Macropod bone apatite isotopic analysis as evidence for recent environmental change at Bandicoot Bay pearling camp, Barrow Island.

Jane Skippington\textsuperscript{a} - jane.skippington@research.uwa.edu.au, m. 0404 134 016

Tiina Manne\textsuperscript{b} - t.manne@uq.edu.au

Alistair Paterson \textsuperscript{a} – alistair.paterson@uwa.edu.au

Peter Veth\textsuperscript{a,c} - peter.veth@uwa.edu.au

\textsuperscript{a}Archaeology, School of Social Sciences, M257, The University of Western Australia, Perth, WA, 6009, Australia

\textsuperscript{b}School of Social Science, The University of Queensland, Brisbane, QLD, 4072, Australia

\textsuperscript{c}ARC Centre of Excellence for Australian Biodiversity and Heritage

Abstract

Stable isotope analysis of bone apatite oxygen ($\delta^{18}$O) and carbon ($\delta^{13}$C) was undertaken for modern and archaeological spectacled hare wallaby (\textit{Lagorchestes conspicillatus}) bone collected from an 1880s indentured labor confinement camp on Barrow Island in Western Australia. $\delta^{18}$O results and historical climate data indicate decreased annual precipitation during occupation of the site and provide insight into the conditions experienced by Aboriginal pearling laborers incarcerated on the offshore island. $\delta^{13}$C values may reflect variation in water availability or a short-term vegetation change resulting from landscape burning. This study is the first application of macropod bone apatite isotopic analysis in an Australian historical context and demonstrates its significant potential for identifying recent environmental changes to a high level of sensitivity.

Keywords

Stable isotopes
Apatite
Bone
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1. Introduction

The settlement and colonisation of Western Australia by the British in the 1800s profoundly and negatively affected Aboriginal communities across the colony. British influence was initially restricted to the southwest concentrated around the Swan River in Perth and King George Sound; however, by the mid-1800s commercial opportunity linked to pastoralism and extractive maritime industries materially expanded activities into northwest Australia (Anderson 2014; Dooley et al. 2018; McCarthy 1988;
McCarthy 1990; Nayton 2011, Shepherd 1975; Paterson 2018). Despite the presence of convict labor in the southwest, the colonial administration banned their presence on the northern frontiers as there was no potential for suitable surveillance of a prison labor force. Instead, like much of Central and Northern Australia, Aboriginal labor was often the cornerstone of colonial activities: particularly pastoralism, pearl fisheries, and domestic labor. This labor was often paid for with rations rather than money, and concerns regarding the poor treatment of Aboriginal men, women and children were common across the frontier. Legislation such as the *Master and Servant Act* 1868 attempted to define and regulate these labor relations on Country. Strengthened by the labor derived from local Aboriginal populations through coercion and kidnapping, pearling fisheries peaked as Western Australia’s most critical colonial exporter in the late 1800s (Kwaymullina 2001; Paterson and Veth 2020), covering a vast coastline between Shark Bay to the west Kimberley.

Historical documents suggest that thousands of Aboriginal laborers were subjected to deplorable maltreatment and translocated large distances from their homelands to support the pearling industry in a practice referred to as “blackbirding” (Colonial Secretary’s Office 1886; Martínez & Vickers 2012). This included marooning laborers on remote offshore islands in periods of hiatus from pearling programs (West Australian 1887; see Bain 1982; Forrest 1996). Importantly, detail regarding the extent and conditions of incarceration on the islands, and the presumably harrowing experiences of interned Aboriginal laborers forcibly separated from their culture and families, are not reflected in the one-sided colonial records. Equally, the resilience of Aboriginal people and the strategies they employed to survive these extraordinary circumstances are not explicitly documented. In addition to Aboriginal labor, pearling ‘Masters’ as they were known voyaged to island Southeast Asia, then the colonial Dutch East Indies, to recruit Asian laborers as indentured workers. Similar to Aboriginal workers, many Asian workers were reportedly mistreated by the pearlers, being poorly fed, and sometimes abandoned on remote islands.

Located approximately 55 km offshore on Barrow Island (202 sq km) in northwest Australia (Figure 1), the Bandicoot Bay settlement site (D24-001) preserves rare and compelling archaeological evidence for the incarceration of Aboriginal peoples as part of the historical pearling fishery and therefore a unique opportunity to investigate Aboriginal agency, adaptation and innovation in the face of coercive colonial practices. The Island itself represents an elevated portion of a now drowned coastal plain that was first occupied at least 50,000 years ago but was abandoned by its Aboriginal inhabitants when rising sea levels separated the land mass from the mainland at 7000 cal BP (Chappell and Thom 1977; Chappell and Shackleton 1986; Veth et al. 2017). Following a long period of discontinuity, human activity on the island was reactivated during the colonial period (late 1800s) in association with the rise of maritime industries (Paterson 2017).

Detailed analysis of the rich historical assemblages at D24-001 – including bone, charcoal, shell, ceramics, metal objects, lithics and flaked glass artefacts – suggests
that indentured laborers were marooned at the site during the 1880s with limited provisions and likely relied on cultural knowledge and the exploitation of local economic resources for physical and emotional survival. Examination of the zooarchaeological and anthracological assemblages suggest that the subsistence strategies employed by internees mirrored the approaches of mainland Aboriginal communities and focused on the procurement and processing of proteins, particularly wallabies (Lagorchestes conspicillatus), derived from local terrestrial habitats (Byrne et al. 2019; Dooley et al. 2020). Based on the absence of evidence for exchange or functional use, it is interpreted that the production of flaked glass points at site likely served a predominantly social purpose; promoting the maintenance of group and individual identity in a time of great distress (Paterson and Veth 2020). The reconstruction of the past environments through isotopic analysis has high potential to provide further insights into the strategies employed by internees to manage the undoubtedly harsh conditions. To further investigate human-environmental dynamics in this context, this study compares apatite $\delta^{18}O$ and $\delta^{13}C$ results from archaeological and modern L. conspicillatus to map probable changes in relative humidity and vegetation. Although the stable isotope compositions of mammalian bone bioapatite are widely used as proxies for past environmental factors in prehistoric studies (Lee-Thorp 2002; Lee-Thorp and Sponheimer 2003), this is the first application of macropod bone apatite analysis in an Australian historical archaeological context. An outline of the theoretical basis for isotopic analyses is provided as background for this study.

2. Stable isotope theory

The mineral component of bone, tooth enamel, and dentin is a highly substituted form of hydroxylapatite, known as bioapatite (Koch 2007). Substantial foundational research has firmly established the relationships between isotopic compositions of bioapatite and various environmental factors (De Niro and Epstein 1978; Longinelli 1984; Luz and Kolodyn 1985; Lee-Thorp et al. 1989; Cerling and Harris 1990; Lee-Thorp and van der Merwe 1991).

In terrestrial mammals, bioapatite composition reflects the $\delta^{18}O$ values of body water which is primarily influenced by the isotopic composition of ingested water (Longinelli 1984; Lutz et al 1984). As such, the relationships between bioapatite $\delta^{18}O$ values and environmental factors, including aridity and temperature, are dependent on animal physiology (Hallin et al. 2012; Kohn and Cerling 2002). In obligate drinkers that rely on surface water for hydration, $\delta^{18}O$ values demonstrate species specific correlations with meteoric sources and are strongly influenced by temperature (Huertas et al., 1995; Kohn, 1996). Herbivorous non-obligate drinkers obtain most of their water through dietary plant sources and, as such, $\delta^{18}O$ values reflect the composition of ingested leaf water (Ayliffe and Chivas 1990; Levin et al 2006; Somerville et al. 2018; Somerville et al 2020.) Leaf water is sensitive to evapotranspiration processes and therefore can be used as a proxy for relative humidity (Ayliffe and Chivas 1990; Luz et al. 1990).
Wallabies are Australian herbivorous marsupial mammals of the family Macropodidae. Water consumption in macropods is variable and habitat dependent. In general, macropods meet between 20% and 45% of their water requirements from dietary plant matter; however, this can be as high as 100% for non-obligate drinkers in arid habitats such as Barrow Island. There is a well-documented inverse relationship linking $\delta^{18}O$ values and relative humidity in macropods (Ayliffe and Chivas 1990; Murphy et al. 2007b; Prideaux et al. 2007; Forbes et al. 2010; Brookman and Ambrose 2012; Montanari et al. 2013). A marginal interactive effect between temperature and humidity has also been noted (Murphy et al. 2007b).

Apatite $\delta^{13}C$ values in herbivores reflects ingested plant matter (Kohn and Cerling 2002). Specifically, the relative contributions of plants that utilize the distinct C3 and C4 photosynthetic pathways (Passey et al. 2005; Murphy et al. 2007a; Forbes et al. 2010). It can therefore be used to extrapolate habitats and vegetation structure. More broadly, $\delta^{13}C$ values in C3 plants increases with increasing aridity (Farquhar et al. 1989). As a result of digestive and physiological fractionation processes, the carbon isotope composition of mammalian bioapatite is offset by several per mil compared to the respective diet and varies between species (Murphy et al. 2007a; Gehler et al. 2012).

In general, enamel bioapatite is preferred for isotopic studies of archaeological material on the basis that its mineral content and crystalline characteristics confer a high-level resistance to diagenesis (Wang and Cerling 1994; Balasse 2002; Balasse et al. 2003). Indeed, early applications of bone apatite were criticised due to the tendency for bone mineral to absorb carbonate from its environment (Lee-Thorp and van der Merwe 1991; Schoeninger and DeNiro 1982). However, over time the integrity of bone apatite in isotopes in archaeological contexts has been verified through multi-tissue studies (Sullivan and Krueger 1981; Lee-Thorp 2002; Lee-Thorp and Sponheimer 2003; Shin and Hedges 2012). Pre-treatment protocols developed to separate and remove diagenetic carbonates further contribute to the viability of bone apatite analyses (Koch et al. 1997; Garvie-Lok et al. 2004; Yoder and Bartelink 2012).

In favourable conditions bone apatite carbonate can remain preserved for up to 1000 years (Koch 2007; Clements 2012). Since the bones in this study were recovered from a historical context and are estimated to be only 130 years, the likelihood of significant diagenesis is extremely low. In addition, the successful extraction of preserved collagen at the site for the purpose of Zooarchaeology by Mass Spectrometry (ZooMS) suggests a chemically stable depositional environment (Peters et al. 2021). Unlike enamel, bone is continually remodelled and therefore bone apatite is a proxy for multi-year average environmental conditions (Longinelli 1984; Hedges et al. 2005).

3. Materials and methods

3.1 The study area and excavation
Barrow Island (202 sq km) is an A-class nature reserve with an arid climate characterised by irregular cross-season rainfall (Hickman and Strong 2003). Due to the influence of the Indo-Australian northern monsoon, summer cyclonic events and winter frontal systems, precipitation is dynamic and averages approximately 318 mm per annum (King and Bradshaw 2010; Moro and Lagdon 2013; Veth et al. 2017). There are no permanent surface water sources on Barrow Island; however, a lens of freshwater floats upon the denser saline ground water at sub-surface depths between 9 m and 53 m (Chevron Australia 2014). Although the island supports over 378 native plant species, vegetation is primarily C4 grassland dominated by spinifex (Triodia spp.). Scattered C3 trees and shrubs include Melaleuca, Grevillea, Pittosporum, Petalostylis, Pentalepis and Acacia species (Moro and Lagdon 2013).

D24-001 is a shallow but expansive site located in a low relief sand dune at the southern end of the island, overlooking a shallow inlet which would have provided protection for the pearling luggers (Figure 2) (Paterson and Veth 2020). An open-area excavation in 2013 and 2014 used a one-metre grid and arbitrary excavations units (c.10 cm) to define the boundaries of the settlement. Dry excavated material was passed through 5 mm and 2 mm nested sieves. Excavations revealed a broad, unstratified deposit retaining good spatial integrity (Byrne 2019).

### 3.2 Sampling

To investigate historical environmental conditions, 17 archaeological *L. conspicillatus* bone samples were recovered from D24-001 (Figure 3). A further 10 modern *L. conspicillatus* bone samples were collected from the surrounding area. All samples were adult specimens.

*L. conspicillatus* specimens were identified at the University of Queensland School of Social Science Zooarchaeology Laboratory. A modern comparative collection of several (deceased) individuals collected from Barrow Island between 2013-2014 facilitated identification. Specimens were identified to taxa and element. All specimens were weighed and measured prior to isotope processing and sampling.

*L. conspicillatus* is a selective browser known to feed on a mixture of monocotyledonous and dicotyledonous species including the tips of *Triodia* spp., shrub foliage and dicot herbs (Main and Yadav 1971; Burbidge and Johnson 1983; Ingleby and Westoby 1992; Strahan 1995).

### 3.3 Pre-analytical processing

Preanalytical processing of bone samples was conducted at the Archaeology Laboratory, University of Western Australia.

Bone samples were cleaned of debris (i.e. organic material, dirt and plaque) using a diamond drill bit, washed in an ultra-sonicator using deionised water, and allowed to
air dry at room temperature. Dry bone samples were then ground to a fine powder using an agate mortar and pestle.

Preparation for carbonate analysis was conducted in accordance with standard contemporary methods (Garvie-Lok et al. 2004; Skippington et al. 2019). Aliquots of the powdered bone samples were treated overnight with 50 μL of 3% hydrogen peroxide per 1.0 mg of bone to remove organic matter. This was followed by a fifteen-minute treatment with 0.1 M acetic acid (50 μL of per 1.0 mg of sample) to remove diagenetic and absorbed carbonate. After each treatment, samples were rinsed with demineralized water, centrifuged four times, and dried in a desiccator.

### 3.4 Isotopic analyses

Isotopic values are given in per mil (‰) difference in the ratio of heavier to lighter isotopes (R) compared to that of a standard and are expressed using the standard delta notion (δ) as follows:

\[
\delta = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000
\]

Analyses were conducted at the West Australian Biochemistry Centre, School of Plant Biology, the University of Western Australia.

Carbonate samples were analyzed for δ\(^{18}\)O and δ\(^{13}\)C values using an GasBench II coupled with Delta XL Mass Spectrometer (Thermo-Fisher Scientific/Germany). Three-points normalization was used to reduce raw values to the international scale (Skrzypek 2013) and normalization was undertaken in accordance with international standards provided by IAEA: L-SVEC, NBS19 and NBS18, IAEA603. Values of international standards for carbon (δ\(^{13}\)C) followed Coplen et al. (2006). The GasBench technique is outlined in Paul and Skrzypek (2007).

### 3.5. Statistical analysis

Statistical visualizations and analyses were conducted using R. Pairwise Wilcoxon rank sum tests.

### 4. Results

Isotopic bone apatite results were recorded for 17 archaeological and 10 modern *L. conspicillatus* bone carbonate samples (Figure 4) (Supplementary Table). Mean values and standard deviations are summarised in Table 1.

Overall δ\(^{18}\)O values range from -3.1‰ to 0.7‰. Statistically significant separation was identified between the historical (mean = -0.4‰, sd = 0.82) and modern (-1.2‰, sd = 0.56) samples (adjusted p-values = 0.0024) (Figure 5).
δ¹³C values range from −8.5‰ to −0.1‰ and clear differentiation is evident between the sample groups (Figure 6). The adjusted p-value (0.023) indicates a statistically significant difference between the archaeological (mean = −4.3 ‰, sd = 1.84) and modern (mean = −6.7‰, sd = 0.94) samples. This notable difference is evident even after a -1.2‰ correction is applied to the archaeological samples to account for depletion in modern δ¹³C resulting from the increase in fossil fuel burning from the end of the eighteenth century (p-value = 0.074) (Friedli et al. 1986; Leurnberger et al. 1992). Overall, the corrected mean archaeological δ¹³C value is 1.3‰ more positive than the sampled modern bone. No discernible intra site spatial trends were identified for either δ¹⁸O or δ¹³C values.

5. Discussion

5.1 Oxygen

A statistically significant shift of 0.8‰ was observed between the mean modern and archaeological δ¹⁸O values. Given that there are no free water sources on the island and the potential influence of physiological factors is diminished by the focus on a single taxon (Koch 1997; Kohn and Cerling 2002), this result is interpreted to reflect the critical link between the oxygen composition of mammalian bioapatite and relative humidity (Ayliffe and Chivas 1990; Luz et al. 1990). Broadly, the results suggest conditions were drier during occupation of the site in the 1880s. Consideration of linear models for bone phosphate bioapatite and enamel carbonate bioapatite by Aycliffe and Chivas (1990) and Murphy et al. (2007b) suggest that isotopic signatures may reflect a change in relative humidity of approximately 3%.

Murphy et al. (2007b) reported a clear interaction between mean annual temperature and relative humidity at lower temperatures whereby an increase in average annual temperature of 10°C results in 12-15% change in relative humidity. While changes of this magnitude may be expected from Pleistocene-era samples spanning the Last Glacial Maximum (Denniston et al. 2013; Fitsimmons et al. 2015; William et al. 2015), shorter term temperatures in Australia have risen on average by a mere 1.44 ± 0.24°C since national records began in 1910 (Australia Government Bureau of Meteorology 2020). Therefore, temperature is not considered to be a factor.

Detailed historical rainfall data is not available for Barrow Island; however, state records from the early 1900s through to contemporary observations indicate that the magnitude and direction of long-term trends in rainfall varies across Western Australia (Jones et al. 2009; Australian Government Bureau of Meteorology 2012; CSIRO 2012; Charles et al. 2015). In general, the northwest has seen an overarching trend toward increased summer rainfall linked to increasing cyclonic events and other closed low, weather systems (Feng et al. 2013); however, rainfall precipitation trends do indicate a decrease between 1961 to 2012 in the western Pilbara (Australian Government Bureau of Meteorology 2012; Charles et al. 2015). Considering the relatively short period of time being examined, combined with the climatic dynamism of the region, it
is possible that the shift in $\delta^{18}$O values reflects isolated changes in local weather. Although it is possible that this shift could be the result of diagenetic alteration of the bone, this is deemed unlikely due to the young age of the archaeological bone. Additionally, preanalytical processing was undertaken to remove potential contaminants including diagenetic carbonates and organic material.

It is plausible that the more positive archaeological isotopic signatures relate to drought conditions experienced at a continental scale in the mid- to late 1880s (Singleton Argus 1889; South Australian Advertiser 1888). Although the change in relative humidity is small, this would represent a significant reduction in an already arid landscape. This demonstrates the sensitivity and relevance of the technique for constrained historical contexts.

Regardless of the magnitude of change, water availability and frequency of precipitation undoubtedly impacted pearling laborers confined on the island. Byrne et al. (2019) and Dooley et al. (2020) present compelling evidence, that the Aboriginal people who occupied the historical settlement at Bandicoot Bay were inadequately provisioned and relied on local resources for survival. Specifically, the complete absence of imported domestic meats and water storage vessels, considered in context with the high representation of local fauna in the zooarchaeological assemblages, indicates a necessity for self-directed subsistence. Given the complete lack of free water on the island and absence of archaeological evidence for water storage and procurement, the isotopic results suggest that interned laborers would have had to rely on traditional and specialised hydrological knowledge to survive their periods of internment. It would have been necessary to dig deep wells to intersect the perched freshwater body on the island. This observation provides further insight into the parlous conditions experienced by interned Aboriginal laborers in the early pearling industry.

**5.2 Carbon**

Based on the known fractionation factor of 11.7 ‰ for marsupial tooth enamel apatite (Murphy et al. 2007a) and an approximation of the enamel-bone isotopic offset (0 ‰ to 2‰) from existing studies of terrestrial mammals (Cerling et al. 1997; Passey et al. 2005), the offset between wallaby bone apatite $\delta^{13}$C and dietary $\delta^{13}$C values is estimated to be between 9.7‰ and 11.7‰. From this, dietary $\delta^{13}$C values for wallabies in this study is projected to be between −18.4‰ and −15.2 ‰ (Table 2).

It is possible that the significant shift in $\delta^{13}$C values between archaeological and modern samples directly reflects variation in water availability (Farquhar et al. 1989), or alternatively, it may be linked to a shift in vegetation resulting from a change in local conditions. Given that *L. conspicillatus* is a selective feeder, it is anticipated that changes in local vegetation would influence dietary composition. In particular, a period of drought may result in a shift away from C4 grasses and the increased intake of C3 shrubs to assist with hydration.
Although a detailed reconstruction of dietary input is not possible, a two-source mixing model was used to approximate and compare the relative contributions of C3 and C4 plants between contexts (O’Leary 1988; Johnston et al. 1997). To calculate the approximate percent of C3 plants in the analyzed wallaby diet, the following equation was used:

\[ \%C3 \text{ diet} = \frac{(\delta_{\text{SAMPLE}} - \delta_{\text{SOURCE2}})}{(\delta_{\text{SOURCE1}} - \delta_{\text{SOURCE2}})} \times 100, \]

where sample is $\delta^{13}$Cdiet, source 1 is the global average $\delta^{13}$C for C3 vegetation ($-28\%o$) and source 2 is the global average $\delta^{13}$C for C4 ($-14\%o$) (O’Leary 1988; Johnston et al. 1997) (Table 2). Based on this, it is estimated that the significant difference in isotopic results reflects a ~9% increase in modern dietary C3 (Table 2). In particular, dietary C3 for archaeological specimens is estimated between 8.3% to 22.6% and modern dietary C3 is estimated between 17.6% to 31.6%.

It is noted that the results from the mixing model are considered rough estimates and do not necessarily provide an accurate representation of dietary composition because $\delta^{13}$C in C3 plants varies with climate and water availability. In this research, global average $\delta^{13}$C values for C3 and C4 plants have been used to allow for direct comparison with other studies of macropods (Montanari et al. 2013). However, it is noted that in arid environments average $\delta^{13}$C for C3 plants may be as high ~22.5% (Kohn 2010). In this case maximum archaeological and modern dietary C3 are estimated to be 37.2% and 52.1% respectively.

Given the $\delta^{18}$O results suggest that historical occupation likely intersected a period of drought (or at least lower relative humidity), it is possible that the lower contribution of C3 plants may reflect a significant decrease in the availability and diversity of vegetation linked to changes in precipitation. However, this seems unlikely based on the small magnitude of the change implied by the $\delta^{18}$O values. Equally, the more positive $\delta^{13}$C results for the archaeological samples are not thought to reflect a behavioral change in the wallabies because it is expected that non-obligate drinkers prone to browse would favor moisture-rich C3 plants over C4 in response to drought conditions.

Instead, the statistically significant change in diet reflected in the $\delta^{13}$Capatite values may be linked to a sharp change in vegetation related to historical anthropogenic burning and/or lightening-induced fire. Such an event has the potential to result in an intense short-term grazing of re-shooting C4 grasses and to also explain the decreased reliance on C3 plants. Earlier historical burning of the Island occurred in 1863 (Perth Gazette and West Australian Times 1865) and it is not improbable that incarcerated pearling laborers undertook cultural firing activities. Aboriginal landscape burning is well documented as tool for managing macropod hunting in northwest Australia (Codding 2011; Codding et al. 2014).

6. Conclusions
Isotopic signatures from archaeological and modern bone have provided further insights into conditions experienced by interned pearling laborers on Barrow Island through the identification of recent shifts in weather conditions and vegetation. Significant variation in δ¹⁸O values between modern and archaeological apatite samples aligns with historical rainfall trends and suggests that local conditions were drier during the period of historical occupation consistent with the wider continental drought. Shifting δ¹³C values may reflect adaptation in animal diet related to landscape burning.

The isotopic and archaeological evidence for the marooning of Aboriginal internees on a remote offshore Island characterised by a lack of free surface water sources in a time of drought demonstrates the shocking extent of exploitative practices utilised to support pearling fisheries in Western Australia in the late 1800s. The arising necessity for Aboriginal people to utilise traditional hydrological knowledge and water procurement practices for survival undoubtedly provided an important economic opportunity for pearling operations to relieve strain on provisions. However, in the context of extreme trauma, the short-term requirement to jointly re-engage cultural skills and practices may also have provided an opportunity for Aboriginal internees to reconnect with group identity and signal resistance. Equally, the potential activation of a cultural firing regime on the Island to assist with hunting would have served to re-enforce important social bonds among internees.

The data generated by this study contribute further to the burgeoning isotopic records for Australia and demonstrates for the first time that isotopic analysis of wallaby bone can be used to track recent environmental history in a historical archaeology context. While faunal reconstructions are valuable for examining the diet of ‘abandoned’ and indentured laborers, they can also provide a direct record of local environment and species behaviour.

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