans, J. A., Shuler, K. A., and Hedges, R. E. M. (2009). Trans-Atlantic slavery: Isotopic evidence for forced migration to Barbados. *American Journal of Physical Anthropology*, 139(4):547–557.

Schurr, M. R. (1997). Stable nitrogen isotopes as evidence for the age of weaning at the Angel site: A comparison of isotopic and demographic measures of weaning age. *Journal of Archaeological Science*, 24(10):919–927.

Schwarcz, H. and Schoeninger, M. (2012). Stable isotopes of carbon and nitrogen as tracers for paleo-diet reconstruction. In Baskaran, M., editor, *Handbook of Environmental Isotope Geochemistry*, Advances in Isotope Geochemistry, pages 725–742. Springer Berlin Heidelberg.

Schwarz, C., Debruyne, R., Kuch, M., McNally, E., Schwarcz, H., Aubrey, A. D., Bada, J., and Poinar, H. (2009). New insights from old bones: DNA preservation and degradation in permafrost preserved mammoth remains. *Nucleic acids research*, 37(10):3215–3229.

Sciulli, P. W. (1997). Dental evolution in prehistoric Native Americans of the Ohio valley area: wear and pathology. *International Journal of Osteoarchaeology*, 7(5):507–524.

Scott, E. C. (1979a). Dental wear scoring technique. *American Journal of Physical Anthropology*, 51(2):213–217.

Scott, E. C. (1979b). Principal axis analysis of dental attrition data. *American Journal of Physical Anthropology*, 51(2):203–211.

Scott, G. R. and Jolie, R. B. (2008). Toothtool use and yarn production in Norse Greenland. *Alaska Journal of Anthropology*, 6:253–264.

Scott, G. R. and Poulson, S. R. (2012). Stable carbon and nitrogen isotopes of human dental calculus: a potentially new non-destructive proxy for paleodietary analysis. *Journal of Archaeological Science*, 39(5):1388–1393.

Scott, G. R. and Winn, J. R. (2011). Dental chipping: Contrasting patterns of microtrauma in Inuit and European populations. *International Journal of Osteoarchaeology*, 21(6):723–731.

Scott, R. M. and Buckley, H. R. (2014). Exploring prehistoric violence in Tonga. *Current Anthropology*, 55(3):335–347.

Scott, R. S., Teaford, M. F., and Ungar, P. S. (2012). Dental microwear texture and anthropoid diets. *American Journal of Physical Anthropology*, 147(4):551–579.

Sealy, J., Armstrong, R., and Schrire, C. (1995). Beyond lifetime averages: tracing life histories through isotopic analysis of different calcified tissues from archaeological human skeletons. *Antiquity*, 69(263):290–300.

Sealy, J. C., van der Merwe, N. J., Thorp, J. A. L., and Lanham, J. L. (1987). Nitrogen isotopic ecology in southern Africa: Implications for environmental and dietary tracing. *Geochimica et Cosmochimica Acta*, 51(10):2707–2717.

Sellen, D. W. (2007). Evolution of infant and young child feeding: Implications for contemporary public health. *Annual Review of Nutrition*, 27(1):123–148.

Selwitz, R. H., Ismail, A. I., and Pitts, N. B. (2007). Dental caries. *The Lancet*, 369(9555):51–59.

Selwood, K. (2010). *Is There a Definable Signature in Dental Pathology for Marine Dependant Diets? A View from the Pacific*. PhD thesis, University of New Zealand.

Sharkey, T. D. (1988). Estimating the rate of photorespiration in leaves. *Physiologia Plantarum*, 73(1):147–152.

Sharp, Z. D. (2007). *Principles of Stable Isotope Geochemistry*. Pearson, Upper Saddle River, NJ, 1st edition.

Shaw, B. (2009). Prehistoric migration in Melanesia: Evidence from isotopic, trace element, and non-metric dental trait analyses. Master's dissertation, University of Otago.

Shaw, B. J., Buckley, H. R., Summerhayes, G., Anson, D., Garling, S., Valentin, F., Mandui, H., Stirling, C., and Reid, M. (2010). Migration and mobility at the Late Lapita site of Reber-Rakival (SAC), Watom Island using isotope and trace element analysis: a new insight into Lapita interaction in the Bismarck Archipelago. *Journal of Archaeological Science*, 37(3):605–613.

Shaw, B. J., Buckley, H. R., Summerhayes, G., Stirling, C., and Reid, M. (2011). Prehistoric migration at Nebira, south coast of Papua New Guinea: New insights into interaction using isotope and trace element concentration analyses. *Journal of Anthropological Archaeology*, 30(3):344–358.

Shaw, B. J., Summerhayes, G. R., Buckley, H. R., and Baker, J. A. (2009). The use of strontium isotopes as an indicator of migration in human and pig Lapita populations in the Bismarck Archipelago, Papua New Guinea. *Journal of Archaeological Science*, 36(4):1079–1091.

Shore, S. W., Unnikrishnan, G. U., Hussein, A. I., and F., M. E. (2013). Bone biomechanics. In Winkelstein, B. A., editor, *Orthopaedic Biomechanics*, chapter 1, pages 3–48. Taylor & Francis, Boca Raton, Florida.

Shykoluk, N. L. and Lovell, N. C. (2010). Technical note: Enhancement of Scott's molar wear scoring method. *American Journal of Physical Anthropology*, 143(3):482–487.

Sinclair, B., Cameron, D. A., and Goldsworth, N. E. (1950). Some observations on dental conditions in Papua-New Guinea, 1947, with special reference to dental conditions. *The Dental Journal of Australia*, 22(2-3):58–93, 120–157.

Skrepcinski, F. B. and Niendorff, W. J. (2000). Periodontal disease in American Indians and Alaska natives. *Journal of Public Health Dentistry*, 60(s1):261–266.

Smith, A. C. (1979). *Flora Vitiensis nova: a new Flora of Fiji (spermatophytes only)*. Pacific Tropical Botanical Garden, Lawaii, Hawaii.

Smith, B. H. (1984). Patterns of molar wear in hunter-gatherers and agriculturalists. *American Journal of Physical Anthropology*, 63(1):39–56.

Smith, G. E. and Jones, F. W. (1910). The archaeological survey of Nubia: Report for 1907-1908. Technical report, Ministry of Finance, Egypt.

Smith, I. E. M., Ward, G. K., and Ambrose, W. R. (1977). Geographic distribution and the characterization of volcanic glasses in Oceania. *Archaeology & Physical Anthropology in Oceania*, 12(3):173–201.

Smith, K. and Rennie, M. J. (2007). New approaches and recent results concerning human-tissue collagen synthesis. *Current Opinion in Clinical Nutrition & Metabolic Care*, 10(5):582–590.

Soares, P., Rito, T., Trejaut, J., Mormina, M., Hill, C., Tinkler-Hundal, E., Braid, M., Clarke, D. J., Loo, J.-H., Thomson, N., Denham, T., Donohue, M., Macaulay, V., Lin, M., Oppenheimer, S., and Richards, M. B. (2011). Ancient voyaging and Polynesian origins. *The American Journal of Human Genetics*, 88(2):239–247.

Sofaer, J. (2011). Towards a social bioarchaeology of age. In Agarwal, S. C. and Glencross, B. A., editors, *Social Bioarchaeology*, chapter 10, pages 285–311. Blackwell Publishing Ltd, Malden, MA.

Sotiropoulos, M. A., Tonn, W. M., and Wassenaar, L. I. (2004). Effects of lipid extraction on stable carbon and nitrogen isotope analyses of fish tissues: potential consequences for food web studies. *Ecology of Freshwater Fish*, 13(3):155–160.

Spencer, H., Warren, J. M., Kramer, L., and Samachson, J. (1973). Passage of calcium and strontium across the intestine in man. *Clinical Orthopaedics and Related Research*, 91(91):225–34.

Spennemann, D. H. R. (1987). Availability of shellfish resources on prehistoric Tongatapu, Tonga: Effects of human predation and changing environment. *Archaeology in Oceania*, 22(3):81–96.

Spennemann, D. H. R. (1989). *'Ata 'o Tonga mo 'ata 'a Tonga: early and later prehistory of the Tongan Islands*. PhD thesis, Australian National University, Canberra, Australia.

Spriggs, M., editor (1990). *Lapita Design, Form and Composition: Proceedings of the Lapita Design Workshop, Canberra, Australia – December 1988*. Occansional Papers in Prehistory. The Australian National University, Canberra, Australia.

Spriggs, M. (1997a). *The Island Melanesians*. The Peoples of South-East Asia and the Pacific. Blackwell Publishers, Cambridge, Massachusetts.

Spriggs, M. (1997b). Landscape catastrophe and landscape enhancement: Are either or both true in the Pacific. In Kirch, P. V. and Hunt, T. L., editors, *Historical Ecology in the Pacific Islands*, chapter 5, pages 80–104. Yale University Press, New Haven, Connecticut.

Spriggs, M. (2010). Geomorphic and archaeological consequences of human arrival and agricultural expansion on Pacific islands:a reconsideration after 30 years of debate. In Haberle, S., Stevenson, J., and Prepple, M., editors, *Altered Ecologies: Fire, climate and human influence on terrestrial landscapes*, number 32 in Terra Australis, chapter 13, pages 239–252. ANU Press, Canberra, Australia.

Stantis, C., Buckley, H. R., Kinaston, R. L., Nunn, P. D., Jaouen, K., and Richards, M. P. (2015a). Isotopic evidence of human mobility and diet in a prehistoric/protohistoric Fijian coastal environment (c. 750–150 BP). *American Journal of Physical Anthropology*, page Early View.

Stantis, C., Kinaston, R. L., Richards, M. P., Davidson, J. M., and Buckley, H. R. (2015b). Assessing human diet and movement in the Tongan maritime chiefdom using isotopic analyses. *PLoS ONE*, 10(3):e0123156.

Stantis, C., Tayles, N., Kinaston, R. L., Cameron, C., Nunn, P. D., Richards, M. P., and Buckley, H. R. (2015c). Diet and subsistence in Remote Oceania: an analysis using oral indicators of diet. In Oxenham, M. F. and Buckley, H. R., editors, *The Routledge Handbook of Bioarchaeology in Southeast Asia and the Pacific*. Routledge, London, UK. in press.

StataCorp (2013). Stata statistical software: Release 13.

Steadman, D. W. (1993). Biogeography of Tongan birds before and after human impact. *Proceedings of the National Academy of Sciences*, 90(3):818–822.

Steadman, D. W. (2006). *Extinction and biogeography of tropical Pacific birds*. University of Chicago Press, Chicago, Illinois.

Steadman, D. W., Plourde, A., and Burley, D. V. (2002a). Prehistoric butchery and consumption of birds in the Kingdom of Tonga, South Pacific. *Journal of Archaeological Science*, 29(6):571–584.

Steadman, D. W., Pregill, G. K., and Burley, D. V. (2002b). Rapid prehistoric extinction of iguanas and birds in Polynesia. *Proceedings of the National Academy of Sciences*, 99(6):3673–3677.

Steckel, R. H., Larsen, C. S., Sciulli, P. W., and Walker, P. L. (2002). Global history of health project.

Steele, K. W. and Daniel, R. M. (1978). Fractionation of nitrogen isotopes by animals: a further complication to the use of variations in the natural abundance of ^{15}N for tracer studies. *The Journal of Agricultural Science*, 90(01):7–9.

Steiger, R. H. and Jäger, E. (1977). Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters*, 36(3):359–362.

Steneck, R. S. and Watling, L. (1982). Feeding capabilities and limitation of herbivorous molluscs: A functional group approach. *Marine Biology*, 68(3):299–319.

Stern, R. J. (1982). Strontium isotopes from circum-Pacific intra-oceanic island arcs and marginal basins: Regional variations and implications for magmagenesis. *Geological Society of America Bulletin*, 93(6):477–486.

Stilwell, B., Diallo, K., Zurn, P., Vujicic, M., Adams, O., and Dal Poz, M. (2004). Migration of health-care workers from developing countries: strategic approaches to its management. *Bulletin of the World Health Organization*, 82:595–600.

Stinson, S., Bogin, B., O'Rourke, D., and Huss-Ashmore, R. (2012). Human biology: An evolutionary and biocultural perspective. In Stinson, S., Bogin, B., and O'Rourke, D., editors, *Human Biology*, chapter 1, pages 1–22. John Wiley & Sons, Inc., Hoboken,NJ.

Stoddart, D. R. (1992). Biogeography of the tropical Pacific. *Pacific Science*, 46(2):276–293.

Stookey, G. K. (2008). The effect of saliva on dental caries. *The Journal of the American Dental Association*, 139(suppl 2):11S–17S.

Storey, A. A., Spriggs, M., Bedford, S., Hawkins, S. C., Robins, J. H., Huynen, L., and Matisoo-Smith, E. (2010). Mitochondrial DNA from 3000-year old chickens at the Teouma site, Vanuatu. *Journal of Archaeological Science*, 37(10):2459–2468.

Stoughton, A. L. and Meaker, V. T. (1932). Sex differences in the prevalence of dental caries. *Public Health Report*, 47(1):26–37.

Stuiver, M. and Polach, H. A. (1977). Discussion; reporting of C-14 data. *Radiocarbon*, 19(3):355–363.

Suchanek, W. and Yoshimura, M. (1998). Processing and properties of hydroxyapatite-based biomaterials for use as hard tissue replacement implants. *Journal of Materials Research*, 13(01):94–117.

Summerhayes, G. (2001). Defining the chronology of Lapita in the Bismarck Archipelago. In Clark, A. G., Anderson, A., and Vunidilo, T., editors, *The archaeology of Lapita dispersal in Oceania*, chapter 3, pages 25–38. Pandanus Books, Canberra, Australia.

Summerhayes, G. R., Leavesley, M., Fairbairn, A., Mandui, H., Field, J., Ford, A., and Fullagar, R. (2010). Human adaptation and plant use in Highland New Guinea 49,000 to 44,000 years ago. *Science*, 330(6000):78–81.

Sutton, A., Mountain, M.-J., Aplin, K., Bulmer, S., and Denham, T. (2009). Archaeozoological records for the highlands of New Guinea: A review of current evidence. *Australian Archaeology*, 69:41–58.

Szabó, K. (2001). The reef, the beach and the rocks: An environmental analysis of mollusc remains from Natunuku, Viti Levu, Fiji. In Clark, G., Anderson, A., and Vunidilo, T., editors, *The archaeology of Lapita dispersal in Oceania*, Terra Australis, chapter 14, pages 159–166. Pandanus books, Canberra, Australia.

Szabó, K. (2009). Molluscan remains from Fiji. In Clark, G. and Anderson, A., editors, *The Early Prehistory of Fiji*, volume 31 of *Terra Australis*, chapter 8, pages 183–211. ANU Press, Canberra, Australia.

Szabó, K. and Amesbury, J. R. (2011). Molluscs in a world of islands: The use of shellfish as a food resource in the tropical island Asia-Pacific region. *Quaternary International*, 239(1–2):8–18.

Szulc, P., Seeman, E., and Delmas, P. (2000). Biochemical measurements of bone turnover in children and adolescents. *Osteoporosis International*, 11(4):281–294.

Tan, B., Gillam, D. G., Mordan, N. J., and Galgut, P. N. (2004). A preliminary investigation into the ultrastructure of dental calculus and associated bacteria. *Journal of Clinical Periodontology*, 31(5):364–369.

Tans, P. P., De Jong, A. F. M., and Mook, W. G. (1979). Natural atmospheric ^{14}C variation and the Suess effect. *Nature*, 280(5725):826–828.

Tanzer, J., Livingston, J., and Thompson, A. (2001). The microbiology of primary dental caries in humans. *Journal of Dental Education*, 65(10):1028–1037.

Tayles, N., Domett, K., and Nelsen, K. (2000). Agriculture and dental caries? the case of rice in prehistoric Southeast Asia. *World Archaeology*, 32(1):68–83.

Taylor, F. W. and Bloom, A. L. (1977). Coral reefs on tectonic blocks, Tonga Island Arc. In Taylor, D. L., editor, *Proceedings of Third International Coral Reef Symposium*, volume 2: Geology. Rosenstiel School of Marine and Atmospheric Science, Miami.

Taylor, P. D. P., De Bièvre, P., Valkiers, S., and Groot, P. A. d. (2004). The nature and role of primary certified isotopic reference materials: A tool to underpin isotopic measurements on a global scale. In *Handbook of Stable Isotope Analytical Techniques*, chapter 41, pages 907–927. Elsevier, Amsterdam.

Taylor, R. M. S. (1962). Non-metrical studies of the human palate and dentition in Moriori and Maori skulls: Part 2. *The Journal of the Polynesian Society*, 71(2):167–187.

Taylor, R. M. S. (1963). Cause and effect of wear of teeth. further non-metrical studies of the teeth and palate in Moriori and Maori skulls. *Acta Anatomica*, 53:97–157.

Taylor, R. M. S. (1971). Dental report on archaeological material from Tonga. *Australian Dental Journal*, 16(3):175–181.

Teaford, M. F. and Walker, A. (1984). Quantitative differences in dental microwear between primate species with different diets and a comment on the presumed diet of Sivapithecus. *American Journal of Physical Anthropology*, 64(2):191–200.

Temple, D. H. and Goodman, A. H. (2014). Bioarcheology has a "health" problem: Conceptualizing "stress" and "health" in bioarcheological research. *American Journal of Physical Anthropology*, 155:186–191.

Temple, D. H., Kusaka, S., and Sciulli, P. W. (2011). Patterns of social identity in relation to tooth ablation among prehistoric Jomon foragers from the Yoshigo site, Aichi prefecture, Japan. *International Journal of Osteoarchaeology*, 21(3):323–335.

Temple, D. H. and Larsen, C. S. (2007). Dental caries prevalence as evidence for agriculture and subsistence variation during the Yayoi period in prehistoric Japan: Biocultural interpretations of an economy in transition. *American Journal of Physical Anthropology*, 134(4):501–512.

Terakado, Y., Shimizu, H., and Masuda, A. (1988). Nd and Sr isotopic variations in acidic rocks formed under a peculiar tectonic environment in Miocene Southwest Japan. *Contributions to Mineralogy and Petrology*, 99(1):1–10.

Terrell, J. E., Hart, J. P., Barut, S., Cellinese, N., Curet, A., Denham, T., Kusimba, C. M., Latinis, K., Oka, R., Palka, J., Pohl, M. E. D., Pope, K. O., Williams, P. R., Haines, H., and Staller, J. E. (2003). Domesticated landscapes: The subsistence ecology of plant and animal domestication. *Journal of Archaeological Method and Theory*, 10(4):323–368.

Terry, J. P., Raj, R., and Kostaschuk, R. A. (2001). Links between the southern oscillation index and hydrological hazards on a tropical Pacific island. *Pacific Science*, 55(3):275–283.

Thoma, K. H. (1917). Oral diseases of ancient nations and tribes. *Journal of the Allied Dental Societies*, 12:327–334.

Thomas, C. J. and Cahoon, L. B. (1993). Stable isotope analyses differentiate between different trophic pathways sup-

porting rocky-reef fishes. *Marine Ecology-Progress Series*, 95:19–19.

Thomas, W. L. (1963). The variety of physical environments among Pacific Islands. In Fosberg, F. R., editor, *Man's place in the island ecosystem*, chapter 2, pages 7–38. Bishop Museum Press, Honolulu, Hawai'i.

Thomson, B. M. and Caballero, B. (1998). Bone. In *Encyclopedia of Human Nutrition (Second Edition)*, pages 220–225. Elsevier, Oxford, UK.

Thylstrup, A., Chironga, L., de Carvalho, J., and Ekstrand, K. R. (1989). The occurence of dental calculus in occlusal fissures as an indications of caries activity. In ten Cate, J. M., editor, *Recent Advances in the Study of Dental Calculus*. IRL Press, Oxford, UK.

Tieszen, L. L. (1991). Natural variations in the carbon isotope values of plants: Implications for archaeology, ecology, and paleoecology. *Journal of Archaeological Science*, 18(3):227–248.

Tieszen, L. L. and Boutton, T. W. (1989). Stable carbon isotopes in terrestrial ecosystem research. In Billings, W., Golley, F., Lange, O., Olson, J., and Remmert, H., editors, *Stable Isotopes in Ecological Research*, number 68 in Ecological Studies, chapter 11, pages 167–195. Springer New York, New York, NY.

Tieszen, L. L., Boutton, T. W., Tesdahl, K., and Slade, N. A. (1983). Fractionation and turnover of stable carbon isotopes in animal tissues: implications for $\delta^{13}C$ analysis of diet. *Oecologia*, 57(1-2):32–37.

Tomczyk, J., Szostek, K., Komarnitki, I., Mańkowska-Pliszka, H., and Zalewska, M. (2013). Dental caries and chemical analyses in reconstruction of diet, health and hygienic behaviour in the Middle Euphrates valley (Syria). *Archives of Oral Biology*, 58(6):740–751.

Tonga Meteorological Services (2006). Climatological information- Nuku'alofa.

Torrence, R. (1986). *Production and exchange of stone tools: prehistoric obsidian in the Aegean*. Cambridge University Press, Cambridge [Cambridgeshire]; New York.

Torrence, R., Specht, J., Fullagar, R., and Bird, R. (1992). From Pleistocene to present: obsidian sources in West New Britain, Papua New Guinea. *Records of the Australian Museum, Supplement*, 15:83–98.

Trickett, M. A., Budd, P., Montgomery, J., and Evans, J. (2003). An assessment of solubility profiling as a decontamination procedure for the $^{87}Sr/^{86}Sr$ analysis of archaeological human skeletal tissue. *Applied Geochemistry*, 18(5):653–658.

Tromp, M. and Dudgeon, J. V. (2015). Differentiating dietary and non-dietary microfossils extracted from human dental calculus: the importance of sweet potato to ancient diet on Rapa Nui. *Journal of Archaeological Science*, 54(0):54–63.

Trust, B. and Fry, B. (1992). Stable sulphur isotopes in plants: a review. *Plant, Cell & Environment*, 15(9):1105–1110.

Tsutaya, T., Sawada, J., Dodo, Y., Mukai, H., and Yoneda, M. (2013). Isotopic evidence of dietary variability in subadults at the Usu-moshiri site of the Epi-Jomon culture, Japan. *Journal of Archaeological Science*, 40(11):3914–3925.

Tsutaya, T. and Yoneda, M. (2015). Reconstruction of breastfeeding and weaning practices using stable isotope and trace element analyses: A review. *American Journal of Physical Anthropology*, 156:2–21.

Tuljapurkar, S., Lee, C., and Figgs, M. (2007). Demography and food in early Polynesia. In Kirch, P. V. and Rallu, J.-L., editors, *The growth and collapse of Pacific Island societies: archaeological and demographic perspectives*, chapter 3, pages 35–51. University of Hawai'i Press, Honolulu.

Turner, B. L. (2013a). Interpreting oral pathology at Machu Picchu, Peru. *International Journal of Osteoarchaeology*, pages n/a–n/a.

Turner, B. L., Kamenov, G. D., Kingston, J. D., and Armelagos, G. J. (2009). Insights into immigration and social class at Machu Picchu, Peru based on oxygen, strontium, and lead isotopic analysis. *Journal of Archaeological Science*, 36(2):317–332.

Turner, B. L., Kingston, J. D., and Armelagos, G. (2010). Variation in dietary histories among the immigrants of Machu Picchu: Carbon and nitrogen isotope evidence. *Chungara: Revista de Antropología Chilena*, 42(2):515–534.

Turner, C. G. (1969). Microevolutionary interpretations from the dentition. *American Journal of Physical Anthropology*, 30(3):421–426.

Turner, C. G. (1979). Dental anthropological indications of agriculture among the Jomon people of central Japan. X. peopling of the Pacific. *American Journal of Physical Anthropology*, 51(4):619–635.

Turner, C. G. and Machado, L. M. C. (1983). A new dental wear pattern and evidence for high carbohydrate consumption in a Brazilian Archaic skeletal population. *American Journal of Physical Anthropology*, 61(1):125–130.

Turner, G. and Anderson, T. (2003). Marked occupational dental abrasion from medieval Kent. *International Journal of Osteoarchaeology*, 13(3):168–172.

Turner, S. A. (2013b). Dietary reconstruction in medieval Holbæk, Denmark using dental microwear and macrowear, isotopic analyses, and dental caries. Master of arts, Georgia State University, Atlanta, GA.

Tuvale, T. (1918). *An account of Samoan History up to 1918*. NZ Electronic Text Centre, Victoria University of Wellington, Wellington, NZ.

Ubelaker, D. H. (1984). *Human skeletal remains: excavation, analysis, interpretation*. Manuals on archeology ; 2. Taraxacum, Washington, D.C.

Ungar, P. S., Grine, F. E., and Teaford, M. F. (2008). Dental microwear and diet of the Plio-Pleistocene hominin *Paranthropus boisei*. *PLoS ONE*, 3(4):e2044.

Ungar, P. S., Grine, F. E., Teaford, M. F., and Pérez-Pérez, A. (2001). A review of interproximal wear grooves on fossil hominin teeth with new evidence from Olduvai Gorge. *Archives of Oral Biology*, 46(4):285–292.

UNICEF (2003). The state of the world's children 2004. Technical report, UNICEF, New York, NY.

University of Otago (2015). Guidelines for the inclusion of material from a research

candidate's publications in their thesis. Online; Accessed 3 March 2015.

Urey, H. C. (1947). The thermodynamic properties of isotopic substances. *Journal of the Chemical Society*, pages 562–581.

Urey, H. C., Lowenstam, H. A., Epstein, S., and McKinney, C. R. (1951). Measurement of paleotemperatures and temperatures of the Upper Cretaceous of England, Denmark, and the Southeastern United States. *Geological Society of America Bulletin*, 62(4):399–416.

USDA (2004). USDA national fluoride database of selected beverages and foods.

Valentin, F., Bocherens, H., Gratuze, B., and Sand, C. (2006). Dietary patterns during the late prehistoric/historic period in Cikobia island (Fiji): insights from stable isotopes and dental pathologies. *Journal of Archaeological Science*, 33(10):1396–1410.

Valentin, F., Buckley, H. R., Herrscher, E., Kinaston, R., Bedford, S., Spriggs, M., Hawkins, S., and Neal, K. (2010). Lapita subsistence strategies and food consumption patterns in the community of Teouma (Efate, Vanuatu). *Journal of Archaeological Science*, 37(8):1820–1829.

Valentin, F., Herrscher, E., Petchey, F., and Addison, D. J. (2011). An analysis of the last 1000 years human diet on Tutuila (American Samoa) using carbon and nitrogen stable isotope data. *American Antiquity*, 76(3):473–486.

Valentine, B., Kamenov, G. D., and Krigbaum, J. (2008). Reconstructing Neolithic groups in Sarawak, Malaysia through lead and strontium isotope analysis. *Journal of Archaeological Science*, 35(6):1463–1473.

van Beek, G. C. (1983). *Dental Morphology: An illustrated Guide*. Elsevier, Philadelphia, PA.

van Klinken, G. J., Richards, M. P., and Hedges, R. E. M. (2000). An overview of causes for stable isotopic variations in past European human populations: Environmental, ecophysiological, and cultural effects. In Ambrose, S. H. and Katzenberg, M. A., editors, *Biogeochemical approaches to paleodietary analysis*, volume 5 of *Advances in Archaeological and Museum Science*, chapter 3, pages 39–63. Kluwer Academic/ Plenum Publishers, New York, NY.

van Klinken, G. J., van der Plicht, H., and Hedges, R. E. M. (1994). Bone $^{13}C/^{12}C$ ratios reflect (palaeo-)climatic variations. *Geophysical Research Letters*, 21(6):445–448.

van Loveren, C. and Duggal, M. S. (2004). Experts' opinions on the role of diet in caries prevention. *Caries Research*, 38(S1):16–23.

van Palenstein Helderman, W., Matee, M., van der Hoeven, J., and Mikx, F. (1996). Cariogenicity depends more on diet than the prevailing mutans streptococcal species. *Journal of Dental Research*, 75(1):535–545.

Veizer, J. (1989). Strontium isotopes in seawater through time. *Annual Review of Earth and Planetary Sciences*, 17:141.

Veizer, J., Buhl, D., Diener, A., Ebneth, S., Podlaha, O. G., Bruckschen, P., Jasper, T., Korte, C., Schaaf, M., Ala, D., and Azmy, K. (1997). Strontium isotope stratigraphy: potential resolution and event correlation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 132(1–4):65–77.

Vellini-Ferreira, F., Cotrim-Ferreira, F. A., Ribeiro, J. A., and Ferreira-Santos, C. I. (2012). Mapping of proximal enamel thickness in permanent teeth. *Brazilian Journal of Oral Sciences*, 11:481–485.

Vieira, A., Marazita, M., and Goldstein-McHenry, T. (2008). Genome-wide scan finds suggestive caries loci. *Journal of Dental Research*, 87(5):435–439.

Viguet-Carrin, S., Garnero, P., and Delmas, P. (2006). The role of collagen in bone strength. *Osteoporosis International*, 17(3):319–336.

Virginia, R. A. and Delwiche, C. C. (1982). Natural ^{15}N abundance of presumed N_2-fixing and non-N_2-fixing plants from selected ecosystems. *Oecologia*, 54(3):317–325.

Virtanen, J. I., Bloigu, R. S., and Larmas, M. A. (1994). Timing of eruption of permanent teeth: Standard Finnish patient documents. *Community Dentistry and Oral Epidemiology*, 22(5PT1):286–288.

Visser, E. P. (1994). *The prehistoric people from Sigatoka: an analysis of skeletal and dental traits as evidence of adaptation*. Phd, University of Otago, Dunedin, New Zealand.

Völkel, S. (2010). *Social structure, space and possession in Tongan culture and language: an ethnolinguistic study*. Benjamins, Amsterdam, Netherlands.

Volker, J. F. (1957). Food and dental caries. In *Clinical Pedodontics*. W. B. Saunders Company, Philadelphia, London.

Vrydaghs, L. and Denham, T. (2007). Rethinking agriculture: Introductory thoughts. In Denham, T., Iriarte, J., and Vrydaghs, L., editors, *Rethinking Agriculture: Archaeological and Ethnoarchaeological Perspectives*, chapter 1, pages 1–15. Left Coast Press, Walnut Creek, California.

Wahlqvist, M. L. (2002). Asian migration to Australia: food and health consequences. *Asia Pacific Journal of Clinical Nutrition*, 11:S562–S568.

Waldron, T. (1994). *Counting the dead: the epidemiology of skeletal populations*. John Wiley & Sons, Chichester, England.

Wang, X., Shaffer, J. R., Weyant, R. J., Cuenco, K. T., DeSensi, R. S., Crout, R., McNeil, D. W., and Marazita, M. L. (2010). Genes and their effects on dental caries may differ between primary and permanent dentitions. *Caries Research*, 44(3):277–284.

Wansink, B., Cheney, M. M., and Chan, N. (2003). Exploring comfort food preferences across age and gender. *Physiology & Behavior*, 79(4–5):739–747.

Wardle, J., Haase, A., Steptoe, A., Nillapun, M., Jonwutiwes, K., and Bellisie, F. (2004). Gender differences in food choice: The contribution of health beliefs and dieting. *Annals of Behavioral Medicine*, 27(2):107–116.

Wasterlain, S. N., Hillson, S., and Cunha, E. (2009). Dental caries in a Portuguese identified skeletal sample from the late 19^{th} and early 20^{th} centuries. *American Journal of Physical Anthropology*, 140(1):64–79.

Waters-Rist, A., Bazaliiskii, V. I., Weber, A., Goriunova, O. I., and Katzenberg, M. A. (2010). Activity-induced dental modification in Holocene Siberian hunter-fisher-gatherers. *American Journal of Physical Anthropology*, 143(2):266–278.

Waters-Rist, A. L. and Katzenberg, M. A. (2010). The effect of growth on stable nitrogen isotope ratios in subadult bone collagen. *International Journal of Osteoarchaeology*, 20(2):172–191.

Watson, J. T. (2008). Changes in food processing and occlusal dental wear during the early agricultural period in northwest Mexico. *American Journal of Physical Anthropology*, 135(1):92–99.

Watson, J. T., Arriaza, B., Standen, V., and Muñoz Ovalle, I. (2013). Tooth wear related to marine foraging, agropastoralism and the Formative Transition on the Northern Chilean coast. *International Journal of Osteoarchaeology*, 23(3):287–302.

Weisler, M. I. and Kirch, P. V. (1996). Interisland and interarchipelago transfer of stone tools in prehistoric Polynesia. *Proceedings of the National Academy of Sciences*, 93(4):1381–1385.

West, T. (1835). *Ten years in South-Central Polynesia: Being reminiscences of a personal mission to the Friendly Islands and their Dependencies*. James Nisbet and Co., London.

Whipkey, C., Capo, R., Chadwick, O., and Stewart, B. (2000). The importance of sea spray to the cation budget of a coastal Hawaiian soil: a strontium isotope approach. *Chemical Geology*, 168(1):37–48.

Whistler, W. A. (1991). *The ethnobotany of Tonga: the plants, their Tongan names, and their uses*. Bishop Museum bulletin in botany. Bishop Museum Press, Honolulu, Hawai‘i.

Whistler, W. A. (1992a). *Flowers of the Pacific Island seashore: a guide to the littoral plants of Hawai'i, Tahiti, Samoa, Tonga, Cook Islands, Fiji, and Micronesia*. Isle Botanica, Honolulu, Hawai‘i.

Whistler, W. A. (1992b). *Tongan herbal medicine*. Isle Botanica, Honolulu, Hawai‘i.

White, T. D. and Folkens, P. A. (2005). *The Human Bone Manual*. Academic Press, San Diego, CA.

Whittaker, D. K., Griffiths, S., Robson, A., Roger-Davies, P., Thomas, G., and Molleson, T. (1990). Continuing tooth eruption and alveolar crest height in an eighteenth-century population from Spitalfields, East London. *Archives of Oral Biology*, 35(2):81–85.

Whittaker, D. K., Molleson, T., Bennett, R. B., ap Edwards, I., Jenkins, P. R., and Llewelyn, J. H. (1981). The prevalence and distribution of dental caries in a Romano-British population. *Archives of Oral Biology*, 26(3):237–245.

WHO (2009). *Infant and young child feeding: Model Chapter*. World Health Organization, Geneva, Switzerland.

Wickler, S. and Spriggs, M. (1988). Pleistocene human occupation of the Solomon Islands, Melanesia. *Antiquity*, 62(237):703–706.

Williams, J. S., White, C. D., and Longstaffe, F. J. (2005). Trophic level and macronutrient shift effects associated with the weaning process in the postclassic Maya. *American Journal of Physical Anthropology*, 128(4):781–790.

Williams, R. J. and Martinez, N. D. (2004). Limits to trophic levels and omnivory in complex food webs: theory and data. *The American Naturalist*, 163(3):458–468.

Willis, A. and Oxenham, M. F. (2013). The neolithic demographic transition and oral health: The Southeast Asian experience. *American Journal of Physical Anthropology*, 152(2):197–208.

Wilmshurst, J. M., Anderson, A. J., Higham, T. F. G., and Worthy, T. H. (2008). Dating the late prehistoric dispersal of Polynesians to New Zealand using the commensal Pacific rat. *Proceedings of the National Academy of Sciences*, 105(22):7676–7680.

Wilmshurst, J. M., Hunt, T. L., Lipo, C. P., and Anderson, A. J. (2011). High-precision radiocarbon dating shows recent and rapid initial human colonization of East Polynesia. *Proceedings of the National Academy of Sciences*, 108(5):1815–1820.

Wilson, A. C., Forsyth, J. S., Greene, S. A., Irvine, L., Hau, C., and Howie, P. W. (1998). Relation of infant diet to childhood health: seven year follow up of cohort of children in Dundee infant feeding study. *BMJ*, 316(7124):21–25.

Wilson, P. R. and Beynon, A. D. (1989). Mineralization differences between human deciduous and permanent enamel measured by quantitative microradiography. *Archives of Oral Biology*, 34(2):85–88.

Wollstein, A., Lao, O., Becker, C., Brauer, S., Trent, R. J., Nürnberg, P., Stoneking, M., and Kayser, M. (2010). Demographic history of Oceania inferred from genome-wide data. *Current Biology*, 20(22):1983–1992.

Wood, J. W., Milner, G. R., Harpending, H. C., and Weiss, K. M. (1992). The osteological paradox: Problems of inferring prehistoric health from skeletal samples. *Current Anthropology*, 33(4):343–370.

Worthy, T. H. (2000). The fossil megapodes (Aves: *Megapodiidae*) of Fiji with descriptions of a new genus and two new species. *Journal of the Royal Society of New Zealand*, 30(4):337–364.

Worthy, T. H. and Clark, G. (2009). Bird, mammal and reptile remains. In Clark, G. and Anderson, A., editors, *The Early Prehistory of Fiji*, volume 31 of *Terra Australis*, chapter 10, pages 231–258. ANU Press, Canberra, Australia.

Wright, E. and White, W. M. (1987). The origin of Samoa: new evidence from Sr, Nd, and Pb isotopes. *Earth and Planetary Science Letters*, 81(2–3):151–162.

Wright, L. E. and Schwarcz, H. P. (1998). Stable carbon and oxygen isotopes in human tooth enamel: Identifying breastfeeding and weaning in prehistory. *American Journal of Physical Anthropology*, 106(1):1–18.

Wright, L. E. and Yoder, C. J. (2003). Recent progress in bioarchaeology: Approaches to the osteological paradox. *Journal of Archaeological Research*, 11(1):43–70.

Wutich, A. and Brewis, A. (2014). Food, water, and scarcity: Toward a broader anthropology of resource insecurity. *Current Anthropology*, 55(4):444–468.

Yamori, W., Hikosaka, K., and Way, D. (2014). Temperature response of photosynthesis in C_3, C_4, and CAM plants: temperature acclimation and temperature adaptation. *Photosynthesis Research*, 119(1-2):101–117.

Yen, D. E. (1973). The origins of Oceanic agriculture. *Archaeology & Physical Anthropology in Oceania*, 8(1):68–85.

Yen, D. E. (1974). *The Sweet Potato and Oceania: An Essay in Ethnobotany*. Bernice P. Bishop Museum Bulletin 236. Bishop Museum Press, Honolulu, Hawai'i.

Yen, D. E. (1980). The Southeast Asian foundations of Oceanic agriculture: A reassessment. *Journal de la Société des océanistes.*, 66-67(36):140–147.

Yoshinaga, J., Minagawa, M., Suzuki, T., Ohtsuka, R., Kawabe, T., Hongo, T., Inaoka, T., and Akimichi, T. (1991). Carbon and nitrogen isotopic characterization for Papua New Guinea foods. *Ecology of Food and Nutrition*, 26(1):17–25.

Yoshinaga, J., Minagawa, M., Suzuki, T., Ohtsuka, R., Kawabe, T., Inaoka, T., and Akimichi, T. (1996). Stable carbon and nitrogen isotopic composition of diet and hair of Gidra-speaking Papuans. *American Journal of Physical Anthropology*, 100(1):23–34.

Yuncker, T. G. (1959). *Plants of Tonga*. Bernice P. Bishop Museum bulletin. Bernice P. Bishop Museum, Honolulu, Hawai'i.

Zanden, M. J. V. and Rasmussen, J. B. (2001). Variation in δ^{15}N and δ^{13}C trophic fractionation: Implications for aquatic food web studies. *Limnology and Oceanography*, 46(8):2061–2066.

Zazzo, A. (2014). Bone and enamel carbonate diagenesis: A radiocarbon prospective. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 416(0):168–178.

Zazzo, A., Balasse, M., and Patterson, W. P. (2006). The reconstruction of mammal individual history: refining high-resolution isotope record in bovine tooth dentine. *Journal of Archaeological Science*, 33(8):1177–1187.

Zero, D. T. (2004). Sugars- the arch criminal. *Caries Research*, 38(3):277–285.

Zohary, T., Erez, J., Berman-Frank, I., and Stiller, M. (1994). Seasonality of stable carbon isotopes within the pelagic food web of Lake Kinneret. *Limnology and Oceanography*, 39(5):1030–1043.

Zuckerman, M. K., Turner, B. L., and Armelagos, G. J. (2012). Evolutionary thought in paleopathology and the rise of the biocultural approach. In Grauer, A. L., editor, *A Companion to Paleopathology*, chapter 3, pages 34–57. Wiley-Blackwell, West Sussex, UK.