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A Novel Application of Sclerochronology: Forging New Understandings of Aboriginal Occupation in the South Wellesley Archipelago, Gulf of Carpentaria

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STATEMENT OF THE CONTRIBUTION BY OTHERS

Contributions by others to this thesis

Sean Ulm provided guidance on the initial research design, sampling strategy, and took overall responsibility for directing fieldwork undertaken as part of this study.

Sean Ulm, Daniel Rosendahl, and Helene Peck undertook the excavation of Thundiy in 2010.

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Sean Ulm and Daniel Rosendahl undertook live-collection of *Polymesoda coaxans* specimens from Mosquito Story in 2012.

Lincoln Steinberger and Sean Ulm prepared location maps and contour maps with elevation transects (Figures 3.3, 10.2, 11.2, 13.1).

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Jen Whan ran isotopic samples through the isotope ratio mass spectrometer and thermal conversion elemental analysis mass spectrometer.

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ABSTRACT

Changing relationships between people and their environments result in modified patterns of land-use and occupation as populations respond to fluctuating conditions across space and through time. Understanding these relationships occurring on a variety of scales is integral to achieving nuanced interpretations of fundamental Aboriginal lifeways. This is particularly salient in contexts characterised by stark seasonal shifts in climate, which have long been suggested to act as key drivers behind fundamental decision-making processes. For Aboriginal groups living along Australia's tropical north coast these seasonal changes coincide with the monsoonal cycle, with ethnographic data demonstrating that seasonality permeates associated behavioural and cultural systems. Numerous authors have attempted to explain change evident in the archaeological record using broad models based upon wide-ranging concepts such as shifts in ENSO intensity. However, these broad models map poorly onto local-scale and/or short-term patterns, masking diversity and complexity. It is therefore integral that researchers re-evaluate how behavioural patterning is characterised and interpreted.

This research explores patterns of Kaiadilt Aboriginal occupation in the South Wellesley Islands, Gulf of Carpentaria, through a targeted study of seasonality in site-use. Select methods from a sclerochronological framework, particularly stable isotopic analyses of molluscan shell carbonates, are utilised to analyse specimens (*Gafrarium pectinatum*, *Marcia hiantina*, and *Polymesoda coaxans*) from both modern and archaeological assemblages. Results from modern specimens are combined with contemporaneous environmental datasets to characterise relationships between ambient conditions and shell geochemistry. This allows the efficacy of target mollusc species to be tested as well as providing an interpretative framework for archaeological data. Seasonality of occupation is determined for archaeological material excavated from three sites across Bentinck Island spanning the last 1500 years to generate a high-resolution chronology of site-use.

Instrumental observations of modern environments highlight stark seasonally timed hydrological shifts, however corresponding fluctuations were not found in all target mollusc taxa. The mangrove bivalve *Polymesoda coaxans* and intertidal bivalve *Gafrarium pectinatum* were both deemed unsuitable for use within the context of this research owing to irreconcilable physiological and ecological complications. Conversely, the subtidal bivalve *Marcia hiantina* was found to be an unambiguous recorder of environmental conditions, as well as being the dominant archaeological species, and thus is employed as the key proxy for characterising patterns of past seasonality.

Archaeological findings demonstrate direct links between seasonal climatic patterns and the timing and periodicity of site-use, although the strength of these relationships fluctuate through time. Early occupation of the South Wellesley Islands from as early as 3500 years ago appears highly seasonal, with periods of use timed to coincide with the dry season to take advantage of conditions that assist wide-ranging foragers in undertaking periodic visitation of the island group. Subsequent to the permanent occupation of the South Wellesley Islands by the Kaiadilt in the last 800 years, patterns of repeated use are evident with groups periodically occupying sites while moving across the local landscape again dominated by dry season use. The most recent periods of occupation in the last 250 – 300 years suggest a move towards decreased mobility with longer residency times and more sedentary behaviour evidenced by both dry and wet season occupation at key sites. Changes to occupation patterns are likely linked with increases in population size and density. Moreover, the recent stabilisation of sea levels along with more frequent inclusions of fish remains within the archaeological record suggest that stone-walled fish trap complexes were increasingly utilised during late periods of occupation. The static nature of this important resource infrastructure together with the need for continuous maintenance likely further encouraged sedentary behaviours, establishing strong ties between Kaiadilt groups and specific areas as well as potentially facilitating the development of ethnographic land tenure systems.

Results demonstrate the efficacy of scleroisotopic methods in tropical Australian contexts, provided relationships between target mollusc taxa and environmental conditions are well understood. This affords the opportunity for archaeologists to approach increasingly nuanced characterisations of fundamental drivers behind Aboriginal decision-making processes that led to changing behavioural and cultural systems. Moreover, findings demonstrate the presence of highly complex patterns of occupation associated with offshore island contexts, requiring local-scale research to accurately characterise as inter-regional or continental models do not accurately reflect responses to change at high-resolutions. Results also contribute to recent discussions regarding changes in social organisation, running parallel to suggestions of a broader trend towards decreased mobility coinciding with growing populations and emerging social complexity. Most importantly, this research provides a salient argument for the construction of broader narratives from local-scale understandings to allow for the complexity and diversity inherent to Aboriginal cultures.

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ABBREVIATIONS

δ	Delta: used to describe the ratio between stable isotopes e.g. $^{13}C/^{12}C$ or $^{18}O/^{16}O$
σ	Sigma: used to describe standard deviations in a population
‰	Per mil: Parts per thousand
$\delta^{13}C_{DIC}$	The carbon isotope ratio in marine dissolved inorganic carbonate (DIC)
$\delta^{13}C_{shell}$	The carbon isotope ratio in shell carbonate
$\delta^{18}O_{water}$	The oxygen isotope ratio in water
$\delta^{18}O_{shell}$	The oxygen isotope ratio in shell carbonate
$\delta^{18}O_{shell\text{-}predicted}$	The modelled oxygen isotope ratio for shell carbonate
AIMS	Australian Institute of Marine Science
ARC	Australian Research Council
AMS	Accelerator mass spectrometry
ANOVA	Analysis of variance
BOM	Bureau of Meteorology
BP	Radiocarbon years before present (i.e. before AD 1950)
cal BP	Calibrated years before present
CRA	Conventional radiocarbon age
ENSO	El Niño Southern Oscillation
DIC	Dissolved inorganic carbon
FS	Field specimen
FS#	Field specimen number
FTIR	Fourier transform infrared spectroscopy
GISP	Greenland ice sheet precipitation (water standard)
L-SVEC	Lithium carbonate standard
LCS	Liquid scintillation counting
LGM	Last glacial maximum
IPO	Interdecadal Pacific oscillation
IRMS	Isotope ratio mass spectrometer
ITCZ	Inter-tropical convergence zone
MNI	Minimum number of individuals

NBS	National Bureau of Standards (referring to NBS-18 and NBS-19 carbonate standards)
PMSL	Present mean sea level
PSU	Practical salinity units
SHRIMP	Sensitive high resolution ion microprobe
SIMS	Secondary ion mass spectrometry
sp.	Species (only one descending from a genus)
spp.	Species (more than one descending from a single genus)
SQ	Square
SST	Sea surface temperature
SU	Stratigraphic unit
TC/EA IRMS	Thermal conversion elemental analysis mass spectrometer
VPDB	Vienna Pee Dee Belmnite (international carbonate standard)
VSMOW	Vienna standard mean ocean water (international water standard)
XU	Excavation unit

Chapter 1 Localised Short-Term Change, Human Behaviour, and Island Environments

1.1 Introduction

Changes in environment and climate act as key structuring agents on human lifeways, influencing fundamental decision-making processes (Rowland 1983a, 1999a). Populations commonly respond to such changes by altering patterns of subsistence, land-use, occupation, demography, and mobility (e.g. Attenbrow 2006; Bird and Bliege Bird 1997; Davies 1985; Meehan 1982; Memmott 2010; Sutton 2010; Williams et al. 2015a, 2015b). While these modifications manifest at a variety of scales, changes to some of the most fundamental components of behaviour occur at sub-annual timeframes. Behaviours associated with sub-annual cycles have been characterised as 'so diverse, an onlooker might be pardoned for concluding that they were different peoples' (Thomson 1939:209). Differential responses are also evidenced within regions sharing similar environments, suggesting a high degree of behavioural localisation (see Davies 1985; Meehan 1982; Sutton 2010; Thomson 1939 for examples of diverse responses to environmental change). It must also be acknowledged that geographic and temporal variability in culture can further alter behavioural patterns in unison with or independent of environmental changes (Faulkner 2013; Rowland 1999; Veth et al. 2000). Thus, characterising localised short-term change is crucial not only to approaching increasingly robust interpretations of human-environment relationships, but also as evidence of the diversity inherent to hunter-gatherer lifeways.

Yet when questions regarding the impacts of environmental change are approached archaeologically, discussions often centre on broad supra-regional patterns that occur over extended periods of time conflating those that are enacted over smaller spatial and temporal scales (e.g. Allen 2006; Birks et al. 2014; Brockwell et al. 2013; Hiscock 1994). Claassen (1991:249) posits that such normative thinking results in the distortion of the archaeological record through the homogenisation of variation in adaptive responses. While archaeologists have begun to challenge the validity of broad-scale models and renew their interest in geographically targeted research (Attenbrow 2006; Holdaway et al. 2008; Ulm 2006a, 2013), a reliance on low-resolution methodologies remains ingrained throughout much of the discipline (see Ulm 2013). Although these methods provide crucial insight into general patterning, they cannot generate the fine-grained data required for detailed localised interpretations of the past (Brockwell et al. 2009; Holdaway et al. 2002). This has culminated in a paucity of high-resolution investigations into site occupation, a long-standing obstacle that must be surmounted to approach better understandings of past behaviours. In order to achieve this researchers must secure detailed chronologies of site-use, thus providing temporal context for indicators of change. A number of suitable techniques have proven efficacious internationally, although most have been slow to gain favour within the Australian archaeological community (Ulm 2006a, 2013). Thus, a unique opportunity exists for internationally recognised methods to be deployed in novel Australian contexts, allowing researchers to approach innovative solutions to enduring problems.

Accurate characterisations of site-use, particularly the timing and periodicity of occupation, underpin the validity of many higher-order interpretations (Brockwell et al. 2009; Jones and Quitmyer 1996; Ulm 2006a, 2013). Acknowledging and addressing site-use becomes particularly salient in contexts where the permanency of site occupation is highly variable, such as along high latitude coasts where complex interplay between environment, climate, and human decision-making processes facilitate regular change (Rowland and Ulm 2012). Important facets of Aboriginal lifeways have been linked to coastlines, characterising them as focal points for cultural contact, trade and exchange, colonisation, technological innovation, and settlement (Bailey 2004).

Islands are integral to the coastal archaeological record, which frequently exhibit unique patterns of human interactions and behaviour (e.g. Barker 2004; Rowland 2008; Vanderwal 1978; Veth 1993). Reputed to be natural 'laboratories', island environments provide archaeologists with contained contexts in which human responses to environment and climate change, physical and cultural isolation, and resource availability can be examined (Burney 1997; Fitzpatrick 2004:4-5; Kirch 1980, 2007). Numerous studies have suggested localised environmental and cultural variables provide catalysts for human expansion into and use of marginal environments such as offshore islands (Sim and Wallis 2008; Williams et al. 2015a). These same stimuli likely play an important role in the nature of land-use subsequent to initial visitation, influencing the timing and periodicity of human movement and occupation within these locales. To address fundamental questions of how, when, and why Aboriginal populations brought island landscapes into use, archaeologists must characterise and interpret localised human-environment relationships. This research investigates sub-annual patterns of Aboriginal occupation in the South Wellesley Islands, Gulf of Carpentaria, contextualising and comparing them against regional and inter-regional models of indigenous land-use proposed for Australia's tropical north.

1.2 Seasons, Localisation, and Human Behaviour

1.2.1 Seasonal Change and Localised Responses

The fact that archaeological deposits rarely represent a single continuous occupation but rather an amalgamation of depositions accumulating as a result of repeated patterned use is an important underlying assumption in many modern studies of hunter-gatherer societies. Researchers have postulated that site occupation is often linked with the scheduling of events or behaviours, such as resource exploitation, timed to coincide with patterns of seasonal change (Monks 1981). These connections have led many archaeologists to propose seasonal cycles are a principal driver behind human behavioural patterning, exerting significant influence on cycles of land-use, mobility, cultural events, and subsistence (Burchell et al. 2013a, 2013b, 2013c; Frankel et al. 2013; Hallmann et al. 2013; Monks 1981; Pike-Tay and Cosgrove 2002), thus imbuing certain behaviours with seasonality. As higher-order interpretations of hunter-gatherer mobility and demography are often underpinned by questions of the timing and periodicity of site occupation as well as human-environment relationships, understandings of seasonality are implicit in building meaningful accounts of intra- and inter-regional sequences (Andrus and Crowe 2000; Hallmann et al. 2009, 2013; Milner 2001; Rowland 1999a; Ulm 2006a, 2013). Therefore, addressing interactions between human decision-making and short-term change is essential to producing nuanced interpretations of past behaviour and culture.

Patterns of behavioural modification are frequently localised within geographic boundaries. Much of this spatial bounding can be attributed to the interplay between cultural systems, climatic conditions, and local environments. It is unreasonable to assume broader climate cycles, such as those that characterise seasonal change, uniformly effect diverse environmental niches. For instance, monsoonal systems impacting wide areas may elicit differential environmental responses at local levels. Factors such as landforms, drainage, or vegetation density and type may determine whether an area is subjected to flooding. This potentially influences decision-making processes of local human populations as flooding may act as a physical or cultural barrier, lead to increases in biting or stinging insect populations, or change resource availability (e.g. Davies 1985; Memmott 2010). Furthermore, human responses to environmental change are tempered by cultural, political, and economic factors that often differ within regional or intra-regional boundaries (Davies 1985; Memmott 2010; Tindale 1963). Permissions to access land controlled by other groups may require negotiation, potentially dictating the timing of use and availability of some resources (e.g. Davies 1985). Alternatively, cultural events may lead to the fusion of populations for periods of time (e.g. Meehan 1982). It is therefore imperative that localised internal cultural stimuli and external environmental factors are incorporated into interpretive frameworks when approaching questions tied to seasonal human-environment relationships.

1.2.2 Highlighting Seasonal Change through Ethnography

The potential significance of short-term environmental and climatic change to past human decision-making processes has long been recognised. Early researchers such as Thomson (1939:209-211) highlighted the importance of these patterns to furthering understandings of hunter-gatherer societies in northern Australia. This notion is frequently reflected within traditional calendars of Aboriginal groups (Figure 1.1), where marked seasonality is delineated by factors such as resource availability, cultural events, strength and direction of wind, amount of precipitation, mobility, and temperature among others (e.g. Davies 1985; Meehan 1982:22-41; Memmott 2010:21-30; Rosendahl 2012:56, 60). These, along with other ethnographic sources, provide a modern analogue from which hypotheses regarding past human-environment interactions can be established. However, caution must be exercised when incorporating ethnographic data into investigative frameworks, primarily owing to the potential for discontinuity between behavioural patterns of the past and those observed in the ethnographic present (Hiscock 1999:101-102). Ethnographies are therefore used to guide the development of questions to be tested by the archaeological record (Faulkner 2013:9).

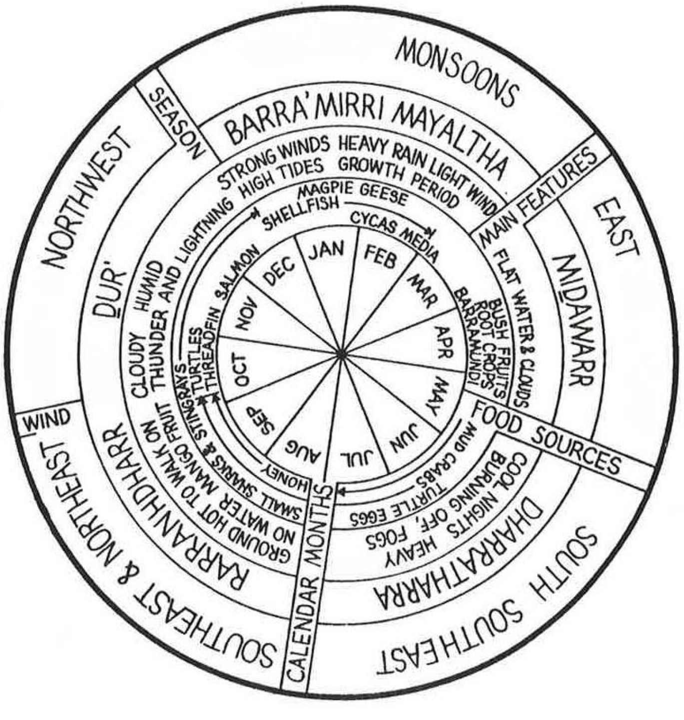

Figure 1.1 Representation of the traditional annual cycle employed by the Yolngu people from the Crocodile Island and Castlereagh Bay area, Arnhem Land (from Davies 1985:301).

Comparing traditional calendars reveals localised behavioural patterns that differ between populations, sometimes within the same language group (see Meehan 1982:22-41 for a comparison between different language groups within the Gidjingali people), emphasising the need for targeted analysis. Unique local-level interactions are evidenced in ethnographic accounts of the Yolgnu from the Castlereagh Bay area, Arnhem Land (Davies 1985), and the Lardil from the North Wellesley Islands, Gulf of Carpentaria (Memmott 2010; Tindale 1963). As these two populations occupy environmentally similar regions, comparisons demonstrate the potential for variability linked with cultural differences. The Yolngu modify patterns of mobility, occupation, and demography in accordance to seasonal oscillations. During the wet season the population takes on a sedentary lifestyle, erecting camps near extensive shellfish beds (Davies 1985). Moreover, rough seas confine hunting activities to the mainland. The dry season sees an increase in mobility with hunting parties ranging to the nearby Crocodile Islands to establish temporary hunting camps and bases for gathering turtle meat and eggs (Davies 1985). Conversely, the Lardil remain comparatively mobile throughout the year, moving across the landscape to take advantage of seasonally available resources and avoiding areas that may prove to be seasonally inclement (Memmott 2010; Rosendahl 2012; Tindale 1963). As some seasonal factors cannot be avoided by changing location, such as dense wet season mosquito populations, the structure and configuration of camps is altered to mitigate these effects (Memmott 2010).

Meehan's (1982) ethnography of the Anbarra people of Arnhem Land, *Shell Bed to Shell Midden*, provides a salient example of connections between short-term change and the accuracy of interpretation. Discontinuities in subsistence patterns were observed subsequent to the destruction of important *Tapes hiantina* shellfish beds during a particularly inclement wet season, causing the Anbarra to temporarily adjust exploitation strategies (Meehan 1977, 1982). When questioned informants indicated damage to seemingly essential shellfish stocks was a recurring event (Meehan 1977), suggesting previous instances of this important – although relatively brief – economic episode may be evident within the archaeological record. Thus, provided appropriate methods are employed, characterising this short-term change in behaviour would allow archaeologists to approach increasingly nuanced interpretations of local human-environment interactions and their impact on behavioural mechanisms (see Section 1.2.3 for further discussion).

With increasing data resolution attainable by archaeological methods, it has become clear diverse human behaviours manifest within regional boundaries. Short-term trajectories associated with environment and climate play an integral role in structuring aspects of behaviour and culture unique to individual populations. Behavioural patterns of people living in regions exhibiting variable environmental and climatic conditions often move in rhythm with the ever-changing landscape (Davies 1985; Meehan 1982; Meehan and White 1990; Memmott 2010; Sutton 2010; Thomson 1939). Populations undergo fusion and fission, vary resource exploitation, alter patterns of settlement and mobility, and undertake firing and other forms of land management in response to sub-annual, annual, or longer-term cycles (e.g. Davies 1985; Meehan 1982; Meehan and White 1990; Memmott 2010; Sutton 2010; Thomson 1939). By characterising local-level patterns in behaviour archaeologists are able to investigate the validity and accuracy of interpretations, building a sophisticated narrative of human-environment interaction. However, conventional archaeological methods of data recovery and analysis are often unable to generate the sub-annual information required for accurate interpretation, thus meaningfully approaching these nuanced understandings has proven difficult for many investigations.

1.2.3 Characterising Responses to Seasonality from the Archaeological Record

The diverse range of human responses associated with seasonally-timed change manifest within the archaeological record in a variety of forms, including discontinuities in occupation, short-term modification to diet, and the inclusion of seasonally available flora and fauna. While a number of methods have proven efficacious in characterising seasonal patterning, the ability of archaeologists to access and accurately interpret this evidence is variable. Thus, it is critical that replicable methods of seasonal determination and their incorporation into broader interpretive frameworks are explored, ensuring robust methodological foundations are constructed.

The characterisation of seasonal behaviours operates at very different temporal scales when compared to other archaeological investigations of occupation (Pike-Tay and Cosgrove 2002), relying largely on the ability to differentiate sub-annual events within the archaeological record. This need for high-resolution data has encouraged researchers to explore a variety of markers and proxies. Inferences have been made using the presence of seasonally restricted or migratory faunal remains (Frankel et al. 2013; Rowland 1977; Sullivan 1982), botanical remains or toolsets associated with seasonal plants (Cosgrove et al. 2007; O'Connor 1992, 1994), seasonally-timed physiological features such as epiphyseal fusion or tooth eruption and wear (Monks 1981; Pike-Tay and Cosgrove 2002), or visual and geochemical analyses of accreting skeletal structures (Clark 2005; Frankel et al. 2013; Hufthammer et al. 2010; Thompson and Andrus 2013).

A multitude of factors affect the usefulness, accuracy, and resolution of these proxies. Along with depositional and preservation issues, to which all archaeological research is subject, proxies for seasonality are particularly sensitive to events that may cause seasonal availabilities of resources to overlap, time-lags between the cause and formation of some physiological features, and difficulties associated with differentiating skeletal structures (Claassen 1990; Monks 1981; Pike-Tay and Cosgrove 2002). Thus, it is essential that methodological frameworks be constructed within the constraints of these limitations.

As a majority of hunter-gatherer seasonality cycles are associated with the availability of food resources, accompanying archaeological investigations often centre on questions of subsistence (Andrus and Crowe 2000; Kennett and Voorhies 1996; Killingley 1981; Mannino et al. 2011). Consequently, seasonality is most commonly utilised in the determination of season of resource procurement, a proxy widely employed to estimate timing and periodicity of site occupation. This works under the assumption that material indicative of seasonality is deposited soon after capture or collection. However, a number of authors argue season of resource procurement and season of occupation are two distinct behaviours, with multiple indicators required to accurately infer the latter (Deith 1983; Quitmyer et al. 1997). Others stress evidence indicating occupation during a specific season does not necessarily preclude occupation during other times of the year (Frankel et al. 2013), meaning caution must be exercised in any interpretation of the timing and nature of site-use. Although these are salient arguments, it must be noted that season of resource procurement is one of the few avenues available to estimate season of occupation. Thus, providing these restrictions are acknowledged and interpretations are not extrapolated beyond their limitations, season of resource procurement can be viewed as a relatively accurate assessment of the timing and periodicity of occupation.

1.2.4 Seasonality Studies in Australia

In a review of Australian coastal archaeology O'Connor and Sullivan (1994a) singled out seasonality as a ‘persistent theme’ within Australian archaeological research. While it is true many authors have commented upon the possibility of seasonal patterns of occupation as part of broader research goals (e.g. Bowdler 1981; Flood 1980; Kamminga et al. 1989; O'Connor 1992), little archaeological evidence is presented in support of these discussions. As highlighted previously, archaeological studies of site occupation often place a greater emphasis on establishing broad temporal chronologies (often focusing on establishing the antiquity of initial site occupation) rather than exploring questions relating to short-term trajectories such as seasonality. Consequently, a majority of methodologies employed are coarse-grained as they address extended time-scales. Increasing interest in temporally and geographically constrained research has made it clear that low-resolution methodologies are unsuitable for fine-grained investigations owing to biases inherent in their application and the time-scales at which they operate (Ulm 2013).

Early investigations of seasonality in Australia often relied upon indirect sources of evidence, including ethnohistorical accounts and modern ecological data (Godfrey 1988). A widely cited example of this is work undertaken by Flood (1980) in the southeast Australian Highlands. Ethnohistoric accounts of large seasonal quantities of Bogong moths (*Argotis infusa*) being consumed were used as a primary indicator for seasonal occupation of the region. It was claimed these moths represented an essential seasonal source of sustenance, allowing the prolonged occupation of an otherwise harsh, inhospitable area during the summer months (Flood 1980). Bowdler (1981) and later Argue (1995) built upon this interpretation, incorporating reviews of archaeological findings from the wider region as well as assessments of modern ecological conditions, concluding that there was indeed the potential for seasonal occupation associated with seasonal gluts of Bogong moths.

Similar approaches have been applied on a handful of Australian offshore islands, primarily employing presence/absence studies as well as other forms of indirect evidence. Rowland (1980, 1982a:115) synthesised ethnohistoric accounts of explorers to assess the possibility of seasonal occupation of the Keppel Islands, concluding that documented sightings did not ‘equate to any seasonal pattern that [he was] aware of’. Further north, Barker (1989, 1991) posited continuous occupation of the Whitsundays throughout the Holocene owing to a combination of ethnohistoric accounts and steady rates of deposition. For islands along the south coast of New South Wales and in the Bass Strait the presence of seasonal faunal remains, primarily seal and mutton bird, has been used as an indicator of seasonal visitation (Coutts et al. 1984; Jones and Allen 1979; Sullivan 1982). Similarly, O'Connor (1992) and Border (1999) utilised the presence of seasonally available fruits and turtle eggs to argue for summer exploitation on northern Australian islands, however both cases revealed year-round occupation.

These examples highlight a number of potential problems when attempting to accurately characterise seasonality. Firstly, interpretations based upon indirect evidence are not easily testable as critical evidence simply does not exist within the archaeological record. Ethnohistoric accounts are only representative of narrow periods of observation and are subject to inherent biases that may reflect cultural perspectives rather than actual significance (Argue 1995; Hiscock 2008:3-4), making their accuracy difficult to establish. Likewise, while depositional rates provide a basic assessment of the intensity of site-use, they grant little temporal context and thus cannot be utilised to evaluate the permanency of occupation. Relying on modern ecological data is equally problematic as it does not necessarily reflect conditions or species diversity of the past, although this is largely dependent on time-depth and region. While some researchers recognise the limitations of indirect evidence, instead employing more direct archaeological linkages to demonstrate seasonal occupation (e.g. Border 1999; Coutts et al. 1984; O'Connor 1992; Pike-Tay and Cosgrove 2002; Sullivan 1982), research focusing on seasonality continues to be rare in Australian contexts. This reflects a general scarcity of high-resolution data recovery and analysis techniques employed in Australia as well as a relatively late move towards research that acknowledges temporal and geographic variability (Ulm 2006a, 2013).

While these examples focus on the study of seasonality within Australia, the methodological issues outlined here are widely applicable to international research – particularly regarding the need for increased resolution and the use of indirect evidence. It must also be acknowledged that seasonal change is implicit in shaping innumerable behavioural adaptations throughout a variety of geographic and climate zones (e.g. Burchell et al. 2013b; Kennett and Voorhies 1996; Meehan 1982; O'Connor 1992). Thus, by employing more precise, higher-resolution methodologies capable of pinpointing short-term variations in human behaviour archaeologists can garner more nuanced interpretations of human-environment relationships. Only then can higher-order, inter-regional questions regarding demography, mobility, and occupation strategies be meaningfully addressed.

1.3 The Challenge of Characterising Behavioural Complexity

Localised short-term trajectories, particularly those related to seasonality, are often cited as central to holistic understandings of human decision-making processes (Burchell et al. 2013c; Monks 1981; O'Connor and Sullivan 1994a), yet are rarely meaningfully incorporated into investigative frameworks. Many archaeologists, particularly those within the Australian tradition, appear reluctant to approach sub-annual interpretations with anything but cursory discussion. While a portion of this unwillingness is likely tied to the apparent challenges inherent to this type of investigation considerations must also be given to the impact of recent shifts in focus within the methodological frameworks of the discipline as a whole.

1.3.1 Repercussions of Past Models

Much of the attention ascribed to broad interpretations can be attributed to synthesisers such as Lourandos who advocated the importance of broad continent-wide processes. While the work of Lourandos popularised many concepts now integral to Australian archaeology, in particular refuting the assumption of Aboriginal cultural stability through time and emphasising the importance of Holocene change (see Lourandos 1980, 1983, 1997), it was also implicit in shifting focus away from diverse localised trajectories (Ulm 2013). The widely-cited theory of intensification posed by Lourandos suggests significant behavioural and cultural changes occurring throughout the Holocene were a response to pan-continental processes of socio-economic change (Lourandos 1980, 1983, 1985, 1988, 1997). Many proponents of intensification saw it as an alternative to the largely processual traditions within the discipline, advocating it as less deterministic than previous models (Hughes and Lampert 1982; Lourandos 1980, 1983, 1985, 1988, 1997; Lourandos and Ross 1994). Conversely, a majority of its detractors argued cultural factors, while important, could not be used as the sole explanation of Holocene restructuring and that other variables, such as environment and climate, must also be considered (Holdaway et al. 2008; Rowland 1989, 1999a). Others, who recognised the importance of local patterns of change, raised concerns regarding the potential impact of homogenisation from broad supra-regional extrapolations inherent to intensification (e.g. Bird and Frankel 1991).

While notions of pan-continental change have largely been discarded, with amorphous concepts of intensification replaced with more nuanced views of Holocene change (see Holdaway et al. 2008; McNiven et al. 2014; Rowland 1999a; Ulm 2013), its repercussions are still evident throughout the discipline. Most acute is the devaluation of local and intra-regional patterning as a primary locus of change (Ulm 2013). By placing an emphasis on continentally based models, diverse sets of temporally and spatially unique behaviours are homogenised into generic overarching explanations (e.g. Lourandos 1997). Without these we lack the fine-grained data required to approach higher-order questions, thus interpretations are restricted to broad abstractions and our ability to form nuanced narratives is severely limited.

In the wake of the intensification model, an increasing number of researchers have begun to move away from broad inter-regional explanations, instead highlighting the importance of locally derived patterns (Cosgrove et al. 2007; Frankel 1995; Holdaway et al. 2008; Ulm 2006a, 2013). As a result, archaeologists have been prompted to renew their focus on geographically targeted regional and intra-regional research (e.g. Godfrey 1989; Holdaway and Porch 1995; Holdaway et al. 1998, 2002; Ulm et al. 2010; Ulm and Hall 1996). In Australia this conceptual shift has not been accompanied by an equivalent move towards higher-resolution data recovery and interpretation, leaving many underlying issues associated with the effects of homogenisation unresolved (Ulm 2013). Continued reliance on low-resolution methodological frameworks, designed to mesh with the broad continental explanations of the past, has simply resulted in the homogenisation effect shifting from a spatial to a temporal context.

1.3.2 Overcoming Temporal Homogenisation

Temporal homogenisation refers to the conflation of varied short-term trajectories into a single indistiguishable signal or event. Similar to spatial homogenisation this can lead to the introduction of latent inaccuracies or biases and the loss of diverse behaviours, severely impacting the validity and accuracy of archaeological interpretation. However, some of the low-resoution techniques that potentially cause homogenisation are deeply engrained within archaeological inquiry, such as the use of radiocarbon sequences to establish site-use chronologies. While there is no dispute as to the importance of radiocarbon, its incorporation into methodological frameworks is crucial to approaching fundamental understandings of human behaviour (e.g. Bird and Frankel 1991; Brockwell et al. 2009; Holdaway et al. 2002; Ulm and Hall 1996), a number of methodological and practical issues restrict its ability to provide accurate fine-grained data.

For instance, a widespread paucity of robust dating practices in Australia significantly impacts basic confidence in archaeological chronologies. Radiocarbon dating strategies have historically targeted basal deposits (e.g. Smith and Sharp 1993; Ulm and Hall 1996; Williams et al. 2014), making accurate chronologies of the remaining sequence difficult, if not impossible, to secure. This is particularly problematic when combined with the tendency to assume continuous occupation from initial settlement until European contact (Bird and Frankel 1991). A review of Australian dating regimes found researchers undertake an average of 3.1 dates/site, however Holocene sites returned an average of only 2.4 dates/site (Williams 2012). Studies employing such limited dating strategies cannot hope to produce meaningful site chronologies, and so are incapable of attaining centennial let alone annual or sub-annual resolution.

Some researchers have sought to overcome these issues through more intensive dating strategies (e.g. David et al. 2004; David and Wilson 1999; Wright and Jacobsen 2013). While this does increase archaeological resolution, sites subjected to more rigorous dating regimes are not entirely shielded from temporal homogenisation. However, even the most rigorous radiocarbon chronologies only represent a series of low-resolution snapshots of individual episodes of site-use, with shorter-term trajectories linked with sub-annual, annual, or even decadal patterns remaining effectively masked. Thus, patterns related to archaeologically brief changes in behaviour remain lost to temporal homogenisation. To accurately characterise these patterns, archaeologists must complement broad chronologies with techniques that can detect sub-annual discontinuities within the archaeological record. Only then can more sophisticated interpretations of occupation and land-use patterns be approached.

The characterisation of short-term change within the archaeological record is integral to achieving nuanced characterisations of intra- and inter-regional relationships. As archaeologists our ability to achieve this rests on the methodological frameworks we employ to gather, analyse, and interpret data. With higher levels of importance now being ascribed to detailed, localised understandings it has become clear that interpretations of regional and intra-regional patterns generated using lower-resolution methodologies are no longer enough to satisfy increasingly fine-grained questions (Brockwell et al. 2009; Faulkner 2008; Holdaway et al. 2002; Holdaway and Porch 1995; Ulm 2013). Thus, it is essential that methodological frameworks begin to reflect this new emphasis by combining geographically targeted research aims with high-resolution data collection and analysis techniques.

1.4 Localised Understandings of Aboriginal Island Use

Over recent decades Australian offshore islands have undergone extensive archaeological investigation, with researchers focused on securing occupation chronologies (e.g. Barker 2004; Border 1999; Bowdler 1995; David et al. 2004; Draper 2015; Lampert 1972, 1981; O'Connor 1992; Roberts et al. 2013; Rowland 1984; Sim and Wallis 2008; Ulm et al. 2010; Wright 2011). While many questions regarding the antiquity and nature of island use have been addressed, few studies have explored short-term trajectories associated with the timing and periodicity of island settlement. However, evidence of seasonal exploitation, multiple colonisation events, and significant variation in the timing of island use (Bowdler 1995; Sim and Wallis 2008; Sullivan 1982) coupled with ethnographic observations of seasonally-derived occupation patterns of coastal hunter-gatherers on the adjacent mainland (Davies 1985; Meehan 1982; Memmott 2010; Sutton 2010; Tindale 1963) suggests the presence of complex behavioural patterns linked with the use and occupation of island environments.

1.4.1 Island Formation and Holocene Change

A vast majority of Australia’s islands were formed during the most recent period of marine transgression. Commencing from c.18,000 BP, the rate of marine transgression intensified throughout the terminal Pleistocene with sea levels rising steadily until the early-to-mid-Holocene (Chivas et al. 2001; Lewis et al. 2013; Reeves et al. 2007). While the extent and timing of Holocene sea level variability is still debated, current data suggest a high-stand of +1.0 – +1.5m was reached between 7700 BP – 7000 BP for the east coast before falling to current levels after 2000 BP (Lewis et al. 2007, 2013; Sloss et al. 2007, 2015). Similar high-stands have also been reported for the Gulf of Carpentaria with sea levels reaching +2.0m until c.4000 BP (Sloss et al. 2015). Consequently, with transgression many low-lying portions of the continental shelf were submerged, disconnecting higher regions from the mainland to create a series of offshore islands and ultimately the current shape of the Australian coastline. While the timing of island formation is variable, dependant on distance from the mainland, slope of the continental shelf, and position along the coast, a majority of islands were formed by c.7000 BP (Reeves et al. 2008). Yet, current evidence indicating Aboriginal use of offshore islands suggests there may have been a significant time lag between formation and utilisation of some islands (Sim and Wallis 2008).

Initial visitation and exploitation of many Australian offshore islands has been widely linked with change occurring throughout the Holocene, but particularly during the mid-to-late-Holocene (David et al. 2004). Significant environmental, cultural, and behavioural upheavals during this time facilitated and encouraged the modification of fundamental lifeways across much of Australia. While widespread, the nature and timing of these changes is highly variable owing to diverse relationships between culture, environment, and behaviour. Evidence indicates Aboriginal populations began to broaden their diets, incorporating new food sources including cycads, cereals, and some marine resources; undertake technological innovation, producing toolsets for processing new resources and new or improved watercraft; alter stone tool types and rock art styles; establish new site types, including fish traps and shell mounds; and exploit marginal landscapes, such as rainforests, the arid zone, and offshore islands, for the first time (Beaton 1985; Bowdler 1995; Cosgrove et al. 2007; Faulkner 2008, 2009; Flood 1980; Hiscock 1994; Lourandos 1993, 1997; Lourandos and David 1988; Lourandos and Ross 1994; Memmott et al. 2006; Roberts et al. 2015; Robins et al. 1998; Rosendahl 2012; Rowland 1983a; Sim and Wallis 2008).

Researchers have variably linked these transformations to a range of explanations including differential site visibility and preservation (Bird 1992, 1995; Godfrey 1989; Head 1983; Holdaway et al. 2008; O'Connor and Sullivan 1994a; Rowland 1983a, 1989; Rowland and Ulm 2012), shifts in environment and climate that may have impacted resource availability (Bailey 1983a; Beaton 1985; Rowland 1983a, 1989, 1999a), increases in population requiring the augmentation of subsistence strategies and the exploitation of new regions (Beaton 1985; Hall and Hiscock 1988; Hughes and Lampert 1982; Lampert and Hughes 1974), the introduction of new technologies (Beaton 1985; Sullivan 1987; Vanderwal 1978), and changes to fundamental social elements, including population restructuring (Barker 1996, 2004; Lourandos 1997). The variability of responses to this wide range of stimuli makes it difficult to accept broad inter-regional interpretations of change. Instead research aimed at characterising local level change is required to better understand the impact of mid-Holocene transformations on human decision-making and enable it to be meaningfully positioned within the broader continental narrative. As

Australian offshore islands represent temporally and geographically bounded contexts, they provide the ideal backdrop with which to explore localised human responses to environmental, climatic, and cultural transformations.

1.4.2 Variability in Island Use

Aboriginal use of offshore islands is often assumed to follow a unidirectional path that intensifies after initial colonisation (Figure 1.2). A widely cited model posits the bulk of Australian islands remained unused by Aboriginal populations until c.3000 BP when settlement and exploitation intensified dramatically (Bowdler 1995). While a majority of islands fall within this general pattern (Barker 1996), arguments for continuous, steadily intensifying occupation can be seen as overly simplistic as they fail to account for behavioural, environmental, and cultural diversity. Moreover, recent exhaustive dating of some islands suggest earlier periods of intensified use and periods of abandonment or reduced use (David et al. 2004; Wright and Jacobsen 2013), reinforcing the need for targeted high-resolution chronologies to characterise regional diversity.

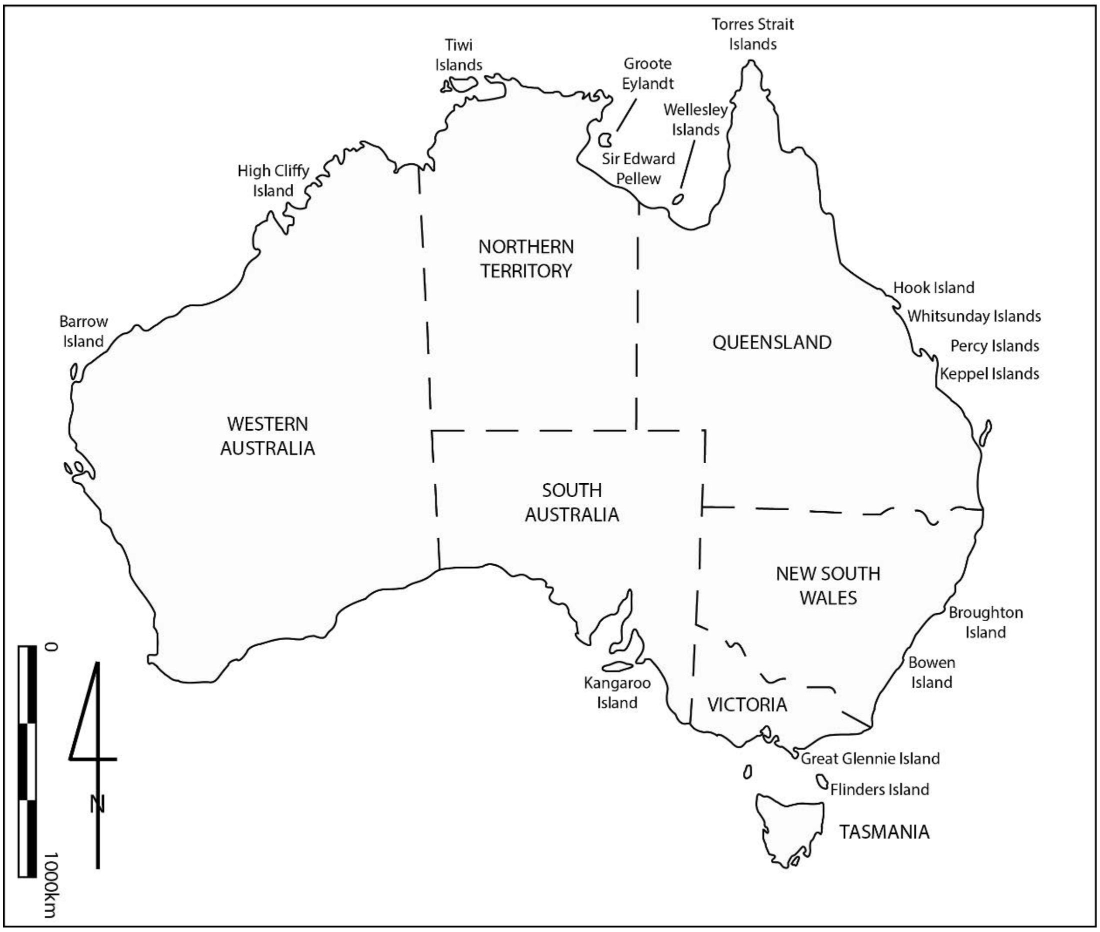

Figure 1.2 Islands containing key archaeological sites around the Australian coast.

Current interpretations of island use highlight substantial variability in the nature and antiquity of interactions between Aboriginal groups and island environments. Islands situated along the temperate south coast primarily saw seasonal exploitation and visitation throughout the mid-to-late Holocene (Jones and Allen 1979; Sullivan 1982; Vanderwal 1978), whereas islands in the tropical north exhibit far greater variability (Barker 1991, 2004; David et al. 2004; O'Connor 1992, 1994; Rowland 1980, 1982a, 1984; Sim and Wallis 2008; Veth 1993; Wright 2011). Along the northeast coast of Queensland and in the Torres Strait evidence suggests while a limited number of sites may have been occupied or used throughout the marine transgression (Barker 1991, 2004; Border 1999; David et al. 2004; Wright 2011), most were only exploited after sea levels stabilised (McNiven et al. 2014; Rowland 1982a, 1982b, 1999a). The Keppel Islands indicate differential use within the island chain itself with North Keppel utilised earlier and more intensively than South Keppel (Rowland 1980, 1981, 1982a, 1982b, 1983b, 1985, 1999b), again highlighting the importance of locally derived interpretation.

Complex occupation chronologies have been characterised in the Gulf of Carpentaria with Sim and Wallis (2008) suggesting multiple colonisation events, abandonments, and occupational hiatuses closely linked with environmental change for Vanderlin Island in the Sir Edward Pellew Group. Similar hiatuses during initial island formation with re-occupation subsequent to the marine transgression have been suggested for the Keppel Islands (Rowland 2008) and islands off the Kimberley Coast (O'Connor 1999a, 1999b). Finally, while preliminary data suggest that the South Wellesley Islands (Ulm et al. 2010) conform to the suggested continental pattern of occupation expansion from c.3000 BP (Williams et al. 2010), further evidence is required before the permanency and nature of this use can be accurately evaluated.

1.4.3 Explaining Aboriginal Interactions with Island Environments

Many attempts have been made to explain the highly variable timing and use of Australian islands in order to contextualise them within the broader continental narrative. For Tasmania, Jones (1977a) applied biogeographic theory, utilising variables such as distance from the mainland, size, and carrying capacity, to gauge the likelihood of occupation. It was argued that cultural diversity was analogous to species diversity and could be measured by the quantity and variety of archaeological material. Assuming this was the case, the size and diversity of sites should share an inverse relationship with distance from the mainland and decreasing island size. However, further research has demonstrated that Australian islands do not easily conform to these expectations (Border 1999; Bowdler 1995; Rowland 2008).

O’Connor (1992:49) proposed separate northern and southern patterns in island use directly related to a disparity in the nature of resource availability, stating that there are ‘fundamental differences in the seasonality of resource bases in the northern and southern regions’. While islands situated in the tropical north saw an abundance of resources, including fish, turtles, and dugong, they did not adhere to any regular seasonal cycle and thus required continuous monitoring in order to ensure successful exploitation. Conversely, islands in the temperate south exhibit evidence of highly seasonal resources, such as seal and mutton bird (Jones and Allen 1979; Sullivan 1982), allowing the precise scheduling of hunting expeditions without ongoing observation. An exception to this pattern can be seen in the Shoalwater Bay Islands, central Queensland. McNiven et al. (2014) propose these islands were subject to repeated short-term visits by mainland marine specialists. Turtle remains suggest hunting trips scheduled to coincide with turtle availability (mid-September to early April) and ensure supplies of drinking water (McNiven et al. 2014). However, it is also posited the exploitation of local quartz sources may have equal or greater influence over the timing of island visitation (McNiven et al. 2014), making it difficult to distinguish between seasonal use and low-level exploitation.

Sim and Wallis (2008) suggest intensifying climatic variability during the mid-Holocene was crucial in the exploitation of offshore islands. Increased frequency of El Niño Southern Oscillation (ENSO) events and variability in weather patterns were thought to have severely limited island visitation, leading to the abandonment of some island environments, with more permanent occupation occurring only once sea levels and climate had stabilised (Sim and Wallis 2008). While this model fits the local archaeological record for Vanderlin Island, attempts to extrapolate it to the entirety of Australia’s north coast should be viewed with caution as localised variations in environmental conditions are ignored (Rosendahl 2012). Moreover, this discounts the possibility of differential human responses to change, leading to geographic normalisation of behaviours. To explore the validity of the environmentally driven pattern of island use proposed by Sim and Wallis (2008) further archaeological and environmental data from a variety of locations are required to establish local and regional models.

Physical and cultural isolation has been suggested as an important factor affecting the nature of island use. Numerous islands around the Australian coast exhibit evidence of early Aboriginal occupation that ceased well before European contact (Bowdler 1995; Draper 2015; Lampert 1972, 1981; Sim 1990, 1994; Veth 1993; Veth et al. 2007). These relict populations were likely stranded during initial island formation as part of the most recent marine transgression. Once isolated from the mainland many of these island landscapes were unable to support permanent occupation owing to resource scarcity and small population sizes (e.g. Veth et al. 2007). Thus, populations were forced to either face localised extinction or abandon the islands.

The exception to this is Tasmania where evidence suggests long-term isolation from mainland Australia commencing c.14,000 BP until European contact (Davidson and Roberts 2008). Some researchers have suggested this extended period of physical and cultural isolation resulted in a reduction in knowledge, citing archaeological evidence of reduced innovation and the loss of specialised foraging skills (e.g. Diamond 1993; Flannery 1994). Most infamously Jones (1977b:203) suggested that for Tasmanian Aborigines isolation brought about a simplification of culture, describing it as a 'squeezing of intellectuality' and 'a slow strangulation of the mind'. Conversely, Vanderwal (1978) argued for *in situ* late-Holocene behavioural and technological adaptation, focusing on the (re)invention/innovation of watercraft allowing exploitation of a wider range of resource zones including islands surrounding Tasmania.

More recent discussion has been dominated by two conflicting arguments. Authors such as Henrich (2004, 2006) suggest changes in population (decreases or dislocation from the mainland) may have disrupted the retention or transmission of cultural knowledge associated with complex tools or traditions. Alternatively, Read (2006) has argued that, rather than degradation of culture, the loss of some technologies and resources may indicate adaptation to changing conditions with some facets found unnecessary and thus discarded, a pattern that has likely been repeated by various other groups in similar circumstances (see Davidson and Roberts 2008; Rosendahl 2012:49). A particularly salient example of this can be seen in dietary shifts from scale-fish to shellfish and crustaceans (see Bowdler 1984). Whatever the reason for the loss or abandonment of certain cultural components and technologies, it is clear that isolation played a significant role in altering fundamental aspects of Tasmanian culture and highlights the potential for similar patterns to emerge in other island environments.

Finally, authors such as Vanderwal (1978), Beaton (1985), and Sullivan (1982) have argued technological innovation was fundamental to patterns of island use. The innovation of tools specialised towards marine subsistence (e.g. fishhooks) may have allowed new resources to be exploited (Sullivan 1982). Similarly, simply accessing offshore island environments requires watercraft technology (Beaton 1985; Rowland 2008; Vanderwal 1978). While some groups employed specialised designs that incorporated outriggers and the like, the complexity of watercraft was not a limiting factor to island use. The most salient example of this comes from the Percy Islands, the most distant island group off the east coast of Australia, where very basic sewn bark canoes were used to traverse distances of at least 27km between islands (Rowland

1984, 1987, 1995). Thus, a relatively minor technological barrier must be negotiated prior to exploiting or colonising island landscapes. This requirement has led some researchers to suggest the mid-Holocene increase in island exploitation coincided with a resurgence in watercraft in the last 3000-4000 years (e.g. Bowdler 1995). However, archaeological evidence of watercraft use is rare with indirect evidence frequently used as a primary source of information (Rowland 2008). Given the importance of the coast to many Aboriginal populations, some archaeologists have argued the perceived hiatus in watercraft use prior to the mid-Holocene may be an artefact of missing evidence rather than abandonment and subsequent reinvention of the technology (Rowland 2008). Although without explicit evidence to the contrary it we cannot effectively rule out the loss of boat-building knowledge (Fitzpatrick et al. 2007).

When viewed within the wider discussion of the impact localised short-term phenomena have on human decision-making processes, it becomes more apparent that accurate interpretations of Aboriginal island use require increased archaeological resolution. The diversity of forces influencing human interaction with island environments combined with the variable nature of human-environment relationships in coastal contexts suggests complex patterns of change cannot be accurately approached at inter-regional scales. Thus, wide-ranging models are unlikely to deliver a convincing holistic interpretation of Aboriginal island use. While the physically isolated nature of islands assists in removing some issues associated with geographic homogenisation, in that individual small islands can often be treated as singular cohesive regions, researchers must complement this serendipitous advantage with techniques that allow the characterisation of temporally discrete phenomena. Only then can we approach a more sophisticated understanding of how, when, and why Aboriginal populations utilised island environments.

1.5 Approaching Key Questions

The Holocene is widely recognised as a key period of behavioural, cultural, and environmental change across the Australian landscape. Yet, previous discussion surrounding this period has largely centred on cause rather than effect, with disagreements regarding the influence of environment versus culture dominating associated discourse (see Bailey 1983b; Barker 1996, 1999, 2004; David 2002; David and Lourandos 1999; Lourandos 1993, 1997; Rowland 1983a, 1999a, 2008). While culture remains integral to interpretations of change an increasingly large body of research has demonstrated human-environment relationships play a crucial role in Holocene restructuring, convincing even the most stalwart proponents of socially driven transformation of the importance of environmental mechanisms (e.g. Barker et al. 2012; David and Badulgal 2006; McNiven et al. 2012, 2014). With the significance of these ties now widely accepted, discussion has shifted towards characterising how changing human-environment interactions influenced behaviour and culture rather than debating why. Thus, archaeologists are faced with a new suite of questions that require an increasingly sophisticated understanding of human decision-making at a variety of scales. One of the most fundamental among these is: *How are shifting human-environment interactions reflected in changes in behaviour and culture?* While addressing human responses to Holocene change may require fundamental modifications to how we approach facets of archaeological inquiry, associated outcomes would better position researchers to characterise patterns of change and approach holistic interpretations of Aboriginal life during the Holocene (Ulm 2013).

While it is agreed that Aboriginal populations likely sought to minimise risk through shifts in mobility, technological innovation, and demographic restructuring, debate surrounds how these modifications altered cultural frameworks. Key researchers Attenbrow (2006) and Hiscock (1994, 2006:87-88) argue that hunter-gatherers mitigated risk through increased mobility, resource stockpiling, and diversified toolkits (e.g. backed artefacts, tula adzes, and seed-grinders). Yet, others suggest increased toolkit diversity may instead indicate movement towards a more sedentary lifestyle or changes in logistical strategies (Smith 2013; Williams et al. 2010). Building upon this, Williams et al. (2015a) employ a synthesis of radiocarbon dates from across Australia to hypothesise a model of Holocene change centred on decreased mobility, population growth and concentration, emerging social complexity, and more permanent expansion into marginal environments such as the arid zone and offshore islands (see also Williams et al. 2015b). While these approaches provide a heuristic framework for inquiry based on empirical evidence, it is extremely difficult to directly apply them to specific locations owing to a reliance on data derived from temporally and geographically broad contexts (following Young 1994).

Building upon ideas proposed by continental models requires testing via direct archaeological evidence. Doing so in well-defined contexts with established chronologies and spatial boundaries can assist in ameliorating issues associated with homogenisation. Thus, offshore islands provide an ideal framework in which the efficacy of wide-ranging models of change can be explored in microcosm. Constrained geographically and temporally (Burney 1997; Fitzpatrick 2004:4-5; Kirch 1980), archaeological deposits found on offshore islands frequently exhibit a high abundance of material suitable for generating high-resolution chronologies, e.g. molluscan shell or fish otoliths (see Andrus 2011; Deith 1983; Oschmann 2009; Prendergast and Stevens 2014). Moreover, as island landscapes are featured prominently within Australian archaeological and ethnographic research there exists an extensive body of work to draw upon. Such research has demonstrated the diversity of human-environment relationships present within these contexts, highlighting often unique interactions between culture, decision-making processes, and environment (e.g. Barker 2004; Border 1999; Bowdler 1995; David et al. 2004; O'Connor 1992; Rowland 1984; Sim and Wallis 2008; Vanderwal 1978; Wright 2011). As these interactions occur at a variety of scales, researchers can potentially characterise and interpret sub-annual, annual, and longer-term trajectories. Thus, the archaeological record of offshore islands not only provides an ideal testing ground for the broader applicability of inter-regional models but also highlights the importance of targeted research to holistic interpretation.

Ensuring robust outcomes requires the coupling of suitable contexts with appropriate methodology. Methods employed within the Australian archaeological tradition have a tendency to lag behind those used by international researchers, particularly with regards to high-resolution techniques. However, this affords Australian archaeologists the unique opportunity to apply internationally tested methods to novel contexts, where results offer previously inaccessible solutions to fundamental questions. As behavioural change frequently manifests within the archaeological record as variably scaled discontinuities, interpretations require methods capable of characterising these patterns. Further, attention must be given to the context within which methods will be deployed. Differing environments and cultures may require techniques tuned specifically for archaeological material common in those contexts. For coastal populations, high-resolution analytical tools, such as sclerochronology – the aquatic equivalent of dendrochronology (Andrus 2011; Oschmann 2009), provide the ideal methodological framework to test assertions taken from broader models of change (see Chapter 2 for a detailed review of sclerochronology). By deploying established techniques in well-defined contexts archaeologists can reach nuanced understandings of changing human behaviours and decision-making processes as well as elucidate broader patterns of mobility, demography, and permanency.

1.6 Occupation Permanency

Approaching solutions to how changing human-environment interactions are reflected within modifications to behaviour and culture will likely require researchers to reconsider the efficacy of traditional archaeological methodology, particularly in relation to how we characterise and interpret patterns of occupation. Discussions of land-use have previously focused on timing and antiquity as they provide essential temporal context, however this can lead to the erroneous assumption of static occupation (see Section 1.2). Moreover, changing interactions between humans, culture, and the environment may modify patterns of use and occupation as populations negotiate fluctuating conditions (e.g. Williams et al. 2015a, 2015b). It is therefore imperative that we consider the concept of occupation permanency in addition to timing and antiquity to improve upon occupation chronologies while simultaneously affording insight into additional higher-order patterns associated with mobility and demography.

The stark changes occurring across northern Australia during the mid-to-late Holocene provide a particularly salient testing ground for interpretations of permanency. Numerous authors have discussed changing patterns in Aboriginal occupation of marginal environments, such as offshore islands, in relation to larger environmental and cultural trajectories (Barker 1999, 2004; McNiven et al. 2014; Rowland 2008; Rowland et al. 2015; Sim and Wallis 2008; Williams et al. 2015a, 2015b). Broad continental models suggest a linear progression that escalates from ephemeral visitation and exploitation to more permanent colonisation, a pattern that is frequently linked to increasing climate variability owing to changing ENSO conditions (Williams et al. 2015a, 2015b). However, as resolution is increased to local scales, more complex patterns begin to emerge. The mechanisms implicit in associated decision-making processes likely encompass a variety of localised cultural, environmental, and behavioural factors and thus require holistic explanations to accurately characterise.

1.7 The South Wellesley Islands

The South Wellesley Islands are situated along Australia’s north coast in the southern Gulf of Carpentaria. Consisting of 10 variably sized islands as well as numerous reefs and sandy cays (Figure 1.3), this region is the traditional country of the Kaiadilt – one of four Aboriginal language groups from the greater Wellesley’s area. Initial linguistic modelling proposed Kaiadilt occupation of the South Wellesley’s only in the last millennium (Evans 2005; Memmott et al. 2006), however recent archaeological research, augmented with further linguistic analysis, has revealed a significantly longer and more complex chronology (Memmott et al. 2016; Nagel et al. 2016; Peck 2016; Ulm et al. 2010). Ethnohistoric observations made by Flinders indicate the South Wellesley’s were occupied at the time of his arrival (November 1802) with Aboriginal groups observed on Sweers, Bentinck, and Horseshoe islands (Flinders 1814:121-131, 145). Moreover, visitation by Macassan trapangers is evidenced by the presence of pottery sherds, tamarind trees, and stone line arrangements across parts of Fowler and Bentinck islands (Oertle et al. 2014). Sporadic contact continued between Europeans and the Kaiadilt with a handful of encounters recorded throughout the contact period (e.g. Boyd 1896; Chimmo 1857; Laurie 1866; Roth 1901, 1903; see Tindale 1962a:265-271 for a complete list of contact during this period). The Kaiadilt maintained traditional lifeways until the late 1940s when a period of drought coupled with a large tidal surge that contaminated freshwater sources across Bentinck Island led to increased resource strain, internal tensions, and fighting (Tindale 1962b). Consequently, all Kaiadilt were forcibly relocated to the mission on Mornington Island by late 1948 (Memmott 1982a; Memmott et al. 2006:42).

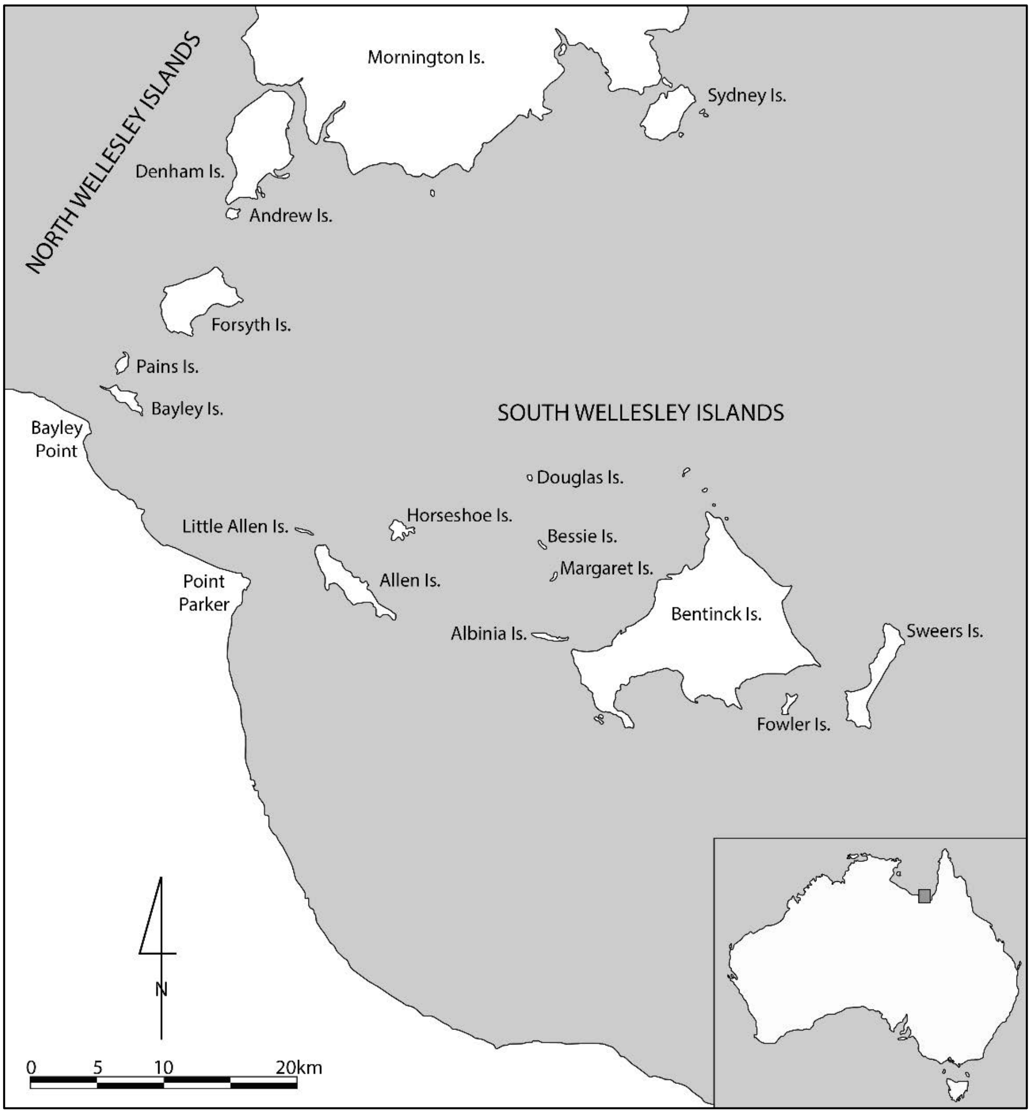

Figure 1.3 Map of the South Wellesley Islands located in the southern Gulf of Carpentaria, Australia. This region is the traditional country of the Kaiadilt people.

Local environmental and climatic oscillations are driven by the Australian monsoonal cycle, broadly delineating the year into two seasons, wet and dry, bringing with them stark variations in local conditions (Figure 1.4). The wet season (November to March) is typified by frequent episodes of intense rainfall (92% – 95% of annual precipitation), tropical cyclones, high humidity and temperatures, increased flora and insect activity, and northwesterly winds (BOM 2016; Memmott 2010:21; Tindale 1962a). The remainder of the year (April to October) constitutes a long dry season. During this time the region experiences little to no rainfall, lower humidity and temperatures, decreased flora and insect activity, and strong southeasterly winds that reach their peak during July (BOM 2016; Memmott 2010:21).

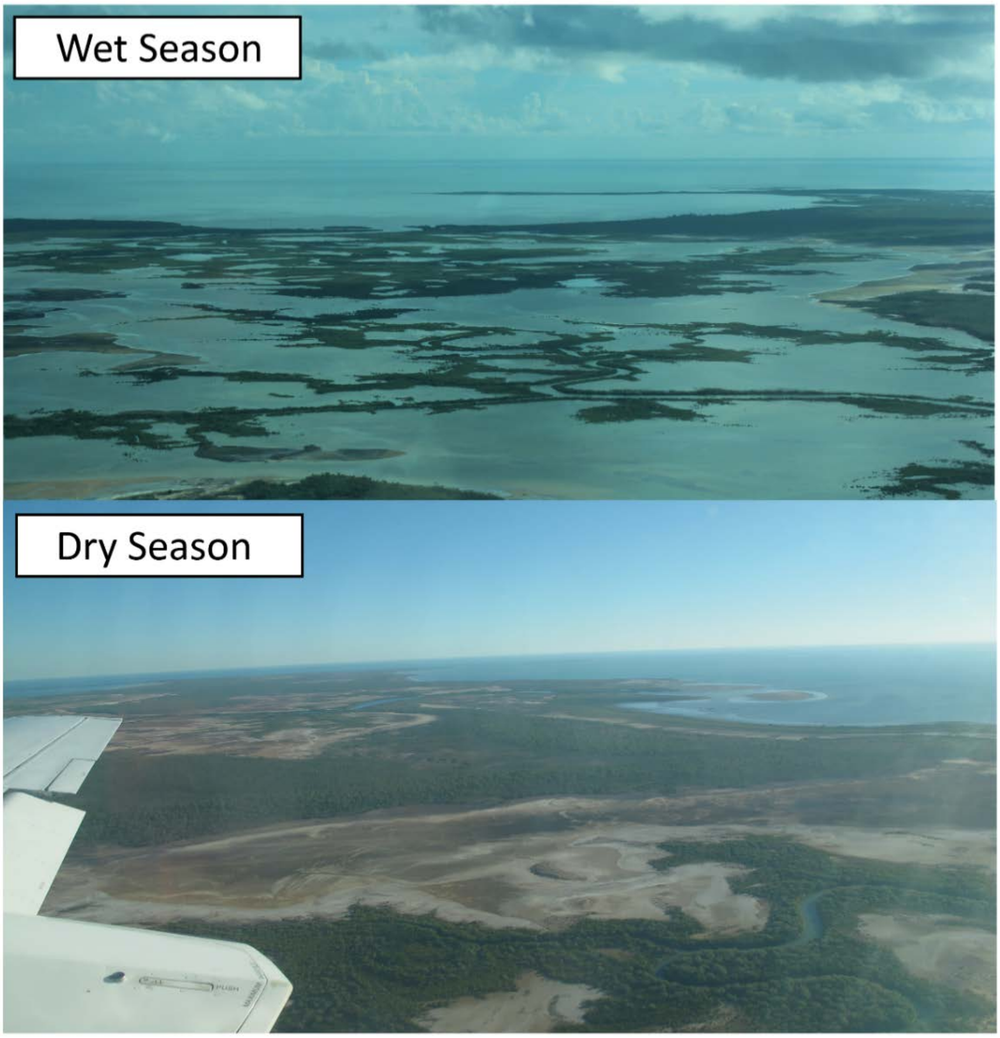

Figure 1.4 Aerial photographs taken in wet (top) and dry (bottom) seasons overlooking Bentinck Island bring differing conditions into stark relief (Photographs: Daniel Rosendahl, 2014; Anna Kreij, 2014).

Given the substantial changes brought about by sub-annual climate phenomena in this region, it is unsurprising that local ethnographic observations have documented strong links between seasonal environmental and climatic cycles, human decision-making processes, and behavioural variability across both North and South Wellesley Island groups (Memmott 2010; Tindale 1962a, 1962b, 1963). Many aspects of local life are therefore imbued with seasonality (see Chapter 3 for a detailed review). Such behaviours are well documented among the Lardil who utilise a traditional calendar consisting of five separate seasons characterised by patterns of mobility, resource use, and campsite configuration (Memmott 2010). Moreover, Memmott (2010) suggests the seasonality of people's movements are heavily influenced by wind direction, mosquito abundance, and resource availability. The peak of the dry season is accompanied by intense wind conditions that force some groups to seek shelter inland away from the coast (Memmott 2010:21), potentially reducing access to some marine resources. Similarly, periods of high rainfall during the wet season cause the otherwise highly mobile Lardil to temporarily assume a more sedentary lifestyle, establishing 'wet weather' camps that are used for up to six weeks at a time (Memmott 2010:24). Other campsite types are utilised as barriers against mosquitoes during the wet summer and cold during the dry winter (Memmott 2010:21).

Similar strategies were likely employed by the Kaiadilt to negotiate seasonal cycling, however significantly less information (ethnographic or otherwise) is currently available. That said, observations by Tindale hint at the possibility of sub-annual behavioural patterning in the South Wellesley's (Tindale 1962a). On Bentinck Island, Tindale (1962a) noted access to certain hunting grounds and resources were dictated by seasonal environmental conditions including strong winds, rainfall, and inclement ocean conditions. Monsoonal rainfall during the wet season floods substantial portions of the low lying Bentinck Island, restricting movement and access to resources and land (Figure 1.5). Moreover, strong winds during the first half of the dry season limit hunting expeditions to some sandbars where turtle meat and eggs are collected (Tindale 1962a). These same conditions can limit movement between islands (Tindale 1962b), even with the assistance of modern watercraft (personal observation, July 2013, March 2014, June 2014). Further, it has been suggested some infrastructure, such as fish traps along the islands north coast, may have been utilised on a seasonal basis owing to changes in wind direction and intensity (Tindale 1962a).

Figure 1.5 Large portions of Bentinck Island are subjected to seasonal flooding owing to heavy monsoonal rainfall and tidal banking (Photograph: Daniel Rosendahl, 2014).

When viewed in the wider context of seasonally-timed behaviour across Australia's north coast, many parallels can be drawn between the South Wellesley Islands and the wider region (see Davies 1985; Meehan 1982; Sutton 2010; Thomson 1939). Much like their mainland counterparts, regular seasonal patterns of environmental and climatic cycling appear to directly influence decision-making processes in the South Wellesley Archipelago with fundamental behaviours altered in response to sub-annual climatic fluctuations and episodic events. Characterising these short-term behavioural discontinuities provides increasingly nuanced understandings of responses to environmental change, allowing archaeologists to approach sophisticated interpretations of localised human-environment interaction and address higher-order questions.

Little work has explored permanency of occupation in the South Wellesley Islands, however preliminary interpretations coupled with sum probability plots generated from available radiocarbon dates suggest a general trend (see Memmott et al. 2016; Rosendahl et al. 2014a; Ulm et al. 2010). Use of Bentinck Island commenced c.3500 BP with what has been postulated as a phase of ephemeral or sporadic visitation (Ulm et al. 2010), before gradually intensifying after c.2000 BP. While a continuous occupation signal is present from 2000 years ago (Memmott et al. 2016), it is relatively weak, raising the possibility of seasonal use, multiple colonisation attempts, or similar low-intensity occupation (Ulm et al. 2010:43). A distinct increase in use is apparent from c.800 BP with another significant upturn in the last 300 years (Memmott et al. 2016), potentially indicating the commencement of permanent Kaiadilt occupation. While this model provides a working foundation for characterising changing patterns of occupation permanency further development is required. This becomes increasingly salient with Rosendahl et al. (2014a) suggesting that environmental factors may have played a relatively minor role in regional colonisation patterns. In particular, sub-annual chronologies provided by high-resolution analyses (such as sclerochronology) will aid in increasing the accuracy and resolution of permanency modelling.

While fundamental understandings of interactions between Kaiadilt populations and the South Wellesley's landscape are beginning to crystallise (Memmott et al. 2016; Moss et al. 2015; Nagel et al. 2016; Rosendahl et al. 2014a; Sloss et al. 2015; Ulm et al. 2010), questions relating to the permanency, timing, and development of occupation remain largely unresolved. Broader interpretations of human responses to Holocene environmental change suggest far-reaching cultural and behavioural transformations that altered fundamental components of Aboriginal life. Moreover, evidence indicates marginal environments were increasingly relied upon, with previously sporadic or ephemeral patterns of exploitation moving towards more permanent use.

This may be linked with demographic restructuring and changes in mobility as suggested by Williams et al. (2015a, 2015b). Further, regional sequences from similar island contexts indicate patterns of multiple abandonments and reoccupation (Sim and Wallis 2008) as well as seasonal visitation and exploitation (McNiven et al. 2014). While it would be relatively simple to extrapolate and apply these models to the South Wellesley Islands (or any other region), this would provide an overly simplistic and fundamentally flawed interpretation as unique localised cultural, behavioural, and environmental trajectories would certainly be lost.

Data gathered from the South Wellesley Islands can assist in illustrating changing occupation patterns in the Holocene. Of particular interest is how permanency of use may have changed through time. Numerous authors have suggested occupation patterning is frequently characterised by initially ephemeral visitation or exploitation tied to favourable weather conditions and seasonally available resources, shifting towards more permanent occupation, with increases in site establishment and population sizes (e.g. Barker 2004; see Faulkner 2013:1-3). This unidirectional pattern of occupation is popular, particularly with marginal environments such as offshore islands or the arid zone. Yet, it is increasingly clear that patterns of occupation are substantially more complex and diverse. By applying internationally recognised high-resolution data recovery and analysis methods to the novel context of the South Wellesley Islands, an increasingly nuanced view of Kaiadilt occupation patterns can be reached. This dataset can be utilised to test broad assumptions of unidirectional occupation patterns and approach long standing questions of landscape use.

The solutions to these increasingly important problems cannot be found within the normative thinking of broad homogenised models. Instead, they must be addressed at scales that allow the variability and complexity of relationships between Aboriginal culture, behaviour, and environments to be acknowledged and integrated. Answers must also be demonstrated directly within the local archaeological record, thus ameliorating results from latent inaccuracies and biases associated with extrapolation and abstraction. The South Wellesley's present a unique opportunity to test a variety of potentially widely applicable models relating to mid-to-late Holocene change. This thesis utilises a high-resolution chronology of Kaiadilt occupation to investigate broad claims of shifting patterns in land-use, human-environment interactions, and fluctuations in mobility and demography within the temporally and geographically constrained context of the South Wellesley Islands.

1.8 Aims of Research

This thesis presents the highest resolution study of island occupation patterns undertaken in Australia to date, situating it within a framework of practical and methodological issues emerging in both Australian and international archaeological investigation. It has the primary aim of evaluating the place Bentinck Island holds within the broader pattern of island use in Australia's tropical north and mid-to-late Holocene patterns of change. In order to approach this outcome, the following objectives have been set:

Locally, to:

- Gain a sophisticated understanding of environmental and hydrological cycles affecting Bentinck Island, Gulf of Carpentaria, with a focus on the Mirdidingki Creek system and surrounding area.
- Using high-resolution data recovery methods to characterise relationships between environmental conditions and isotopic records found in the shell carbonates of commonly exploited shellfish taxa.
- Generate a high-resolution model of occupation periodicity and seasonality for Bentinck Island from archaeological shellfish assemblages using sclerochronological methods.
- Explore how seasonal shifts in environment and climate affect Kaiadilt mobility and demography in the South Wellesley Islands.

Regionally, to:

- Contextualise localised chronologies from the South Wellesley Islands against broad interpretations of island use to test burgeoning notions of complex occupation patterning, e.g. abandonments, multiple colonisations, and intensified usage.
- Determine the efficacy of established continental models associated with shifts in mobility, demography, and land-use trajectories during the mid-to-late Holocene using Bentinck Island as a case study.

Methodologically, to:

- Highlight the importance of localised high-resolution investigations of environment and human behaviour in coastal and island landscapes.
- Test the efficacy of applying sclerochronology in a tropical Australian setting.
- Refine methodological protocols, procedures, and analytical frameworks within sclerochronology.

1.9 Thesis Overview

Chapter One introduced key themes associated with characterising and interpreting short-term behaviour and environmental patterning within the archaeological record. Limitations associated with current methods of establishing occupation chronologies were outlined, highlighting a paucity of high-resolution investigations into site occupation within Australia. Coarse-grained representations of human behaviour are particularly problematic when addressing archaeological questions of occupation, mobility, and demography in island contexts given the highly variable timing and nature of use.

Chapter Two provides an overview of literature surrounding the use of environmental proxies in archaeological research and highlights their importance to understanding short-term trajectories. Key data recovery method – sclerochronology – is introduced and its use within archaeological inquiry is discussed.

Chapter Three introduces the South Wellesley Islands by defining the physical, cultural, and palaeoenvironmental setting to contextualise this study within a local framework.

Chapter Four reviews the ecology and biology of the three target mollusc taxa, *Polymesoda coaxans*, *Gafrarium tumidum*, and *Marcia hiantina*, along with the advantages and limitations presented by these factors. Their economic and cultural importance to Aboriginal populations, including the Kaiadilt, are also discussed.

Chapter Five outlines field and laboratory methods employed for this study. Procedures required in gathering modern environmental data are detailed and justified along with methodological choices regarding the selection of modern and archaeological mollusc specimens, preparation of specimens for sclerochronological analysis, carbonate sampling, and isotopic analysis of water and carbonate.

Chapter Six presents the results of modern environmental monitoring. Modern environmental and hydrological cycles are characterised, contrasted, and discussed in relation to how they may impact shell geochemistry.

Chapters Seven, Eight, and Nine explore how environmental cycles characterised in Chapter Six are reflected within the shell geochemistry of target taxa. Live-collected specimens are isotopically analysed to gauge the efficacy of each species for radiocarbon dating and as palaeoenvironmental proxies. Those species deemed suitable are then aligned to environmental data as modern analogues.

Chapters Ten, Eleven, and Twelve present results associated with archaeological material excavated from key sites across Bentinck Island. Archaeological shellfish are analysed using sclerochronological techniques and contextualised through modern analogues. A summary and interpretation of the results is provided at the conclusion of each chapter.

Chapter Thirteen provides a synthesis of the results with a discussion of the broader implications of the findings and an emphasis on the importance of high-resolution site-use chronologies. Higher-order questions of mobility and demography are also addressed. Finally, this chapter revisits the key aims of the thesis and addresses how these have been met. Directions for future research are also identified.

Chapter 2 Sclerochronological Analysis of Archaeological Mollusc Assemblages

2.1 Introduction

Archaeologists are increasingly citing environment and climate as important variables impacting human decision-making in the past (e.g. Brockwell et al. 2013; Burchell et al. 2013c; Faulkner 2013; Hallmann et al. 2013; Hiscock 1999; Nunn 2003; Rowland 1999a; Sim and Wallis 2008). Gaining increased understandings of the environments with which past populations engaged is therefore an integral first step towards more accurate interpretations of human behaviour. However, as large-scale palaeoenvironmental reconstructions can be geographically removed from contexts of interest (Shulmeister 1992), archaeologists must employ proxies which are tied more directly to the archaeological record under investigation (e.g. Carré et al. 2005a, 2005b; Colonese et al. 2012; Hallmann et al. 2008) to generate fine-grained local palaeoenvironmental data (Ulm 2013). Environmental proxy data derived from archaeological assemblages allow researchers to extend historical instrumental records and explore the effects of environment and climate on aspects of human behaviour at intra-regional levels (Andrus 2011). Yet, many archaeological studies instead rely upon regionally scaled or geographically removed environmental reconstructions (e.g. Brockwell et al. 2013; Stephens et al. 2008), potentially subjecting associated interpretations to latent biases and inaccuracies.

A growing body of research is exploring the efficacy of utilising accreting skeletal tissues to produce high-resolution reconstructions and interpretations of palaeoenvironmental conditions and their effects on past human behaviours (see Burchell et al. 2013c; Carré et al. 2005b; Eerkens et al. 2013; Fenger et al. 2007; Hallmann et al. 2008; Hufthammer et al. 2010; Jew et al. 2013; Mannino et al. 2003; Prendergast et al. 2013; Wurster and Patterson 2001; among others). Aspects of the ambient environment are recorded within the sequential growth structures of accreting skeletal tissues, preserving high-resolution time-series information (potentially reaching sub-daily scales) ideal for localised palaeoenvironmental reconstruction. Studies of a wide range of accreting skeletal tissues, including fish otoliths (Disspain et al. 2016; Dufour et al. 2008; Wurster and Patterson 2001, 2003), teeth (Pike-Tay and Cosgrove 2002), coralline sponges (Böhm et al. 2000), some mammalian bone – including deer (Frankel et al. 2013) and wallaby (Pike-Tay and Cosgrove 2002) – and molluscan shell (Burchell et al. 2013b; Hallmann et al. 2009), show the rapidly expanding application of these techniques into a range of archaeological materials and investigations. Here we focus on one class of materials that is ubiquitous in coastal archaeological contexts – molluscan shell.

To access environmental archives preserved within shell structures researchers employ fine-scale data recovery methods, such as sclerochronology. Often referred to as the aquatic equivalent of dendrochronology (Andrus 2011), sclerochronology is the study of information preserved in the sequential growth structures of accretionary hard tissues (Andrus 2011; Gröcke and Gillikin 2008; Oschmann 2009). While the term was originally coined by Buddemeier et al. (1974) and Hudson et al. (1976) in reference to the study of density bands in stony head coral, its definition has since broadened to encompass a variety of physical and geochemical techniques (Oschmann 2009).

This chapter focuses upon two commonly employed sclerochronological techniques – growth feature analysis and stable isotope analysis – although it must be noted that other techniques, such as trace element analysis (e.g. Batenburg et al. 2011; Bougeois et al. 2014; Foster and Chacko 1995; Goodwin et al. 2013; Putten et al. 2000), are also gaining popularity. Growth feature analysis is commonly used to assess macro- and microscopic physical variability in the growth regimes of accreting skeletal tissues (Burchell et al. 2013b, 2013c; Claassen 1988), while stable isotope analyses allow the reconstruction of 'daily', seasonal, or longer-term environmental cycles as well as other facets of the palaeoenvironment (e.g. Carré et al. 2005b; Cohen et al. 1992; Hallmann et al. 2008; Kennett and Voorhies 1995). Similarly, growth feature analysis and stable isotope analysis are increasingly applied to address archaeological questions relating to population dynamics including occupation periodicity and seasonality, mobility, and demography (e.g. Burchell et al. 2013c; Deith 1983; Eerkens et al. 2013; Jones et al. 2005; Shackleton 1973), allowing increasingly nuanced interpretations of human-environment relationships. While these methods are routinely implemented by researchers from a variety of disciplines (e.g. geosciences, fisheries and environmental sciences) coastal archaeologists are increasingly utilising this toolset in a variety of geographic locations and climate zones, with special issues or sections of *The Journal of Island and Coastal Archaeology* (see West 2013) and other peer-reviewed sources providing a dedicated discourse (Figure 2.1).

While the potential of employing proxies derived from archaeological deposits to assist with palaeoenvironmental reconstruction has long been recognised (e.g. Aguirre et al. 1998; Kirby et al. 1998), a number of methodological challenges continue to hinder accurate interpretation. The use of poorly calibrated or inappropriate proxies and broad extrapolations of localised results can severely limit the accuracy and validity of analysis and associated data. While robust sampling strategies and careful selection of proxies can assist in minimising the effects of these issues, the literature indicates that many studies are unsuccessful in incorporating such measures (e.g. Brockwell et al. 2013; Kennett and Voorhies 1996; Lightfoot and Cerrato 1988;

Stephens et al. 2008). Thus, many datasets are potentially poorly calibrated or do not operate at the resolution required for meaningful interpretation.

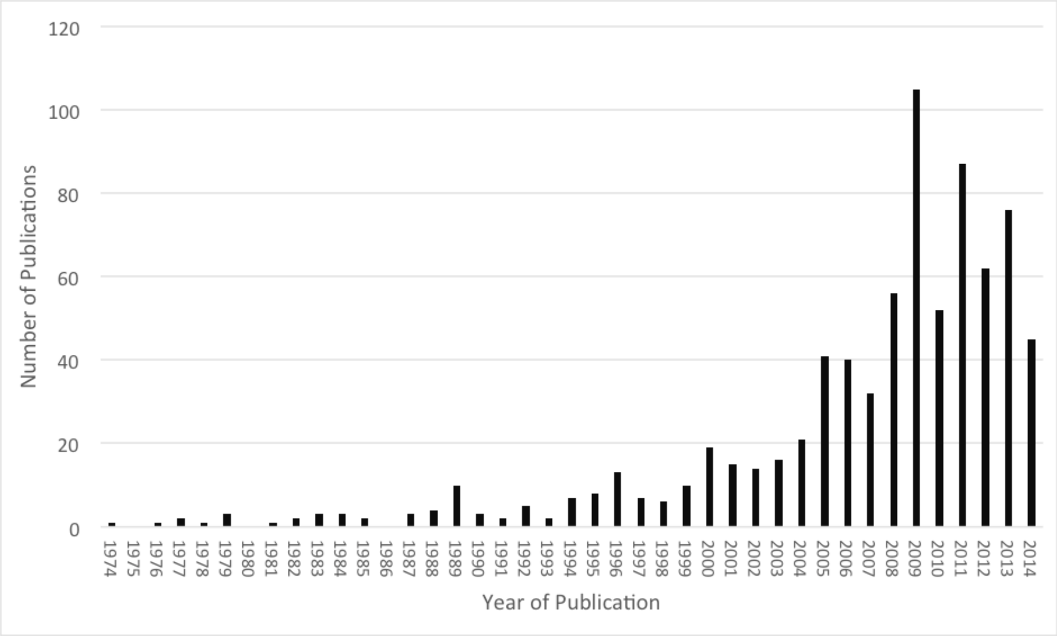

Figure 2.1 Yearly number of publications from a variety of disciplines (including archaeology, geosciences, fisheries, and environmental sciences) from peer-reviewed sources with the search term sclerochron* between 1974 and 2014. Data from Web of Science database search on 03 November 2014.

This chapter examines previous attempts to characterise the palaeoenvironment and explore human-environment interactions through archaeological proxies, highlighting methodological advantages and limitations of sclerochronology. Provided a variety of methodological and practical criteria are met, it is posited that applying sclerochronological techniques to the accreting skeletal tissues of molluscan shell provides a means to accurately and meaningfully interpret past human-environment relationships.

2.2 Understanding Human-Environment Relationships through Environmental Proxies

Environmental proxies allow researchers in many disciplines to extend instrumental records, characterise past environments, and identify relationships between environmental conditions and human behaviour (e.g. Burchell et al. 2013c; Carré et al. 2005b; Chivas et al. 2001; Cornu et al. 1993; Hassan et al. 2012; Kennett and Voorhies 1996; Reeves et al. 2007; Shulmeister and Lees 1995). A wide array of *in situ* proxies (e.g. ice cores, speleothems, tree rings, and sediments) are employed to gather information regarding aspects of the palaeoenvironment – including temperature, salinity, biotic responses to climate change, ENSO cycles, and broad-scale climate variations (Birks et al. 2010; Böhm et al. 2000; Boyd 2008; Carré et al. 2005b; Cohen et al. 1992;

Marwick and Gagan 2011; Prendergast et al. 2013; Taft 2013). While these proxies provide vital information for archaeologists interested in exploring temporally or spatially expansive trends (e.g. Smith et al. 2008; Turney and Hobbs 2006; Williams et al. 2010), increases in resolution require finer time resolved data. As such, archaeologists must instead rely on environmental analogues recovered from archaeological deposits – including molluscan shell, fish otoliths, terrestrial fauna remains, environmentally sensitive flora, and charcoal (see Dufour et al. 2008, 2014; Faulkner 2008; Frankel et al. 2013; Hallmann et al. 2013; Hufthammer et al. 2010; Pike-Tay and Cosgrove 2002). Unlike other environmental proxies, those extracted from archaeological settings provide direct linkages between environment and human activity (Prendergast and Stevens 2014), allowing researchers to locally contextualise environmental records and approach archaeological questions regarding human decision-making processes.

Employing proxies derived from the archaeological record requires researchers to overcome a variety of practical and methodological limitations. While a wide selection of proxies are often available, their viability or usefulness can be restricted by a series of research-specific factors. Geographic location, climate, temporal and spatial scale, required resolution, type of information sought, and issues related to preservation and deposition/taphonomy all potentially affect the accuracy and validity of interpretations made from proxy sources. Failure to consider these can introduce latent inaccuracies and biases into datasets. For instance, the extrapolation of high-resolution proxies that document localised environmental conditions at short timescales (sub-daily or seasonally) into broader temporal and geographical contexts can diminish the accuracy of interpretations (e.g. Brockwell et al. 2013). Detail is lost as localised patterns are homogenised into generic overarching explanations (for further discussion on the impacts of normative methodologies see Claassen 1991). Thus, in order to mitigate the impacts of these potential issues archaeologists must carefully select proxies that fit criteria specific to the aims of their research.

While the selection of appropriate material assists in ameliorating interpretations from erroneous data (Burchell et al. 2013b; Hallmann et al. 2013; Kingston et al. 2008), a nuanced understanding of the biology, ecology, and potential limitations associated with the chosen proxy is essential in generating meaningful and robustly interpretable results. Archaeologists are increasingly employing calcium carbonates derived from accreting skeletal tissues as a staple palaeoenvironmental proxy. The robust nature and ubiquity of accreting skeletal tissues in archaeological depositions has allowed their efficacy as palaeoenvironmental proxies to be rigorously examined (e.g. Campana 1999; Monks 1981:193-211; Schöne 2008). Most importantly, the effects of environmental conditions on chemical and physical elements of accreting skeletal tissues (e.g. growth regimes and isotopic fractionation) have been thoroughly tested and characterised in both laboratory and field settings (e.g. Epstein et al. 1953; Foster et al. 2009; Grossman and Ku 1986; Kim and O'Neil 1997; Turner 1982). This provides researchers with a comprehensive methodological foundation that accurately describes interactions between accreting skeletal tissues and the environment.

2.3 Growth Features and Stable Isotopes

Growth feature and stable isotope analysis are widely used to access and interpret fine-grained information archived within the growth structures of accreting skeletal tissues to construct temporally sensitive data profiles (Álvarez et al. 2011; Andrus 2011; Gröcke and Wortmann 2008). While the foundations of these techniques have been in place since the early 1950s (Epstein et al. 1951, 1953; Haskin 1954; McCrea 1950; Orton 1923; Urey 1947; Urey et al. 1951), sclerochronological protocols have only recently been widely applied to archaeological contexts (e.g. Burchell et al. 2013a; Hallmann et al. 2013; Schöne 2013; among others). Recent advances in sampling and analysis have led to significant increases in resolution and accuracy (Merritt and Hayes 1994; Spötl and Mattey 2006; Wurster et al. 1999) encouraging increasingly routine application of these techniques. Thus, the efficacy of utilising growth features and stable isotopes in a range of climatic and environmental settings is under constant review, with results developing into an increasingly nuanced theoretical foundation that highlights and addresses discipline specific challenges (Goodwin et al. 2004a; Schöne 2008).

The fundamental concepts of sclerochronology rely on aspects of local environmental conditions being archived sequentially within the biogenetic carbonates of skeletal structures (Epstein et al. 1953; McCrea 1950; Pannella and Copeland 1968; Rhoads and Pannella 1970; Urey 1947). Thus, underlying requirements for target material are that carbonates precipitate in equilibrium with the ambient environment and are deposited in periodic growth layers to allow precise temporal alignment of the chemical record with the environmental changes being recorded (Schöne and Surge 2012). While these attributes have been observed in a variety of skeletal material found within the archaeological record, molluscan shell (particularly bivalves) is most frequently utilised owing to its broad geographic distribution throughout a diverse range of environments and climates, sensitivity to environmental change, sequential growth patterning, high potential for preservation, and extensive history of research (Bailey et al. 1983; Clark 1974; Rhoads and Lutz 1980).

During shell growth the chemical and physical interactions between precipitating calcium carbonates and the ambient environment imprint molluscan skeletal tissues with representations of environmental and hydrological cycles (Eisma et al. 1976; Grossman and Ku 1986; Rhoads and Lutz 1980). While these cycles primarily reflect regular occurrences such as tides or seasonal variation, irregular events including extreme weather or physiological change can also be recorded (Andrus and Rich 2008; Jones et al. 2005; Rowland 1977). Therefore, employing high-resolution data recovery techniques, such as sclerochronology, to systematically analyse molluscan shell allows the generation of detailed chronological life histories and reconstructions of the ambient environment. The application of these methods to archaeological assemblages provides the opportunity to address broader questions regarding palaeoenvironments, climate change and their effects on human behaviour (Burchell et al. 2013b; Clark 1974; Schöne and Surge 2005).

2.3.1 Growth Feature Analysis

Researchers use growth patterns to understand life history traits of target taxa, assist in palaeoenvironmental reconstruction and provide temporal context for higher-resolution analysis (Andrus and Rich 2008; Hallmann 2011). Shifting environmental and climatic conditions as well as biological processes act as fundamental controls on the growth regimes of molluscs. Variations in water temperature and mixing can significantly alter shell precipitation rates, a process which manifests as discrete growth banding (Clark 1974; Lutz and Rhoads 1977; Rhoads and Lutz 1980). Biological (circadian) clocks, operating at regular rhythms, ensure that growth banding continues to be produced when molluscs are not exposed to significant environmental change (Richardson 1987, 1988; Schöne 2008, 2013). Visible on the exterior, hinge and in cross-section, growth banding is comprised of two basic structures: lines and increments (Figure 2.2). Lines represent periods of growth slowdown brought about by environmental stressors that exceed the tolerances of the mollusc. It must be noted that cases of total growth cessation are not evidenced within the skeletal structures of molluscan shells as carbonates are not precipitated during this time (Schöne 2008). Increments correspond to periods of normal or accelerated growth, often correlating to more optimal environmental conditions. As the deposition of banding is maintained and regulated by biological clocks and recurring environmental events, the periodicity of which range between diurnal tidal cycles and annual cycles (Andrus 2011; Clark 1974; Deith 1983; Richardson 1987, 1988; Schöne 2008, 2013), researchers are able to interpret growth features as physical expressions of time, provided the drivers of band formation are known.

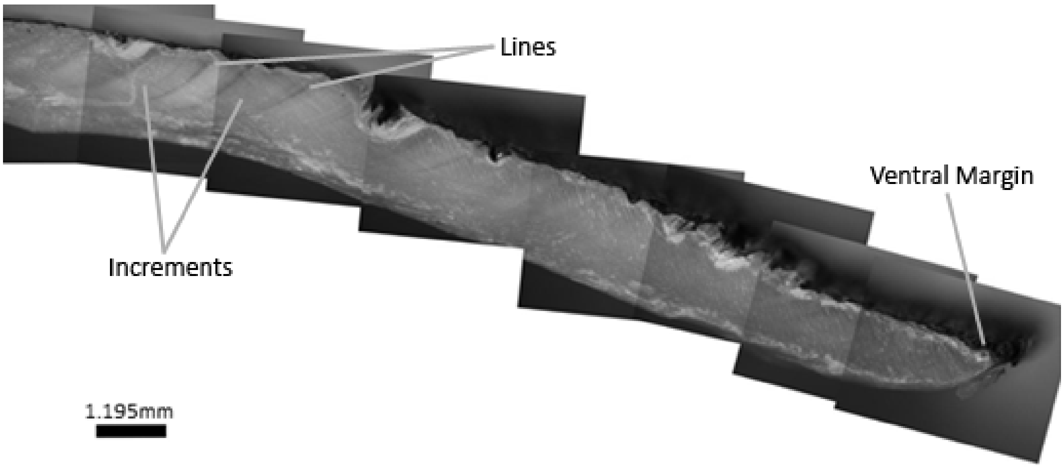

Figure 2.2 Growth lines and increments from a live-collected *Polymesoda coaxans* (adapted from Hinton 2012:33).

Early research concentrated on macroscopically visible growth features, applying visual and metric analysis (a process Deith (1983:425) termed ‘growth-line analysis’) to infer season of death and age of individuals (e.g. Coutts 1970; Deith 1983; Lightfoot and Cerrato 1988, 1989; Rowland 1977). Growth-line analysis protocols assumed that shell growth remained consistent between taxa as well as through time and space, except during the winter when lowered temperatures would cause growth to slow forming a distinctive ‘winter’ growth line (Monks 1981; Rhoads and Pannella 1970). Pairs consisting of a line and an increment were used to delineate annual cycles allowing counts to be employed as an estimate of age. Season of death was determined by measuring and dividing full years of growth into equal segments representing ‘seasons’ (Monks and Johnson 1993). As the final pair is often truncated by the death of the organism, the size disparity between it and the previous year’s growth was used to align the time of death to specific ‘seasons’ (Monks and Johnson 1993).

Recent high-resolution studies of shell growth regimes have revealed that growth-line analysis is overly simplistic as environmental stimuli do not produce uniform effects in molluscan growth, with distinct variability detected between taxa and through time and space (Bernstein 1990; Henry and Cerrato 2007; Jones and Quitmyer 1996). The wide variety of ecological zones inhabited by molluscs requires further consideration of interactions between shellfish and environmental conditions. For instance, tropical zones frequently experience more stable temperatures than temperate areas, meaning changes in growth may be attributable to other variables, including hydrological changes or availability of nutrients (Gillikin et al. 2005; Kennett and Voorhies 1996; Stephens and Rose 2005). Many researchers now consider the visual inspection of macroscopic growth features alone inadequate to accurately determine season of death or age (see Andrus 2011). Consequently, the study of macroscopic growth features has been repurposed with researchers employing them in conjunction with complementary finer-scaled techniques to provide temporal and spatial context for high-resolution analyses. As each growth structure represents a discrete period of time, growth features provide a physical framework that allows archaeologists to study isolated time-intervals at a variety of scales. Thus, researchers have begun employing this method when undertaking carbonate sampling for stable isotope analysis, allowing individual samples to be contextualised within a broader temporal setting while maintaining spatial control (e.g. Andrus and Rich 2008; Burchell et al. 2013a, 2013b; Elliot et al. 2003).

Researchers have begun testing the efficacy of utilising micro-growth features (Figure 2.3) to increase the accuracy and resolution of archaeological interpretation (e.g. Burchell et al. 2013a, 2013b; Custer and Doms 1990; Hallmann et al. 2009; Schöne et al. 2005a). Formed in a similar fashion to macroscopic banding, micro-growth features correspond to significantly shorter periods of time. While the timing and periodicity of micro-growth formation is primarily regulated by the biological clock of molluscs, tidal regimes may also be reflected (Mirzaei et al. 2014; Richardson 1987, 1988; Schöne 2008, 2013). When some intertidal molluscs are submerged during high tide shell precipitation is accelerated and a micro-growth increment is produced (Goodwin et al. 2001), as the tide subsides and the shellfish is aerially exposed growth slows forming a micro-growth line (Evans 1972). This process also causes physical discrepancies between tides with variable amplitudes (primarily neap and spring) owing to the amount of time the mollusc is exposed to the corresponding condition (Hallmann et al. 2009). Neap tides, which see reduced tidal variation, produce much broader increments and less defined micro-growth lines while the increased tidal amplitude associated with spring or king tides generate highly defined micro-growth lines and narrow increments (Hallmann et al. 2009). Provided attributes of the local tidal regime and target species are known, groupings of micro-growth features can be utilised as an exceptionally high-resolution expression of time allowing researchers to precisely characterise growth rates, differentiate regular and irregular growth stoppages, and when the date/time of capture are known, accurately align growth features to calendar dates (Burchell et al. 2013b; Carré et al. 2009; Hallmann et al. 2009).

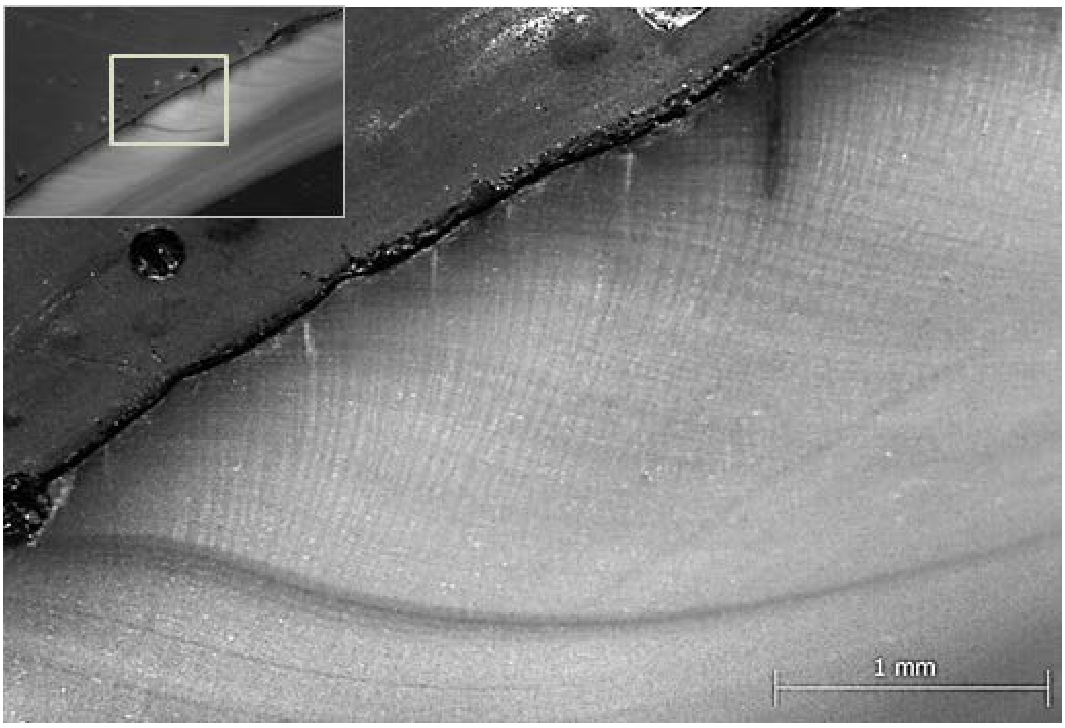

Figure 2.3 Micro-growth features in comparison to a larger macroscopic growth-line found in a *P. coaxans* valve live-collected from Bentinck Island, Gulf of Carpentaria, Australia.

2.3.2 Stable Isotope Analysis

Stable isotope analysis applies mass spectrometry to measure relative abundances of isotopes in carbonate samples extracted from accreting skeletal tissues. While both stable and unstable (radiogenic) isotopes are detected, this research focuses primarily on stable isotope analysis as they are of most use to palaeoenvironmental reconstruction. The resulting isotopic signals provide detailed information regarding modern and past environments, allowing archaeologists to approach higher-order interpretations of human-environment relationships. This method assumes that during growth shell calcium carbonates are imprinted with a chemical depiction of environmental conditions owing to changes in rates of isotopic fractionation and the isotopic composition of ambient water. Relative abundances of isotopes are expressed in delta notation (e.g. $\delta^{18}O$), a ratio of heavy isotopes (e.g. ^{18}O) to light isotopes (e.g. ^{16}O) measured against international reporting standards such as the Vienna Pee Dee Belemnite (VPDB). Due to the extremely small differences being described, delta values are reported as parts per mil (‰) variations from a standard with a defined value of 0‰. More positive values (e.g. $\delta^{18}O$ = +3.1‰) signify a higher ratio of heavier isotopes, while more negative values (e.g. $\delta^{18}O$ = -2.3‰) indicate a higher ratio of lighter isotopes (Fry 2006:22-23). The generation of delta values requires isotopic content of the material in question to be measured against an appropriate standard using Equation 2.1:

$$\delta(‰) = [(R_{sample} / R_{standard} - 1)] \times 1000 \qquad \text{(Equation 2.1)}$$

Where *R* is the ratio of the heavy-to-light isotopes, R_{sample} is the isotopic ratio of the sample being assessed, and $R_{standard}$ is the international standard (Epstein et al. 1953).

2.3.2.1 Oxygen Isotopes

Studies attempting to characterise past environments and population dynamics typically focus on analysing the relationship of oxygen isotope values in molluscan calcium carbonates ($\delta^{18}O_{shell}$) to environmental variation (Figure 2.4). As a majority of studied bivalves precipitate their shells near to oxygen isotopic equilibrium with ambient conditions (Mook and Vogel 1968), water temperature and composition act as primary controls on oxygen isotope fractionation between environment and shell. Variations in either are recorded chemically within the shell matrix. Temperature shares an inverse relationship with $\delta^{18}O_{shell}$, i.e. more negative values represent higher temperatures and vice versa (Epstein et al. 1953; Urey 1947), owing to a negative correlation between temperature and the fractionation process whereby every 4.34°C of temperature variation causes an approximately 1‰ change in $\delta^{18}O_{shell}$ values (Goodwin et al. 2001; Grossman and Ku 1986; Shackleton 1973). Conversely, the $\delta^{18}O$ of water – a function of evaporation, precipitation, terrestrial runoff, and water mixing (Bemis and Geary 1996; Dansgaard 1964) – shares a positive correlation with $\delta^{18}O_{shell}$. The process of evaporation or input of marine waters increases the $\delta^{18}O$ value of source water while simultaneously increasing the salinity of the environment (Bemis and Geary 1996). Conversely, influxes of freshwater, for example precipitation or run-off, simultaneously lower salinity and the $\delta^{18}O$ value of source water (Dansgaard 1964). However, it must be noted that while salinity and $\delta^{18}O$ frequently co-vary they are not directly linked and therefore interpreting any perceived association must be approached with caution.

In archaeological settings, variations in $\delta^{18}O_{shell}$ values are most commonly used to explore timing and periodicity of occupation. Pioneered by Shackleton (1973), this method takes advantage of the well-documented correlations between relative oxygen isotope abundances, temperature and water constitution to provide precise seasonal determinations (Böhm et al. 2000; Keith et al. 1964; McCrea 1950). As molluscs precipitate shell carbonate sequentially, the outer-most growth features formed most recently. Thus, oxygen isotope values procured from these structures potentially reflect the ambient environment at the time of the organism's death. These signals can be aligned to seasons via comparisons with modern control samples, generated using data from modern specimens, water samples, and observed environmental records, allowing an accurate determination of season of death/capture (Andrus 2011; Milner

2001). When applied throughout archaeological assemblages high-resolution histories of occupation can be generated, in some cases allowing researchers to approach higher-order interpretations of population dynamics including mobility and demography (Burchell et al. 2013a, 2013b, 2013c; McManus et al. 2013; Thompson and Andrus 2013).

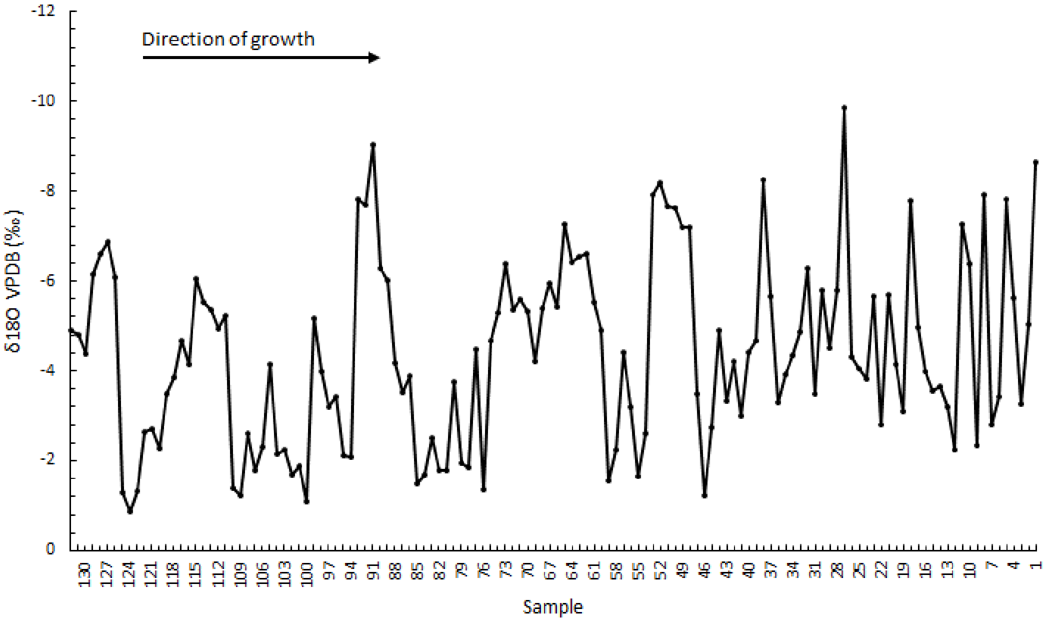

Figure 2.4 Oxygen isotope profiles of molluscs can provide insight into the environmental conditions experienced by the organism throughout its lifetime. Note the regular oscillations occurring throughout ontogeny of this *P. coaxans* valve. These can become increasingly difficult to interpret owing to increased crowding of growth structures through ontogeny, as seen in samples 1 – 12 of this specimen (adapted from Hinton 2012).

Mounting interest in increased archaeological resolution has led many researchers to apply these methods to gain nuanced understandings of human-environment interactions (e.g. Hallmann et al. 2013; Kennett and Voorhies 1995, 1996; Mannino et al. 2011), such as exploring links between intensity of shellfish harvest and seasonal shifts in environmental conditions (see Burchell et al. 2013b). It should be noted that many of these studies have been undertaken in temperate zones where significant oscillations in temperature are common between seasons (Kennett and Voorhies 1996). Tropical regions are subject to lower amplitude shifts in temperature, thus its impact on mollusc growth and chemistry is lessened. However, other environmental cycles that impact molluscan calcium carbonates, such as influxes of freshwater from monsoonal rainfall, frequently coincide with seasonal change in the tropics, generating an equally practical chemical record (see Hinton 2012; Kennett and Voorhies 1995, 1996; Stephens et al. 2008).

Due to the relationship between oxygen fractionation and temperature (Goodwin et al. 2001 report a 1‰ change in $\delta^{18}O_{shell}$ reliably equating to a 4.34˚C temperature variation), $\delta^{18}O$ values derived from carbonate are widely used as part of palaeotemperature modelling (e.g. Cornu et al. 1993; Goodwin et al. 2001; Prendergast et al. 2013; Urey et al. 1951). Carbonate samples are collected through shell ontogeny and resulting isotopic values are transformed into temperature estimates using palaeotemperature equations (see Grossman and Ku 1986). The relationship between temperature and $\delta^{18}O_{shell}$ values differ between calcium carbonate polymorphs (Böhm et al. 2000; Epstein et al. 1953; Grossman and Ku 1986). A majority of molluscan shells are formed from calcite, aragonite, or a combination of both (Claassen 1998:22; see Nehrke et al. 2012 for an example of molluscs and incorporate a third carbonate polymorph, vaterite), thus care must be taken to accurately identify the polymorph being analysed prior to applying equations (see Section 4.2 for further discussion). Variations in temperature can then be characterised over the life span of the mollusc.

This technique has been applied to long-lived organisms, such as corals or deep sea shellfish, to produce extended climate records (Cohen and Tyson 1995; Helama and Hood 2011; Schöne 2013), while shorter-lived taxa, such as foraminifera and molluscs, have been used to produce temporally constrained temperature estimates (Fenger et al. 2007; Jones and Kennett 1999; Mannino et al. 2008; Prendergast et al. 2013). Similar to dendrochronology, long-lived species can be used to generate master chronologies to extend records beyond the lifetime of a single organism via cross-dating techniques (e.g. Butler et al. 2010; Jones et al. 1989; Marchitto et al. 2000; Witbaard et al. 1997). However, equations associated with palaeotemperature reconstruction require precise knowledge of past local $\delta^{18}O_{water}$ values to produce accurate reconstructions (see Epstein et al. 1953; Grossman and Ku 1986; McCrea 1950). This proves problematic within archaeological contexts as data relating to ancient water sources are often unattainable, meaning the composition must be assumed or estimated, introducing an additional source of uncertainty and inaccuracy. Researchers are attempting to address this issue by exploring the efficacy of alternative means of temperature reconstruction such as clumped isotope analysis (see Ghosh et al. 2006, 2007; Schöne 2013). However, the slope of the associated regression line is very shallow, thus requiring large quantities of carbonate (~10 mg) to gain relatively accurate temperature determinations making it impractical in many situations.

As temperature and the isotopic value of ambient water are primary determinants of the oxygen isotope composition of calcium carbonates, the value of $\delta^{18}O_{shell}$ can vary as a function of changes in temperature, influxes of freshwater, or both. In regions with environmental shifts dominated by either temperature or water constitution, establishing causality between isotopic signals from the environment and carbonate is relatively simple. However, in areas subject to the dual influences of temperature and variable water mixing (e.g. estuarine systems or some tropical regions) disentangling these effects can be difficult, particularly with regards to archaeological material where environmental data are not independently known (Andrus and Thompson 2012; Culleton et al. 2009). Some authors have gone so far as to reject all material from such habitats, stating that their inherent complexities make them too difficult or inaccurate to analyse (e.g. Godfrey 1988; Milner 2001). However, a growing body of research has demonstrated the efficacy of utilising oxygen isotopes in areas with more complex temperature-water constitution relationships, particularly when supplemented with high-resolution growth feature analysis, comparative modern baselines, or further stable isotope analysis (Andrus and Crowe 2000; Burchell et al. 2013a, 2013b, 2013c; Jones et al. 2004, 2005; Kennett and Voorhies 1995; Kirby et al. 1998).

2.3.2.2 Carbon Isotopes

Stable carbon isotopes (^{12}C and ^{13}C; $\delta^{13}C$) are also useful to archaeological investigation. However, the parameters controlling carbon isotope fractionation are more complex than for oxygen, and as such are not employed as readily (Kirby et al. 1998; Wefer and Killingley 1980). Functions dictating carbon isotope fractionation cannot be attributed to a single control, such as temperature or water mixing. Instead the $\delta^{13}C$ value is derived from a mixture of environmental dissolved inorganic carbon (DIC) and metabolic CO_2, both of which fluctuate depending on season, community photosynthesis, respiration, and metabolism (Kennett and Voorhies 1995; Kirby et al. 1998; McConnaughey and Gillikin 2008). However, despite the complexities, cautious application of carbon isotopes can provide valuable information concerning biological cycling, vegetation type, water source, and/or diet (Geary et al. 1992; McConnaughey and Gillikin 2008; Petchey et al. 2012, 2013; Stephens et al. 2008).

A majority of the difficulties associated with interpreting carbon isotope signals are derived from chemical and physiological processes that occur during carbonate precipitation. While thought to be relatively uncommon in molluscan shell (McConnaughey and Gillikin 2008), kinetic effects can cause calcium carbonates to precipitate in disequilibrium with the ambient environment – meaning isotope values no longer reflect surrounding conditions. This is primarily a product of discrimination against ^{13}C (or ^{18}O) isotopes at higher rates of carbonate precipitation (McConnaughey 1989; Schöne and Surge 2012), making it likely only in exceptionally fast-growing sections of shell.

Molluscan $\delta^{13}C_{shell}$ values largely reflect ambient $\delta^{13}C$ values, providing chemical information regarding the environment in which the mollusc lived and grew (McConnaughey and Gillikin 2008; Schöne 2008). Some debate surrounds the amount of metabolic CO_2 incorporated into molluscan shell, particularly in detrital feeders and gastropods where large percentages (up to 85%) of shell carbonate can originate from metabolic carbon (Tanaka et al. 1986). This suggests that $\delta^{13}C_{shell}$ signals can be further complicated by carbon derived from diet, causing shell carbonate to enter a state of disequilibrium with the external environment (McConnaughey 1989). For this reason few archaeological studies utilise $\delta^{13}C$ values derived from gastropods as a source of information. Instead, researchers focus on filter-feeding bivalves that only incorporate a small fraction of respired CO_2 into their skeletal structures (Gillikin et al. 2006; McConnaughey and Gillikin 2008; Mook 1971; Mook and Vogel 1968). However, it must be remembered that even though the bulk of carbon may be derived from DIC, $\delta^{13}C_{shell}$ values are potentially altered by a variety of other stimuli, including environmental CO_2/O_2 ratios, DIC content, and physiology (see McConnaughey and Gillikin 2008).

In coastal contexts $\delta^{13}C$ values can assist in tracking shifts in salinity and water mixing. The $\delta^{13}C$ value of fluvial DIC, typically less than -8‰ although this can be highly variable, is often distinctly lower than marine DIC, typically -2‰, due largely to the decomposition of terrestrial plants and soil processes (Keith et al. 1964; Kennett and Voorhies 1995; McConnaughey and Gillikin 2008). Thus, $\delta^{13}C$ values potentially replicate the mixture of marine and fluvial DIC in a positive correlation, i.e. the greater the marine influence the more positive the $\delta^{13}C$ value (Gillikin et al. 2006; Mook and Vogel 1968). When used in conjunction with $\delta^{18}O$ a more precise depiction of mixing regimes is established (McConnaughey and Gillikin 2008), assisting researchers in delineating the dual effects of water constitution and temperature and increasing the accuracy of seasonal determinations (Andrus and Crowe 2000).

2.4 Challenges Associated with Applying Sclerochronology to Archaeological Contexts

A number of methodological and discipline-specific challenges face archaeologists who seek to integrate sclerochronological analyses of molluscs into methodological frameworks. Not only is it essential to possess a sophisticated understanding of the techniques being employed but also of localised environmental cycles and conditions, taxa and location-specific relationships between growth and environmental conditions, the use of appropriate sampling procedures and methods to maintain temporal and spatial control, and the effects of post-depositional alteration on the accuracy and validity of data.

To contextualise these challenges within a ‘real world’ research setting, two recent studies investigating palaeoenvironmental conditions in areas exhibiting complex environmental and hydrological cycles are employed below as examples where appropriate. Both studies examine a combination of modern and archaeological material to characterise environmental conditions in regions affected by strong monsoonal cycles. Hinton (2012) explores the efficacy of archaeological *Polymesoda* (*Gelonia*) *coaxans* (Gmelin, 1971) as palaeoenvironmental proxies for the South Wellesley Islands, Gulf of Carpentaria, Australia, while Stephens et al. (2008) utilises *P. coaxans* (although it is referred to by Stephens et al. (2008) by its synonym *Gelonia erosa*) as a palaeoenvironmental proxy for the area surrounding the Great Cave of Niah in Borneo, Malaysia.

2.4.1 Understanding Localised Environmental Impacts on Shellfish

The phylum Mollusca is highly diverse, consisting of approximately 85,000 extant species that inhabit a wide variety of geographic locations and climate zones. Such diversity makes it likely that shellfish taxa display unique responses to environmental stimuli owing to variable ecological tolerances. Thus, gaining detailed understandings of local environmental conditions and how they impact growth regimes and isotopic fractionation of relevant shellfish taxa is integral to accurate and meaningful sclerochronological analysis. While some differences may be obvious owing to distinct physiological or morphological attributes – e.g. bivalves/gastropods and filter/detritus feeders often produce divergent isotopic signals owing to dietary uptake – others are less so.

Recent high-resolution studies of molluscan growth regimes have characterised intra-species differences in rates of shell precipitation through time and space, demonstrating that oscillations in temperature and water composition can have inconsistent effects on the growth regimes of geographically distinct populations (Bernstein 1990; Henry and Cerrato 2007; Jones and Quitmyer 1996). Moreover, Hallmann et al. (2008) and Gillikin et al. (2005) have demonstrated that individuals from the same population can produce variable isotopic signals, suggesting that this may be indicative of micro-habitat variability or differences in exchange rates between the outer extrapallial fluid (EPF) and the ambient water. Broader species-dependent growth variability has also been documented (e.g. Carré et al. 2005a). These findings add a further layer of complexity to the application of sclerochronology making it essential to treat shellfish populations independently as there is no guarantee as to how the ambient environment will have affected molluscs in that environment. Thus, characterising local environments and establishing their effects on target shellfish taxa is integral to accurately interpreting sclerochronological data.

Establishing causality between modern environmental cycles and the growth regimes and isotopic fractionation of local shellfish populations also plays a vital role in securing meaningful interpretations derived from archaeological material. Although research employing sclerochronology to characterise palaeoenvironments and their effects on human behaviour is largely evidenced by isotopic signals and growth patterning of archaeological material, a contextual framework must be established to accurately parse this information (Andrus 2011; Jones and Quitmyer 1996; Mannino et al. 2003; Milner 2001). Without comparative data, results derived from archaeological material become difficult to accurately interpret.

Many studies have addressed these challenges through monitoring modern environments and shellfish populations in the vicinity of relevant archaeological settings. This not only provides researchers with an understanding of environmental cycles and their effect on target mollusc taxa but also establishes modern baselines that can be used to contextualise archaeological data. While environmental monitoring can take many forms, it often includes one or a combination of the following: water sampling for salinity, $\delta^{18}O_{water}$ and $\delta^{13}C_{DIC}$ values over discrete environmental cycles (tidal, seasonal, or annual) (Andrus and Rich 2008), live-collection and analysis of modern shellfish specimens (Hallmann et al. 2009), recording the ambient environment for temperature, tidal height and salinity (manually or via installing environmental sensors) (Andrus and Crowe 2000; Hallmann et al. 2008), and incorporating third-party observation records (Hinton 2012; Stephens et al. 2008). Ideally, all of these methods would be deployed to generate the most accurate picture of the local environment possible, however the remote nature of some archaeological research sites coupled with time and budget constraints often makes this difficult to achieve. These same restrictions affect the viability of long-term monitoring regimes making it difficult to characterise annual and inter-annual variability.

Archaeologists often address these limitations by employing environmental modelling techniques in order to reconstruct aspects of the modern environment they were unable to directly observe. Equations which employ environmental data (such as sea surface temperature or rainfall records) in combination with isotopic signals from modern live-collected shell specimens or ambient water sources are commonly used to generate predictive models of fractionation factors (Dettman et al. 1999; Grossman and Ku 1986), $\delta^{18}O_{shell}$ (Grossman and Ku 1986; Prendergast et al. 2013) and $\delta^{18}O_{water}$ values (Dettman et al. 1999). Researchers utilise predictive data to proxy missing environmental records (Hinton 2012) and cross-calibrate ambient conditions with physical and chemical characteristics of molluscan shell (Goodwin et al. 2001). Following collection, modelling and analysis, data taken from environmental, sclerochronological sources can be aligned to calendrical dates allowing causality between environmental controls, molluscan growth, and isotopic signals to be characterised (e.g. Andrus and Crowe 2000; Hallmann et al. 2008). This serves as the comparative baseline analogue allowing the accurate interpretation of archaeological data.

Both Hinton (2012) and Stephens et al. (2008) undertook minimal environmental monitoring, instead relying upon third-party environmental records as the basis for modelling and comparisons. The monitoring that did occur took the form of nominal water sampling. Stephens et al. (2008) collected water samples from throughout the target river system over the period of a single day (see Stephens and Rose 2005 for a detailed account of sampling). While this affords geographically extensive knowledge of hydrological conditions throughout the region, it only provides a temporally limited snapshot. Furthermore, no comparisons are drawn between the isotopic signature of the river water and isotope values derived from shell carbonate – likely owing to the temporally restricted nature of the sampling regime. Instead, carbonate samples are matched to observed rainfall records, assuming the impacts of changing water constitution. While these records appear to mesh well, the accuracy of these results cannot be verified without direct evidence of *P. coaxans* response to localised changes in environmental conditions.

Hinton (2012:58) incorporated three water samples in order to 'provide a basic dry-season estuarine isotopic water composition value'. Two samples were taken at the collection site of modern *P. coaxans* at an interval of one month, the third was collected from the mouth of an adjacent creek system to provide an estimate of intra-creek variability. Akin to Stephens et al. (2008), the limited scope of sampling makes comparisons between environment and isotopic values of shell carbonate difficult. To overcome this Hinton (2012) undertook environmental modelling to estimate $\delta^{18}O_{water}$ values from observed environmental data, allowing the generation of a predictive $\delta^{18}O_{shell}$ curve for comparison with isotopic profiles derived from modern specimens. While mathematical modelling does not provide data as accurate or nuanced as direct repeated water sampling, it does allow cautious interpretations of molluscan responses to environmental conditions. Hinton (2012) acknowledges that the limited water sampling may have impacted the scope of interpretation, recommending more intensive sampling for future research to afford increased accuracy and nuance in understandings of interactions between *P. coaxans* and local environmental conditions.

2.4.2 Addressing Post-Depositional Alteration to Carbonate

Issues associated with post-depositional, taphonomic and site formation processes present significant challenges to all archaeological research. The interpretation of coastal sites in particular is often considered extremely complex owing to uncertainties relating to site preservation and post-depositional factors which may distort the archaeological record (Bird 1992, 1995; O'Connor and Sullivan 1994b; Rowland 1992; Rowland and Ulm 2012). While shell-rich features regularly provide excellent preservation conditions for constituent components – raised pH levels and layers of robust shell provide protection for delicate material (Andrus 2011) – damage or change stemming from post-depositional processes can lead to alteration of geochemical and physical elements of the shell itself effecting the accuracy of stable isotope analysis. Molluscan shell is particularly sensitive to modifications that lead to fragmentation, chemical alteration from contact with percolating ground waters, and recrystallisation (Bailey et al. 1983; Kennett and Voorhies 1996; Shackleton 1973).

Taphonomic processes can weaken the structural integrity of shell increasing its susceptibility to fracture and fragmentation (Robins and Stock 1990). While a majority of archaeological shell deposits are subject to some degree of fragmentation, stable isotope studies have largely focused on analysing whole valves (e.g. Gillikin et al. 2005; Mannino et al. 2007; Shackleton 1973). This practice can severely limit specimen selection in assemblages which have undergone extensive fragmentation and may subsequently introduce biases and inaccuracies owing to under- or over-representation of taxa. The apparent reluctance to incorporate fragmented material likely stems from an uncertainty regarding the efficacy of this practice and concerns of isotopic inhomogeneity between varying portions of shell (Kingston et al. 2008). However, a growing body of research is exploring the value of fragmented material, suggesting that high-resolution data are attainable from fragmented assemblages provided caution is exercised when selecting sample material (Burchell et al. 2013a, 2013b; Hallmann et al. 2013; Kingston et al. 2008).

Percolating ground waters, often originating from meteoric water, can chemically alter skeletal structures. Shell that has suffered structural damage or dissolution is particularly susceptible. Oxygen isotope exchange between the two can leave shell carbonate isotopically lighter owing to an abundance of ^{16}O in meteoric water (Bailey et al. 1983; Killingley 1981). Thus, isotopic signals derived from molluscan shell that come into contact with percolating ground water may no longer be representative of the environment in which it grew.

As previously discussed, crystalline forms of a majority of molluscan carbonate are comprised of aragonite, calcite, or a combination of both (Claassen 1998:22). Exposure to temperatures of approximately 150°C will cause the organic matrix, on which the crystalline structure is built (Marin and Luquet 2004; Wilt et al. 2003), to break down and the crystal structure to expand (Collins 2012). As temperatures near 350°C aragonitic structures begin to invert or recrystallise into the more stable polymorph calcite, with complete conversion occurring at approximately 500°C (Collins 2012; Epstein et al. 1953). This change compromises the integrity of geochemical signals derived from the shell and significantly diminishes the accuracy of palaeoenvironmental determinations. As these temperatures are commonly exceeded by hunter-gatherer campfires (Robins and Stock 1990), pre-depositional human activities, such as cooking, discard practices, and reuse of cooking or campfire sites, may lead to recrystallisation. Thus, archaeologists must thoroughly examine and test all potential material for signs of recrystallisation prior to undertaking further analysis.

While modern comparative analogues can assist in evaluating the isotopic integrity of archaeological material (Kennett and Voorhies 1996), particularly in cases where contact with meteoric water is suspected, further steps must be taken in order to ameliorate results from latent inaccuracies associated with post-depositional change. A number of issues can be countered through careful selection of material using criteria suggested by Burchell et al. (2013b:262): 1) a portion of the ventral margin must be intact and preserved; 2) the upper shell layer must be intact and preserved; 3) absence of evidence indicating exposure to fire, e.g. burnt portions of shell or association within a hearth feature; and 4) size of the fragment is sufficient to provide an adequate sample of growth. However, further measures must be taken in order to ensure specimens are not affected by recrystallisation. Thus, it has become common practice for analysts to subject material to X-ray diffraction (XRD), fourier transformation infrared spectroscopy (FTIR), cathodoluminescence or element chemical analyses, raman spectroscopy, or Feigel's solution to determine the crystalline structure (aragonite or calcite) and assess the potential of recrystallisation prior to undertaking further analysis (e.g. Balmain et al. 1999; Burchell et al. 2013b; Fenger 2006; Friedman 1959; Goewert and Surge 2008; Hawkes et al. 1996; Kennett and Voorhies 1996; Petchey et al. 2013).

2.4.3 High-Resolution Sampling

An integral, yet often overlooked, step in stable isotope analysis is the extraction of calcium carbonates from target material. This process not only provides carbonate samples required for isotopic analysis but also plays a significant role in dictating the resolution and accuracy of resulting data. In molluscan shell, macro- and micro-growth structures provide a physical framework that facilitates the study of discrete time-scales ranging in length from sub-daily to annual (Hallmann et al. 2013). However, access to this high-resolution archive is limited by the techniques and technology employed to gather and analyse carbonate samples. Inherent limitations can lead to decreases in attainable resolution and generation of ambiguous results.

Among these, the notion of time-averaging is the most prevalent issue faced by researchers attempting to define discrete isotopic signals from accreting skeletal tissues (Goodwin et al. 2004a).

Time-averaging refers to the homogenisation or dampening of isotopic signals owing to differences in the period of time represented by individual samples. Isotopic analysis of calcium carbonates using mass spectrometry requires powder samples to attain a minimum weight, dependent on the instrument being used, in order to produce an accurate signal (Merritt and Hayes 1994). As growth features in molluscan shell are often tightly spaced, especially micro-growth structures, researchers often find it necessary to utilise samples that represent more than a single point in time, sometimes stretching over multiple growth features. Eerkens et al. (2013) estimated that due to variability in growth rates a majority of their carbonate samples represented anywhere between one and four months of growth. Variations during this period are lost as delta values only represent an average of isotopic composition. Loss of extreme signals through smoothing is especially pertinent to studies modelling palaeotemperatures, where $\delta^{18}O$ values are used as a conversion variable to estimate temperature (see Grossman and Ku 1986). As a 1.0‰ change in $\delta^{18}O$ reliably equates to a 4.34°C variation in temperature (Goodwin et al. 2001; Grossman and Ku 1986), time-averaging has the potential to significantly alter results.

Changes in the rate of shell precipitation stemming from ontogenetic age can also lead to large differences in represented time, for instance samples from ontogenetically older sections of shell frequently correspond to larger time-slices due to slower precipitation causing the compaction of growth features (Burchell et al. 2013a, 2013b). Size of the individual can produce similar patterns of shell formation, with larger mollusc species often exhibiting wider growth features and condensed lines and increments being common in smaller species. Consequently, appropriate sampling regimes must be selected in order to attain adequate resolution and ameliorate datasets from latent inaccuracies.

A review of the literature reveals a pattern of inadequate or inappropriate sampling techniques, which has potentially perpetuated issues associated with time-averaging. Specifically, studies that collect samples at arbitrary distributions (usually 0.5 – 2mm) are of the greatest concern (e.g. Aguirre et al. 1998; Bailey et al. 1983; Brockwell et al. 2013; Culleton et al. 2009; Kennett and Voorhies 1995, 1996). Arbitrarily spaced sampling can facilitate the latent mixing of seasonally derived growth features within individual samples, potentially introducing inaccuracies which may significantly alter interpretations. This issue is frequently exacerbated by the application of unsuitable sample extraction procedures.

The studies cited above utilise micro-drilling, a process in which a dentist's drill, or similar, is used to bore precise vertical holes at predetermined locations across the exterior or cross-section of a shell. The precision of these samples is constrained by the size of the drill bit, making it difficult to sample tightly spaced growth features (Wurster et al. 1999). Moreover, as carbonates are often sampled at intervals, arbitrary or otherwise, associated isotopic profiles are only representative of a series of snapshots taken through ontogeny with no information regarding the intervening time. Numerous studies have conducted comparisons between micro-drilling and other comparable, although potentially higher-resolution, carbonate extraction methods. In particular, Spötl and Mattey (2006:53-54) demonstrated that while both high- and low-resolution techniques can provide insight into environmental oscillations, micro-drilling failed to characterise several features and smoothed peak delta values by up to 1.5‰. This is not to suggest that micro-drilling should be dismissed out of hand, particularly as it has been applied effectively as part of recent archaeological studies (e.g. Burchell et al. 2013a, 2013b), rather it should be seen as an example of the considerations that must be made when undertaking stable isotope analysis. Yet, few studies actively address or acknowledge the potential issues associated with sampling, meaning broad inaccuracies may be present throughout the literature.

Recent technological and methodological advances permit researchers to mitigate some of the issues stemming from time-averaging through high-resolution data recovery. Micro-milling allows greater spatial and temporal control to be maintained over sampling (Wurster et al. 1999). High temporal resolution is achieved by sampling from a series of transects placed parallel to growth structures using a computer-assisted rig (Figure 2.5) (Andrus and Rich 2008; Hinton 2012; Spötl and Mattey 2006; Wurster et al. 1999). This allows for an uninterrupted record of the shell's growth history to be obtained while simultaneously minimising the effects of time-averaging (Burchell et al. 2013b; Goodwin et al. 2004a). Researchers have recently begun applying micro-milling in conjunction with micro-growth feature analysis to great effect, generating high-resolution reconstructions of palaeoenvironments (Carré et al. 2005a; Goodwin et al. 2001, 2003) and determinations of seasonal site use (Burchell et al. 2013a, 2013b, 2013c; Hallmann et al. 2009, 2013). It should be noted that micro-milling is not entirely immune to the effects of time-averaging with resolution still constrained by the size of the drill bit, although to a lesser extent than micro-drilling. Further, minimum sample weights required for mass spectrometry frequently leads to material from multiple adjacent transects being combined to produce a viable sample (e.g. Hanson et al. 2010). The destructive nature of powder sampling, both micro-milling and -drilling, is also problematic as it prevents multiple analyses from being undertaken on individuals and, in the case of archaeological material, damages often irreplaceable specimens.

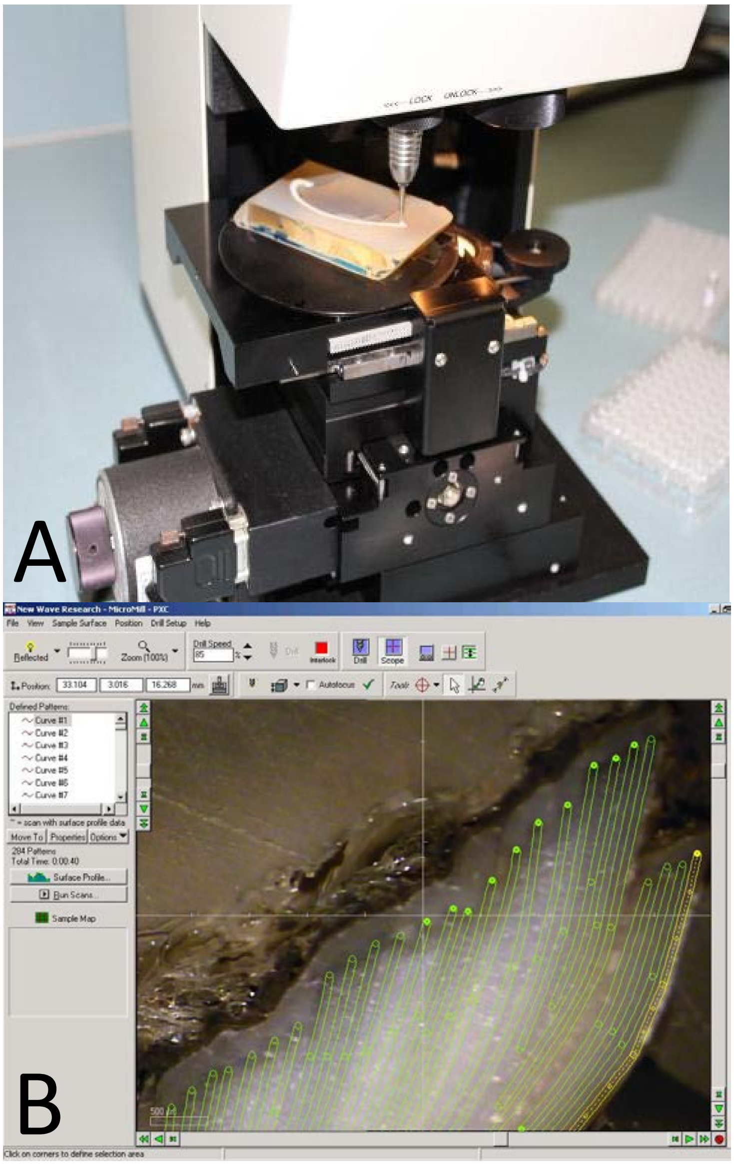

Figure 2.5 (A) Computer-assisted NewWave MicroMill system. (B) Digitised scan lines in preparation for micro-milling (adapted from Hinton 2012:53-54).

To further counter issues associated with time-averaging as well as the destructive nature of carbonate powder collection, the efficacy of applying secondary ion mass spectrometry (SIMS), another high-resolution geochemical analysis technique, to stable isotope studies has been explored (e.g. Hanson et al. 2010; Weidel et al. 2007). SIMS works on the principle that charged particles (secondary ions) are ejected from a sample surface when bombarded by a beam of heavy particles (Griffiths 2008). This occurs in vacuum allowing the secondary ions to be channelled into a mass spectrometer for analysis. The size and intensity of the beam can be adjusted allowing for very precise sampling that inflicts very little damage to the specimen, spot sizes are often 10-15µm in diameter and 2-3µm in depth (Hanson et al. 2010; Weidel et al. 2007). Comparisons between SIMS and micro-milling used in conjunction with continuous flow isotope ratio mass spectrometry (CF-IRMS) have revealed that while micro-milling/CF-IRMS provide better precision, SIMS allows for greater temporal resolution (Hanson et al. 2010). While SIMS holds great potential for the generation of exceptionally detailed isotope profiles, for a majority of researchers, micro-mills/drills remain more accessible and, provided methods have been properly tailored to approaching research questions, are more than capable of producing data at an appropriate resolution.

Comparisons between Stephens et al. (2008) and Hinton (2012) illustrate the impact different sampling methods can have on dataset accuracy. Stephens et al. (2008) utilised laser ablation which employs a focused laser to liberate CO_2 from carbonates either in a vacuum (or helium), the gas is then led directly into a mass spectrometer allowing rapid *in situ* analysis of material (Smalley et al. 1989). However, laser ablation does not provide the resolution attainable by micro-milling or even micro-drilling (see Spötl and Mattey 2006 for a comparison of the techniques). Heat produced by the laser creates a thermal halo around each ablation point limiting how tightly samples can be spaced and potentially altering the chemical composition of adjacent carbonates (Spötl and Mattey 2006; Stephens et al. 2008). This not only decreases precision and attainable resolution but also the amount of shell that can be analysed. Stephens et al. (2008) were forced to truncate sampling as growth features became too closely spaced to ensure individual growth structures were sampled. Conversely, Hinton (2012) employed micro-milling, enabling a continuous profile of modern and archaeological material to be generated. While this higher resolution data depicted a seasonally derived 'saw-tooth' pattern comparable to that found in the material analysed by Stephen et al., previously absent extreme amplitude changes were characterised. However, it is important to reiterate is that no sampling strategy is objectively better (or worse) than any other, rather that methodologies selected to complement research questions will provide more accurate and meaningful interpretations.

2.5 Fundamental Considerations for Archaeological Sclerochronology

Sclerochronological analyses provide unique opportunities for archaeologists to recover data at a resolution that is unattainable using more traditional methods. While the application of these techniques to archaeological contexts has seen increasing interest over recent years, basic limitations appear throughout the literature. Although the fundamental methodologies driving sclerochronology are well established, their incorporation into archaeological investigations is still a relatively new concept. Consequently, with a few recent exceptions, research applications are often underdeveloped. Recent practical and methodological advances potentially afford substantial increases in the attainable resolution and accuracy of data collection and analysis, yet these practices are rarely deployed. Thus, this research outlines a series of recommendations that aim to increase the accuracy and validity of interpretations reached through the application of sclerochronology to archaeological material:

1. *Establish high-resolution localised environmental records to contextualise archaeological data*

The importance of contextualising archaeological data against a localised framework of environmental conditions has been demonstrated by numerous studies documenting varying intra- and inter-regional environmental conditions and their impact on mollusc carbonate precipitation and fractionation (Bernstein 1990; Gillikin et al. 2005; Hallmann et al. 2008; Henry and Cerrato 2007; Jones and Quitmyer 1996). Yet, many researchers continue to rely upon regionally-scaled environmental data or extrapolate local data across geographic boundaries (e.g. Brockwell et al. 2013). This normative practice distorts any interpretation of the archaeological record as it assumes uniform conditions and responses across landscapes and populations that may be substantially different (Claassen 1991). Thus, an increasing number of publications suggest that in order to reach meaningful interpretations of human-environment interactions the archaeological record must be contextualised within a framework of local palaeoenvironmental conditions (e.g. Ulm 2013; White 2011).

If archaeologists are to approach the sophisticated interpretations of past human-environment relationships possible through sclerochronology, the emphasis placed on establishing detailed understandings of local environmental conditions must be substantially increased. While the very nature of data generated through sclerochronology provides the foundations for localised environmental records, it is up to researchers to acknowledge its importance and incorporate it into interpretative frameworks. Yet, few published studies devote adequate time to discussing modern analogues and their use in conjunction with archaeological material. Increased transparency of these processes would better illustrate the advantages of including localised environmental information as the basis for archaeological interpretation, allowing researchers to make increasingly informed decisions regarding methodological choices.

2. *Incorporate appropriate sample sizes to reduce costs and ensure accuracy*

While employing sclerochronology allows the generation of high-resolution datasets, the application of these techniques can be a time consuming, laborious, and expensive process. Researchers often commit significant resources to analysing large quantities of growth features as well as extracting and processing hundreds if not thousands of powder samples per assemblage (e.g. Burchell 2013:18). While numerous aids have been developed to assist in the rapid assessment of growth features, including acetate peels (Pannella and Copeland 1968) and staining solutions (Schöne et al. 2005b), carbonate sampling and analysis remains costly. Thus, commissioning the analysis of large collections can prove to be prohibitively expensive, particularly for researchers whose institutions lack the necessary equipment or expertise required for in-house processing.

In order to minimise costs, researchers frequently undertake rigorous analysis on a limited number of specimens, particularly modern material where it is common for only a handful of individuals to be assessed (e.g. Brockwell et al. 2013; Jew et al. 2013; Stephens et al. 2008). Although high-resolution data is gathered from these specimens, it is unlikely that the results are representative of broader trajectories owing to widely documented variability in local environments and intra- and inter-population responses to environmental conditions (Bernstein 1990; Gillikin et al. 2005; Hallmann et al. 2008; Henry and Cerrato 2007; Jones and Quitmyer 1996). As interpretations of isotopic signals recovered from archaeological material rely on modern contextual data, limited sample sizes of modern specimens can lead to the introduction of latent biases and inaccuracies to archaeological interpretations. Thus, robust modern analogues cannot be sacrificed to minimise costs.

This research posits that the incorporation of strong contextual foundations, which draw upon broad modern collections, not only allow significantly more accurate and meaningful archaeological interpretations but potentially reduce time and budgetary strain. Archaeological material is often heavily analysed with some researchers proposing that a series of samples per specimen is required to provide an adequate proxy for seasonal variation (Andrus and Crowe 2000; Mannino et al. 2003). While this is true for studies attempting to approach detailed palaeoenvironmental reconstructions or generate master chronologies, it is not necessary to maintain this resolution to address many other research questions – for example season of capture determinations only require targeted analysis of the ventral margin and adjacent areas (Culleton et al. 2009; Kennett and Voorhies 1996). In light of this, more robust understandings of modern environments and the impacts they have on contemporary shellfish populations may, in some cases, allow archaeologists to reduce the number of samples required from archaeological specimens, thus minimising cost and allowing larger archaeological assemblages to be analysed.

3. Select powder sampling methods suitable to research aims

Powder sampling regimes play a significant role in dictating the accuracy and resolution of stable isotope results. While micro-milling affords the highest available resolution it is also the most expensive and time-consuming, requiring the extraction and analysis of large quantities of carbonate samples. Micro-drilling requires less processing and analysis time owing to significantly fewer samples extracted from each specimen (Spötl and Mattey 2006), while laser ablation allows *in situ* analysis of material (Stephens et al. 2008). However, in their current states these methods are unable to match the fine scale analysis of micro-milling (Spötl and Mattey 2006), often lead to latent inaccuracies through time-averaging (Eerkens et al. 2013), and can limit the extent to which specimens can be analysed (Stephens et al. 2008). While newer methods, such as SIMS, produce exceptionally high-resolution isotope profiles and are significantly less destructive to the specimen, the equipment and expertise required is not yet widely available (Hanson et al. 2010). Thus, until methods exhibiting increased expediency and attainable resolution are accessible, a balance must be struck between cost and the accuracy or resolution required to address designated research questions.

A rarely considered solution to this involves deploying a combination of sampling regimes. Burchell et al. (2013a, 2013b, 2013c) applied both micro-milling and micro-drilling to analyse *Saxidomus gigantea* specimens. Micro-milling was undertaken at the ventral margin and adjacent areas where growth was found to have slowed significantly, while micro-drilling is utilised in shell portions exhibiting faster growth. This sampling regime was altered on a specimen-by-specimen basis to account for varying size and ontogenetic age. By employing this joint methodology Burchell et al. (2013a, 2013b, 2013c) were able to generate the high-resolution data required for accurate seasonality determinations, while minimising the cost of sampling extensive archaeological assemblages over multiple annual cycles. However, it must be noted that the validity of this methodology may not extend to other studies as it is highly tuned to the morphology of the target taxa. Previous studies provided extensive knowledge of local environmental cycles and their effects on constituent *S. gigantea* populations (see Gillikin et al. 2005; Hallmann et al. 2009). Furthermore, the research undertaken by Burchell et al. (2013a, 2013b, 2013c) focuses on determining the season of capture of archaeological shellfish, meaning precise isotopic analysis was only required at the ventral margin and adjacent areas. Research attempting more extensive palaeoenvironmental reconstruction may require a higher-resolution sampling regime throughout ontogeny. Nevertheless, these studies demonstrate how methodologies can be tuned to minimise time and financial costs while still meeting research parameters and generating meaningful interpretations.

4. *Utilise datasets generated by complementary techniques to contextualise ambiguous results*

While sclerochronology provides information essential to advancing interpretations of past environments and their impacts on human behaviours, these techniques sometimes require supplemental datasets to further contextualise results. For example, comparative data would assist in alleviating difficulties associated with oxygen isotope signals in regions subject to the dual influences of temperature and water constitution (see Andrus and Thompson 2012; Culleton et al. 2009), as well as those stemming from palaeotemperature equations requiring precise knowledge of $\delta^{18}O_{water}$ (see Epstein et al. 1953; Grossman and Ku 1986; McCrea 1950). Incorporating complementary techniques, such as trace element analysis and clumped isotope thermometry, may significantly increase the accuracy of palaeoenvironmental determinations. It must be noted however, that these techniques require further development before they can provide meaningful datasets.

2.6 Summary

The application of high-resolution data recovery techniques has become a fundamental component of broader archaeological frameworks focused on the investigation of human-environment relationships. Palaeoenvironmental proxies derived from archaeological deposits provide information relating to localised conditions and act as a direct link between environment and human behaviour. The fine scale datasets derived from these contexts afford the opportunity for archaeologists to approach more detailed characterisations of environmental conditions within temporally and spatially constrained frameworks. This in-turn informs more nuanced interpretations of the interactions between the environment, culture and human decision-making processes, allowing higher-order questions to be addressed. As a result, techniques such as sclerochronology are increasingly deployed in an attempt to increase archaeological resolution and approach better interpretations. However, as with all novel methodologies it is essential to understand and acknowledge their complexities and limitations along with their advantages. In doing so researchers are able to unlock the full potential of these techniques while ameliorating results from a myriad of latent inaccuracies and biases.

Yet, the literature reveals that these challenges are often not met with the degree of thoughtfulness required to adequately address them. Instead they are often dismissed or ignored altogether. The effects of inappropriate methodology can be seen through the loss of important data and the introduction of a variety of uncertainties relating to the accuracy and validity of results. However, these challenges should not dissuade the use of sclerochronology, it should instead encourage researchers to take care in building methodological frameworks and understand the implications of those decisions. Provided appropriate precautions are taken sclerochronology offers a unique opportunity, enabling archaeologists to gain understandings of fundamental controls that assisted in structuring the everyday lives of past human populations and characterise the impacts of these decision-making processes.

Chapter 3 Environmental and Cultural Background to the South Wellesley Islands

3.1 Introduction

Human decision-making processes are underpinned by a continuous dialogue between environment and culture that shapes numerous aspects of our lifeways. Such interactions are especially salient to characterising and interpreting short-term patterns, such as seasonally-modulated behavioural change as well as shifts in occupation and land-use. Thus, understandings of local environmental and cultural systems provide the contextual frameworks within which archaeological evidence can be integrated. This bolsters the validity and accuracy of interpretation, particularly in coastal regions where the interplay between environment, culture, and human behaviour is frequently typified by complexity and variability (Rowland and Ulm 2012). Moreover, researchers are increasingly advocating the importance of local land formation processes and palaeoenvironmental conditions (e.g. Rosendahl 2012), factors that may well be of significance in defining behaviour. The South Wellesley Islands provide an ideal context in which to explore interactions between human behaviour, environment, and culture owing to their secure chronology, relative isolation, and variability evidenced within environmental and climatic cycles. To this end, this chapter explores the physical and cultural background of the South Wellesley Islands with a focus on the mid-to-late Holocene to contextualise discussion and interpretation found in later chapters.

3.2 Physical Setting

Prior to the terminal Pleistocene, what is now known as the Gulf of Carpentaria was dominated by low-lying plains that connected modern day Australia and New Guinea to form the continental landmass of Sahul. Deglaciation following the last glacial maximum (LGM) caused a significant rise in sea levels (Chivas et al. 2001; Lewis et al. 2013; Reeves et al. 2007), eventually breeching the Arafura (c.14,000 BP) and Torresian (c.9000 BP) sills before inundating the Gulf region. After reaching their peak during the mid-Holocene (Chappell et al. 1982; Rhodes et al. 1980; Sloss et al. 2015), sea levels began to recede and stabilise leaving the Gulf of Carpentaria as an epicontinental sea positioned between Australia and New Guinea (Figure 3.1). Encompassing latitudes 10° to 17°30ˈ south and longitudes 135°30ˈ and 142° east, this region is framed by New Guinea in the north, Cape York in the east, the Carpentaria Plain in the south, and Arnhem Land in the west. Today, the Gulf is characterised by prograded shorelines with numerous islands and archipelagos scattered along its continental margins, including the Torres Strait Islands, Wellesley Islands, Sir Edward Pellew Group, and Groote Eylandt.

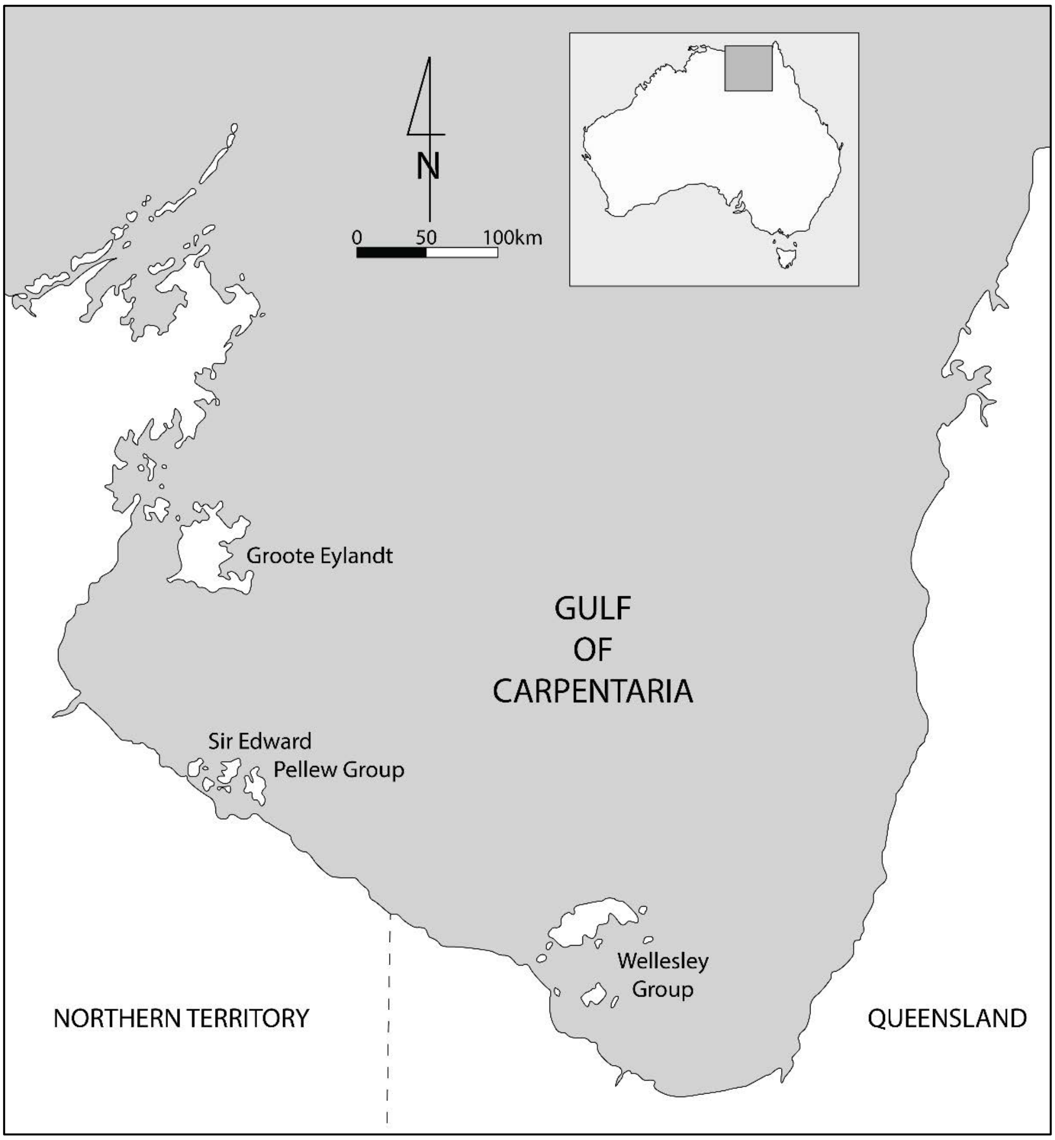

Figure 3.1 The post-transgression Gulf of Carpentaria has multiple island groups scattered along its coastal margins.

The Wellesley Island group is located in the southern Gulf, covering a 5500km^2 area that encompasses 23 variably sized islands as well as numerous reefs and sandy cays (Figure 3.2). The core islands are seaward extensions of the Normanton lateritic formation comprised of an eroded sandy lateritic surface with little relief (Grimes 1979). Initial island formation occurred between 6500 – 8000 years ago as sea levels rose to isolate high formations from mainland Australia (Holt 2005; Reeves et al. 2007, 2008). Divided geographically into north and south groups, an approximate 30km minimum open water crossing separates the two regions. Mornington Island (966.5km^2) dominates the North Wellesley Archipelago, which also encompasses a number of smaller satellite islands – Sydney, Wallaby, Pisonia, North and South

Bountiful, Rocky, and Manowar. Similarly, the South Wellesley group consists of a single large island, Bentinck (143.7km^2), bordered by a series of smaller landmasses – Sweers, Fowler, Albinia, Margaret, Allen, Little Allen, Bessie, Douglas, and Horseshoe islands.

Figure 3.2 The Wellesley Islands, located in the southern Gulf of Carpentaria, are broadly delineated into two geographic zones – the North Wellesley Islands and the South Wellesley Islands.

The South Wellesley Islands are low-lying with a high point of 24m above present mean sea level (PMSL). The islands are principally covered by open eucalypt savannah and spinifex grasslands at elevations greater than 5m above PMSL. Below 5m above PMSL extensive mangrove forests, salt flats, and clay pans dominate (Figure 3.3). Low-lying areas, particularly the salt flats and clay pans, are subject to extensive flooding during the summer monsoon owing to a combination of heavy rainfall and tidal banking. Coastlines are bordered by extensive tidal flats and sand banks that can stretch seaward for up to 800m during peak low-tides. These flats constitute an integral resource collection zone were numerous species of shellfish are gathered, rock-walled fish traps were constructed, and, in the case of offshore sand banks, used for hunting dugong and turtle (Tindale 1962a, 1963).

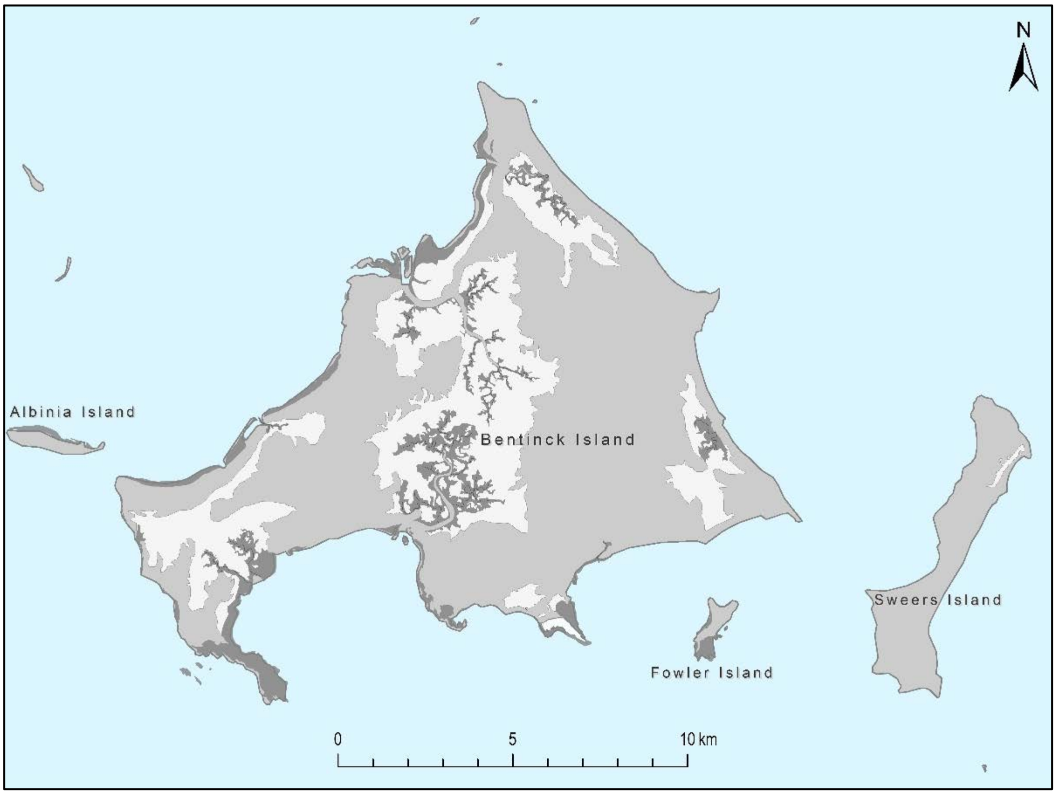

Figure 3.3 Bentinck Island has numerous environmental zones including mangrove forests, open savannah, and extensive clay pans (Map: Lincoln Steinberger, 2014).

3.2.1 Current Climate

Located within the tropical zone that stretches across northern Australia, the South Wellesley Islands are subjected to a highly variable annual climate. Contemporary climate cycles associated with this region are primarily controlled by interactions between the Australian monsoon and southeasterly trade winds, producing a distinct wet (November – March) and dry (April – October) season annually. As their names would suggest, these seasons are primarily delineated by rainfall intensity and frequency with 92 – 95% of the average 1200mm of precipitation occurring during the wet season (Figure 3.4). The onset of monsoonal conditions is governed by the movement of the Inter-Tropical Convergence Zone (ITCZ), which migrates south during the Australian summer bringing with it heavy precipitation and tropical cyclones. Reliance on the ITCZ for rainfall causes this region to be particularly sensitive to El Niño Southern Oscillation (ENSO) variability, with rainfall intensity and frequency decreasing substantially during El Niño phases owing to reduced ITCZ southward penetration and increasing with the onset of La Niña as the ITCZ travels further south (Nicholls 1992). Recent trends towards shorter, less intense wet seasons (BOM 2016) indicates the area is currently experiencing an El Niño phase (BOM 2015b).

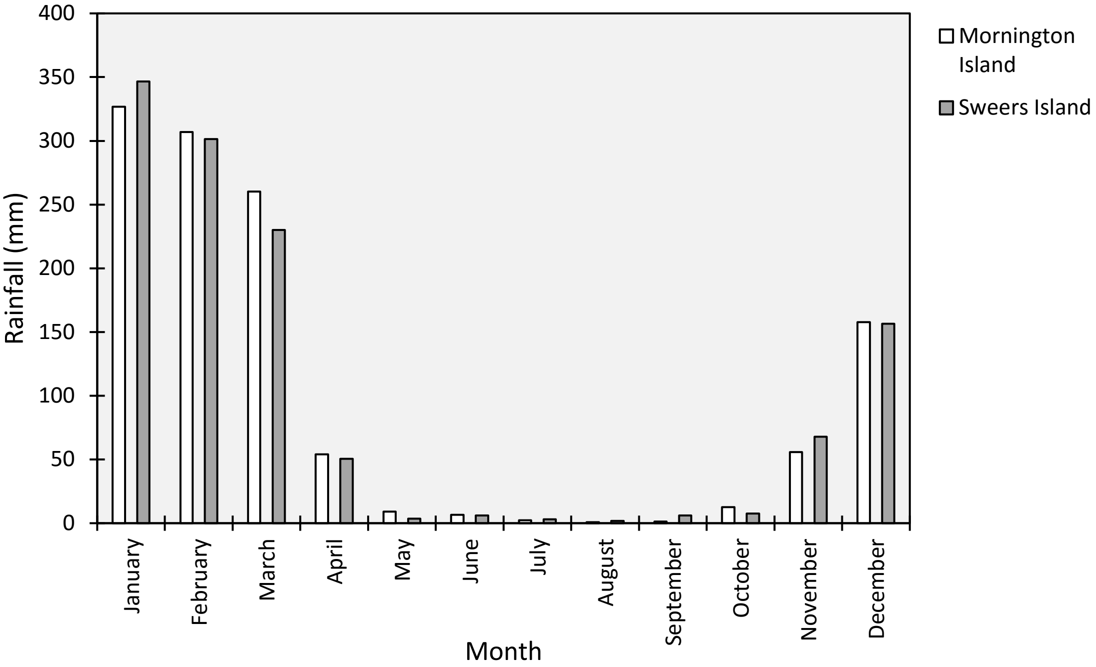

Figure 3.4 Average monthly rainfall from Mornington and Sweers Islands over the past 100 years. The Mornington Island dataset was included as it is continuous from 1914 while Sweers Island is sporadic until 2001. Note the similarities between the two locations (data from BOM 2015b, 2016).

As the monsoon produces substantial quantities of rainfall over relatively short periods of time extensive flooding is common across the South Wellesley Islands, particularly on Bentinck Island where numerous clay pans (including the extensive central pan) and estuarine systems are inundated annually (the potential implications of this for the Kaiadilt are discussed in Section 3.3.4). Moreover, terrestrial run-off and output from estuaries can temporarily alter the hydrology of nearby marine environments (discussed further in Section 3.2.3). Substantial changes to vegetation are triggered by the onset of the wet season owing to an abundance of moisture (Figure 3.5). Large bodies of standing water common throughout the wet season act as ideal breeding grounds for insects, principally mosquitoes, causing an increase in their populations (Memmott 2010; personal observation, March 2014). The dry season lacks heavy rainfall events and thus displays no flooding, resulting in decreased vegetation growth and insect activity as well as an increase in the frequency and intensity of burning events. Notably, rainfall can occasionally occur during the dry season (BOM 2015a, 2016), causing dense evening fogs along coastlines and tidal flats (Tindale 1962a).

Figure 3.5 A comparison between flora in the South Wellesley Islands during the wet (top) and dry (bottom) seasons (Top Photograph: Daniel Rosendahl, 2014).

Annual temperature ranges in tropical regions are commonly characterised as relatively stable, typically fluctuating only a few degrees over the course of a year. The South Wellesley Islands offer little exception to this pattern with mean annual minimums of 23.3°C and maximums of 30.3°C (BOM 2016). During the wet season the highest temperatures peak at 33.7°C during December, while the coolest temperatures occur during the dry season reaching lows of 17.6°C (Figure 3.6). Accompanying these temperature shifts are changes to humidity, which peaks during the wet season. Memmott (1979:48) described this period as 'exhaustingly humid', an account the author of this research can attest to (personal observation, March 2014, February 2016). However, high humidity dissipates with the onset of dry season conditions.

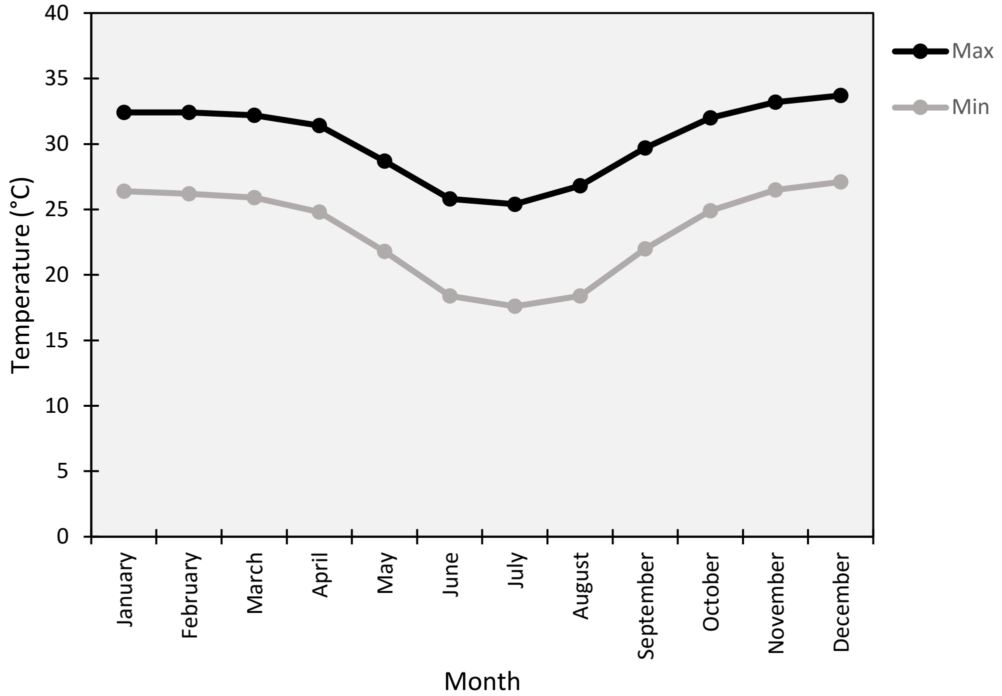

Figure 3.6 Average maximum and minimum temperatures for Sweers Island 2001 - 2015 (data from BOM 2016).

Wind direction and speed play important roles in the annual climate cycle of the South Wellesley Islands. As outlined above, the southeast trade winds are an important component of the north Australian monsoonal cycle. Early in the dry season southeasterly winds build in intensity, reaching their peak during July (Memmott 2010:21). Inclement ocean conditions (e.g. moderate wave action) often accompany these winds, increasing the risk of open water crossings and limiting access to some resources (Tindale 1962a). As the wet season commences, wind direction shifts northwest bringing with it monsoonal rainfall. While not reaching the intensity of dry season winds the northwesterly's can lead to inclement ocean conditions, particularly along northwest-facing coastlines. Moreover, severe thunderstorms are common during this time of year, predominantly between November and December, again increasing the risk of travel between islands. A particularly salient example of this danger is the reported drowning of 14 people during a wet season crossing between Bentinck and Allen islands in late 1946 or early 1947 (Tindale 1962b).

Owing to the latitudinal positioning of the South Wellesley Islands, cyclones are common occurrences during the summer. Between 1906 and 2006 a total of 32 tropical cyclones passed within 100km of Bentinck Island (0.32 per year), 59 came within 200km (0.58 per year), and 101 crossed within 400km (1 per year) (BOM 2015c). Cyclones can significantly impact local environments (Meehan 1982; Moss et al. 2015) and the coastal archaeological record (Bird

1992; Rowland and Ulm 2012) as well as disrupting numerous behavioural cycles (see Section 3.3.2 and 3.3.3).

3.2.2 Palaeoenvironment

Since the commencement of the last marine transgression (c.18,000 BP) climatic oscillations, sea-level fluctuations, and other marine processes (such as progradation and sedimentation) have led to significant alterations to landscapes and environments across the Gulf of Carpentaria. An extensive body of work generated over recent decades has yielded multiple datasets capable of exploring the development of the Gulf region over the past 130,000 years (e.g. Chivas et al. 2001; Gagan et al. 2004; Lewis et al. 2013; Moss et al. 2015; Reeves et al. 2007, 2008, 2013; Shulmeister 1992, 1999; Shulmeister and Lees 1995; Sloss et al. 2007, 2015; Torgersen et al. 1983, 1985; Woodroffe et al. 1985, 1988). However, as the earliest evidence of human use of the South Wellesley Islands occurs c.3500 BP (Ulm et al. 2010), it is the development of climate, landscape, and resources during the mid-to-late Holocene that are most relevant to this research.

While not as severe as shifts during the Pleistocene, climate variability during the Holocene is characterised as relatively large and abrupt with substantial impacts on local environments and human populations (Mayewski et al. 2004). Broad Australasian models suggest a widespread drying trend and shift towards increased climate variability for much of Australia since the mid-Holocene (Donders et al. 2007; Gagan et al. 2004; Prebble et al. 2005; Reeves et al. 2013; Shulmeister 1999), however environmental and climatic patterns in tropical north Australia diverge from continental climate change (Figure 3.7).

Palynological data from Groote Eylandt suggest a period of increased precipitation occurring 3700 – 5000 BP accompanied by temperatures +1 – 3°C above modern values (Shulmeister 1992, 1999; Shulmeister and Lees 1995). Contrasting data from Vanderlin Island, only 300km west of the South Wellesley's, identifies no apparent change in the precipitation regime in the past 5000 years (Prebble et al. 2005). Moreover, some authors argue for an earlier peak in moisture (7000 – 8700 BP) followed by two drying phases at 4500 – 5000 BP and c.2700 BP, although it is postulated that comparisons between upland and coastal regions may be offset by as much as 3000 years (Donders et al. 2007). North Australian climatic patterning appears to converge with the broader trans-continental model c.3700 BP with evidence of decreased precipitation and highly variable climate regimes, largely in response to changing ENSO cycles (Donders et al. 2007; Gagan et al. 2004; Prebble et al. 2005; Shulmeister 1999).

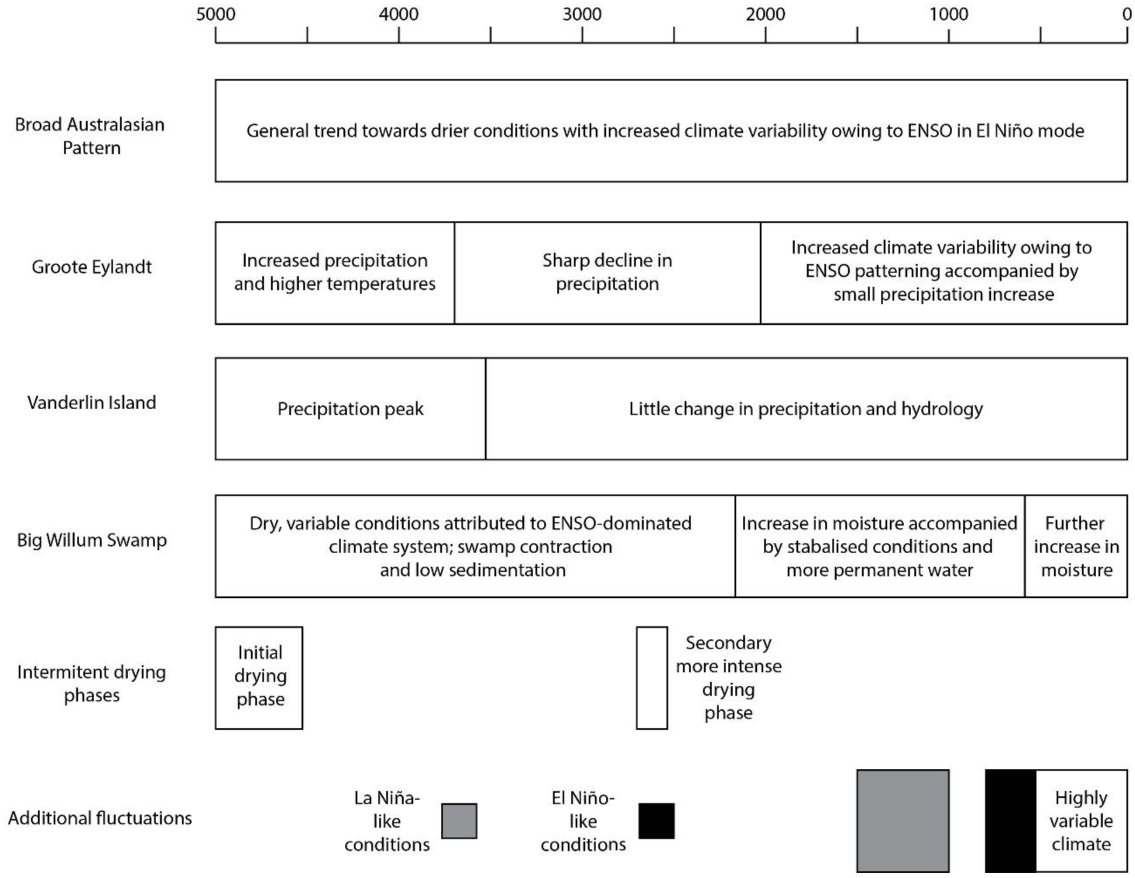

Figure 3.7 Phases of climate change vary at local levels suggesting human responses may follow a similar pattern. Listed from top down data are derived from the following – after Reeves et al. (2013); after Shulmeister et al. (1992, 1999); Shulmeister and Lees (1995); after Prebble et al. (2005); after Stevenson et al (2015); after Donders et al. (2007); after Brockwell et al. (2009); Goodwin et al. (2004b); Mann et al. (2009); Moss et al. (2015); Rein et al. (2004); Shulmeister (1999); Williams et al. (2010).

Two further, although relatively short, oscillations occur from 1000 – 1500 BP (Donders et al. 2007; Mann et al. 2009; Moss et al. 2011; Rein et al. 2004; Shulmeister 1999; Williams et al. 2010) and 500 – 700 BP (Goodwin et al. 2004b; Moss et al. 2011; Williams et al. 2010). Characterised as extended periods of wet La Niña- and dry El Niño-like conditions respectively, some authors have tentatively linked these shifts with the Medieval Climatic Optimum and Little Ice Age (Moss et al. 2011; Williams et al. 2010). However, the timing and nature of these events for the southern hemisphere is not currently well understood (Allen 2006; Gagan et al. 2004). The past 500 years were typified by highly variable climatic regimes extending across the continent that have been linked to further changes in ENSO and the Interdecadal Pacific Oscillation (IPO) (Brockwell et al. 2009; Moss et al. 2011; Williams et al. 2010). Today the climate of Australia’s tropical north can be characterised as dry and variable owing to frequent ENSO events occurring every 2 to 7 years (Gagan et al. 2004).

In addition to the effects of climate change, substantial fluctuations in sea level, shoreline progradation, and sedimentation were implicit in landscape and environment transformation during the mid-to-late Holocene. Sea-level curves suggest a high-stand of +2.5m above PMSL was reached c.6400 years ago and remained close to +2m above PMSL until the late-Holocene (Lewis et al. 2013; Nakada and Lambeck 1989; Sloss et al. 2015; Woodroffe 2009). This process likely inundated low-lying coastal areas across the Wellesley group impacting geological processes and the development of resources. For instance, the expansion of clay pan systems that dominate the modern centre of Bentinck Island correlate with the mid-Holocene high-stand, terminating as sea levels receded and stabilised (Sloss et al. 2015). However, the timing of stabilisation remains uncertain. Sea-level data from other regions of the Gulf suggest stabilisation as late as c.3500 BP (Harris et al. 2008; Reeves et al. 2007; Torgersen et al. 1985) with the possibility of minor fluctuations occurring as late as 2000 BP as identified by Woodroffe (2009) for northeast Queensland.

The commencement of coastal progradation and sedimentation across the Gulf of Carpentaria closely followed the sea-level maximum (c.6000 BP), establishing broad coastal flats on both the mainland (Chappell and Thom 1986; Rhodes et al. 1980) and island formations (Prebble et al. 2005; Rosendahl et al. 2014a). Meanwhile, expansive mangrove forests established during the initial transgression (Woodroffe et al. 1985) began to recede (Prebble et al. 2005; Rosendahl et al. 2014a). These processes gradually shifted the mainland coast an average of 15km seaward and resulted in the establishment of estuarine, freshwater, and mudflat systems as well as the probable incorporation of former nearshore islands into the continental landmass (Prebble et al. 2005; Woodroffe et al. 1986). As sea levels began to fall during the late Holocene smaller islands, potentially used as stepping-stones or staging areas for crossing into the Wellesley group, began to re-emerge and/or form (Rosendahl 2012). Thus, the previously geographically isolated Wellesley Islands became increasingly accessible owing to a significant reduction in the minimum required distance of open water crossings.

Important resource bases such as littoral and intertidal communities, mangrove stands, estuaries, and freshwater sources were also under development. Using a pollen record from Marralda Swamp on the south coast of Bentinck Island, Moss et al. (2015) documented the evolution of a nearshore beach environment into a large mangrove forest c.500 BP. Littoral and intertidal resources were established some time after initial island formation and expanded significantly as progradation and sedimentation led to tidal flat development (Memmott et al. 2016). Moreover, as sea levels fell the positioning of these zones shifted leading to the establishment dune systems, re-emergence of inundated sections of island, and further broadening of the intertidal zone (Moss et al. 2015; Rosendahl et al. 2014a). Large riverine systems such as the Mackenzie and Makati Rivers were likely formed during, or subsequent to, sea-level recession as they largely follow the central salt flat of Bentinck Island. Freshwater sources in the Wellesley Islands principally take the form of ground water lenses that are gradually depleted via drainage and evaporation over the course of a year and are recharged by seasonal rainfall during the summer monsoon (Memmott 2010:20; Robins et al. 1998). Thus, freshwater was likely available in the South Wellesley's from at least the onset of the Australian monsoon, although the permanency of such sources is difficult to establish.

Given the extensive climatic, environmental, and landscape modification that occurred during the mid-to-late Holocene it is unsurprising that numerous researchers from multiple disciplines have explored interactions between these changes and Aboriginal behaviour (e.g. Bourke et al. 2007; Brockwell et al. 2013; Moss et al. 2011; Sim and Wallis 2008; Turney and Hobbs 2006; Williams et al. 2010, 2015b). In particular, authors have implicated changing ENSO patterns in processes leading to behavioural transformation across northern Australia (Sim and Wallis 2008; Williams et al. 2010, 2015a). In the Gulf of Carpentaria, Sim and Wallis (2008) argued changing environmental and climatic conditions brought about by increasingly frequent ENSO events facilitated several phases of ephemeral use, abandonment, and permanent occupation for Vanderlin Island. However, this may not apply beyond the local system with current evidence from the Wellesley Islands indicating no obvious correlations between major environmental events and occupation (Rosendahl et al. 2014a). Further analysis of localised palaeoenvironmental data coupled with geological understandings and archaeological interpretations is required to approach the holistic depictions of human-environment interactions that are vital to characterising patterns of Aboriginal use.

3.2.3 Hydrology

The Gulf of Carpentaria is an expansive, although shallow, hydrological system that covers an area of approximately 500,000km^2 with a maximum depth of less than 70m (Oliver and Thompson 2011; Torgersen et al. 1983). Ocean waters enter the Gulf from the Coral and Arafura Seas in the east and west respectively. The predominant current slowly circulates water in a clockwise direction driven by monsoonal northwesterly winds (Forbes and Church 1983). This process is largely responsible for the deposition of sediments along the Gulf of Carpentaria's prograded southern shoreline. Currents are strongest in the northern Gulf, weakening as they travel south (Forbes and Church 1983). A combination of strong southeast winds and neap tides can lead to a slowing or temporary reversal of circulation during the dry season, particularly in the southern Gulf were tidal variation is most prominent (Forbes and Church 1983). The mainland Carpentaria Plain is drained by numerous large river catchments including the

Nicholson, Leichhardt, Flinders, Settlement Creek, Cloncurry, Saxby, Norman, Clara, Yappar, Gilbert, Einasleigh, and Staaten (Twidale 1966) (Figure 3.8). The substantial increase in precipitation during the summer monsoon leads to significant inputs of fresh water (up to 92,000GL) into the marine system (Oliver and Thompson 2011), significantly altering the productivity and hydrology of the surrounding region (Burford et al. 2009).

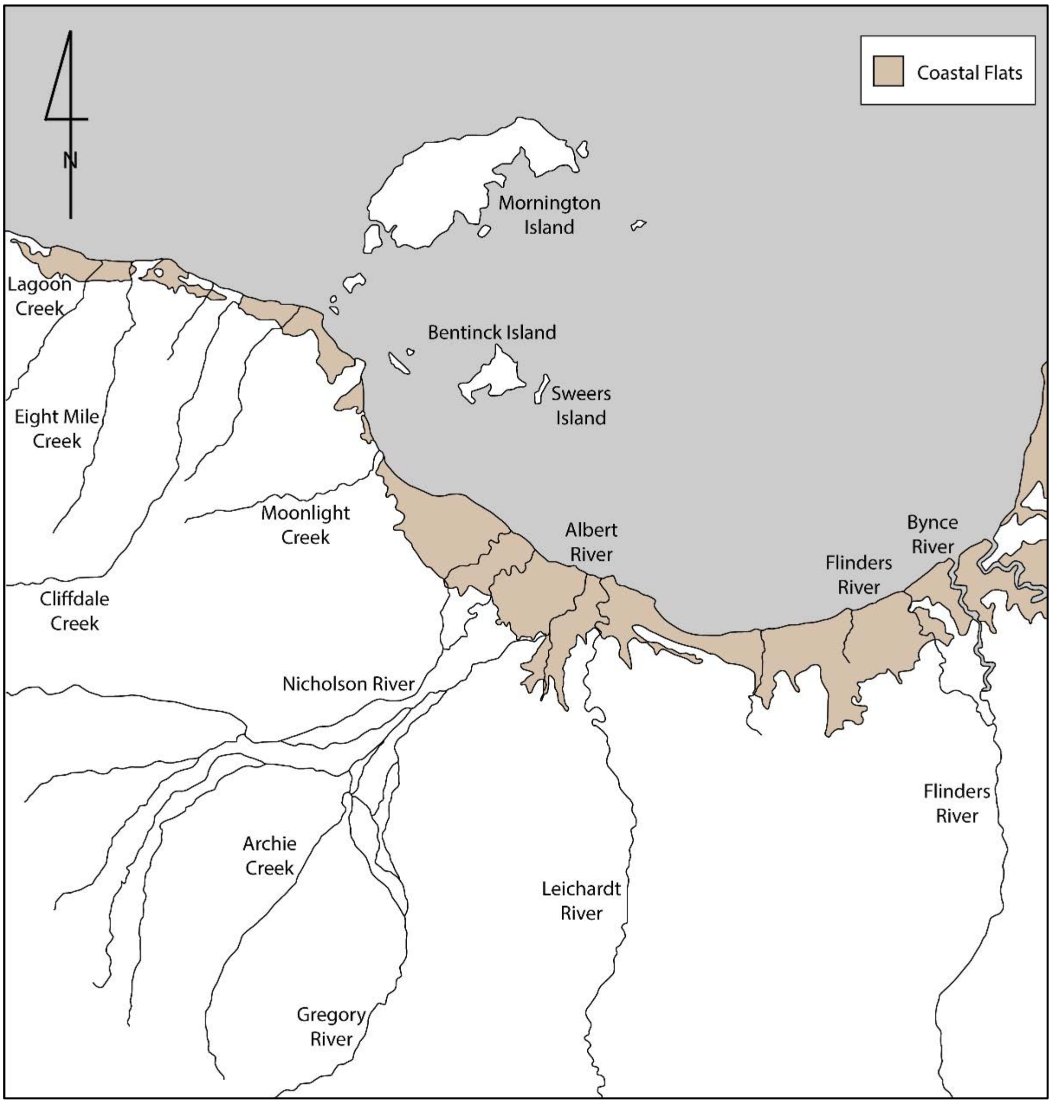

Figure 3.8 Mainland river catchments that expel substantial amounts of meteoric runoff into the southern Gulf of Carpentaria during the wet season.

Similar seasonal variations can be observed in the South Wellesley Islands, particularly around Bentinck Island. The shallow waters (<20m) surrounding the South Wellesley's (Torgersen et al. 1983) tend to be well mixed with very little stratification (Somers and Long 1994), thus hydrological changes commonly effect the entire zone rather than single layers. Tidal variations primarily follow a daily diurnal pattern (one high and low tide a day), with heights ranging between -0.08 and +4.32m around the zero tide mark (BOM 2014). However, for one to three days every fortnight tides shift to a semi-diurnal ‘double tide’, during which relatively little water movement occurs. Fluctuations are most prominent during the wet season owing to tidal banking driven by strong northwesterly winds (Memmott 1982b). Records from the nearest sea surface temperature (SST) recording station (Karumba (1999 – 2006), ~150km southeast of Bentinck Island) indicate that for much of the dry season SSTs are relatively low, averaging 23.8°C, while wet season SSTs are approximately 7°C higher, averaging 30.7°C (AIMS 2015). These temperatures are largely consistent with atmospheric temperatures, although exhibit slightly less variability (BOM 2015a, 2016).

While little data regarding seasonally derived fluctuations in hydrology and productivity around Bentinck Island exists, some broad estimations can be made. The lack of precipitation during the dry season suggests stable marine conditions dominate the region for much of the year. This may be offset, particularly in and around estuarine systems, by gradual input from draining terrestrial freshwater sources and incomplete exchange with the open ocean potentially producing slightly more brackish conditions. Likewise, productivity may vary in and around estuarine systems owing to high concentrations of decaying plant matter and other detritus associated with the extensive mangrove forests that surround these features. These impacts may be exaggerated during peak high tides when mangrove stands are inundated by tidal waters, increasing the quantity of plant matter, sediment, and detritus being flushed into adjacent estuarine and marine systems.

The primary annual driver of change in the local hydrological cycle is the onset of monsoonal rainfall. A combination of terrestrial runoff, output from flooded estuarine systems, and direct input from precipitation has the potential to considerably modify hydrological conditions. A particularly salient example of this is found in ethnohistoric observations that suggest the open marine zone near Bentinck Island can become so diluted with freshwater it is rendered drinkable (Earl 1842:141; Memmott 1982b). This influx clearly substantially alters salinity values, but also likely impacts oxygen and carbon isotope composition. Dansgaard’s (1964) ‘amount effect’ states that as precipitation increases $\delta^{18}O_{water}$ values trend more negatively (see also Rozanski et al. 1993). As meteoric input from the Australian monsoonal cycle is substantial, there is likely a negative shift in $\delta^{18}O_{water}$ values associated with marine, estuarine, and mangrove systems during the wet season. Similar shifts in $\delta^{13}C_{water}$ values may also be present, with increases in fluvial dissolved inorganic carbon (DIC) leading to more negative signals (e.g. Gillikin et al. 2006; Mook and Vogel 1968). These effects may linger after the monsoon has dissipated as terrestrial runoff and estuarine systems drain flood waters (e.g. Kennett and Voorhies 1995, 1996), thus a potential time-lag must be accounted for when assessing local hydrological conditions.

A key component of this research is to better characterise seasonal hydrological changes in the South Wellesley Islands. Doing so will allow a more nuanced understandings of short-term environmental oscillations occurring at local scales and how they may impact constituent flora, fauna, and human populations. Moreover, these changes underpin decision-making processes associated with human occupation, mobility, demography, and land-use, making them integral to interpretations of Kaiadilt behavioural patterns.

3.3 Cultural Setting

The Wellesley Islands are the traditional country of four distinct, although closely related, Aboriginal language groups – the Lardil, Yaangkal, Kaiadilt, and Ganggalida (Figure 3.9). Modern boundaries afford a bulk of the North Wellesley Islands to the Lardil, with the stepping-stone islands between Mornington Island and the mainland claimed by the Yaangkal. The country of the Ganggalida stretches along the mainland coast, sharing ownership of the nearshore islands with the other groups. The Kaiadilt are the traditional owners of the South Wellesley Islands with current archaeological data suggesting use of this region since c.3500 BP (Peck 2016; Ulm et al. 2010). Aboriginal use and habitation of the South Wellesley's continued through periods of contact with both Macassans and Europeans until the late 1940s when a series of environmental and cultural events caused the Kaiadilt to be forcibly evacuated to Mornington Island, making them the last group of coastal dwelling Aboriginal Australians to be disrupted by European intervention (Memmott 1982b; Memmott et al. 2006; Tindale 1962a, 1962b, 1977). Thus, there exist detailed ethnographic and ethnohistorical observations and descriptions as well as local oral histories of traditional lifeways employed by the Kaiadilt (e.g. Boyd 1896; Chimmo 1857; Flinders 1814; Laurie 1866; Memmott 1982b, 2010; Memmott et al. 2006; Memmott and Trigger 1998; Roth 1901, 1903; Stokes 1846; Tindale 1962a, 1962b, 1963, 1977). One of the most prolific ethnographers for this region was Norman Tindale who worked closely with numerous members of the Kaiadilt community during the 1960s (a number of Tindale's key informants, including Darwin Ludinathi, Pluto Tarurukinati, and Percy Loogatha, were adults at the time of forced removal and lived traditionally through a portion of their lives (see Tindale 1962b, 1963)).

Bentinck Island shows signs of the most intensive Kaiadilt occupation with a combination of deeply stratified deposits and variably sized surface scatters (Nagel et al. 2016; Peck 2016; Ulm et al. 2010). Additionally, inter-island travel is evident in ethnographic, oral, and archaeological records, with voyages ranging from close by Sweers and Fowler Islands to as far as Allen Island (Memmott 1982b; Tindale 1962a; Ulm et al. 2010). Owing to extensive coastal resources afforded by island landscapes, marine environments were highly significant across the South Wellesley Islands with intense geographic naming and boundary marking focused along the coastal margin (Best 2012; Memmott and Trigger 1998; Tindale 1962a; Trigger 1987). Thus, the Kaiadilt hold an extensive body of traditional knowledge concerning coastal margins and marine environments, including constituent flora and fauna, weather, and tides, allowing them to effectively exploit these zones (Memmott and Trigger 1998; Tindale 1977). As a particularly salient demonstration of the coastal-centric culture associated with the Kaiadilt, Tindale (1977) presents a representation of the concept of country as drawn by a Kaiadilt man who places the sea (ʻ*mala*) at its centre (Figure 3.10).

By couching archaeological research within a robust framework of ethnographic, ethnohistorical, and oral histories researchers are able to establish and test questions posed by these records as well as better contextualise associated findings. The detailed nature of these for the South Wellesley Islands presents a unique opportunity to better understand the identity and history of the Kaiadilt people, which in turn informs interpretations of the local archaeological record.

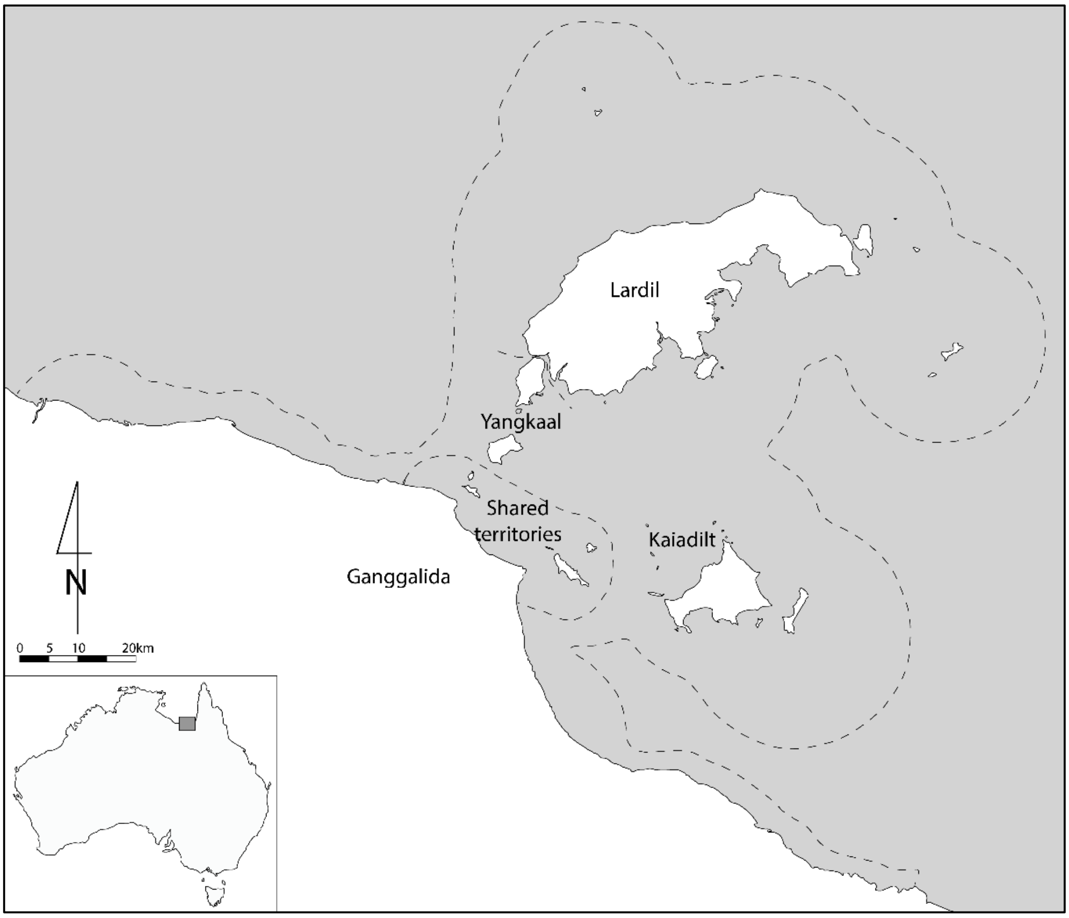

Figure 3.9 Modern boundaries claimed by the four Aboriginal language groups of the Wellesley Islands (redrawn from Rosendahl 2012:46 after National Native Title Tribunal 07/12/2004; www.nntt.gov.au).

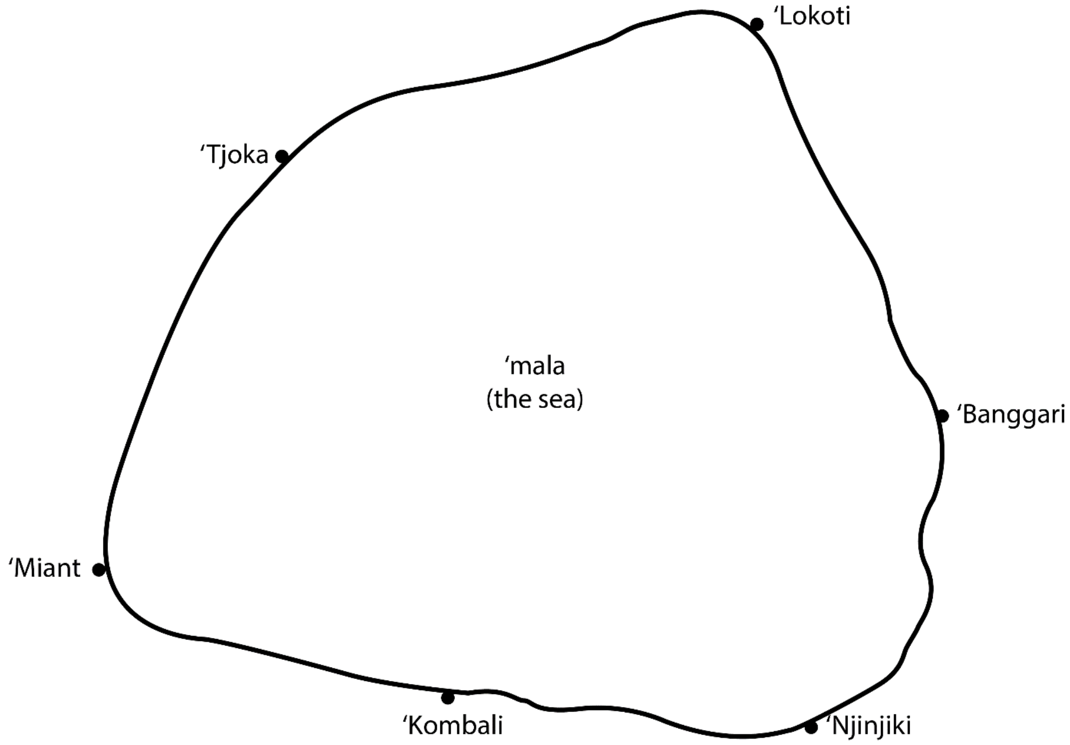

Figure 3.10 The Kaiadilt concept of country as drawn by a Kaiadilt informant. Note the central positioning of the sea (redrawn from Tindale 1977:248).

3.3.1 Kaiadilt Lifeways

The origins of the Kaiadilt and their language Kayardild remain under investigation with evolving linguistic models driving much of the associated research. Many authors have grouped the four Aboriginal populations of the Wellesley Islands together as the Tangkic languages, based on the assumption they are derived from a common language known as Proto-Tangkic (Evans 1985, 1995, 2005; Keen 1983; Memmott et al. 2016; O'Grady et al. 1966). Currently, it is thought multiple instances of fission and fusion originating from Mornington Island led to the formation of the four distinct language groups as we know them today (Memmott et al. 2016). While they potentially share a common foundation, processes of isolation and cultural exchange have encouraged each group to develop its own unique identity beyond language, manifesting within material culture, economy, ceremony, and social organisation (Best 2012; Memmott 2010; Memmott et al. 2006; Trigger 1987).

Discussions centred on the Kaiadilt tend to focus on their apparent isolation and how this may have impacted their development, with authors frequently citing many aspects of Kaiadilt culture that deviate from other Wellesley region peoples. In particular, there are a number of well described differences between Aboriginal people from the north and south island groups, suggesting separate cultural-geographic contexts (Memmott et al. 2006). Authors have highlighted differences in the diversity of material culture between these two populations as a key differentiating factor. The Lardil have a larger suite of tools and artefacts (~70 in total) than the Kaiadilt who exhibit a much smaller assemblage of approximately 30 individual pieces (Memmott 2010; Memmott et al. 2006). While this has been previously linked with the perceived isolation of the Kaiadilt (Tindale 1977), interviews with senior Kaiadilt men indicate that many of the additional material culture innovations from the North Wellesley's were known in the southern islands, however were often deemed unnecessary and thus discarded (see Rosendahl 2012:49).

An alternative hypothesis suggests the diminished Kaiadilt tool kit may in fact be linked with the prolific use of rock-walled fish traps across the South Wellesley's (Memmott et al. 2006). While fish traps occur throughout the region (Figure 3.11), their distribution is not uniform between the four Aboriginal groups. The highest concentration is found on Bentinck and Sweers Islands, averaging one site per 0.4km of coastline, while by contrast Lardil territories demonstrate the lowest density with only one site per 8km of coast (Memmott et al. 2008; Rowland and Ulm 2011). Moreover, Kaiadilt traps show deviations in basic design, which may indicate a variation in harvesting practices (Memmott et al. 2008). These factors suggest the Kaiadilt were substantially more reliant on fish traps as part of subsistence economies potentially to the point of specialisation in this mode of resource exploitation, which may account for their less complex material culture repertoire (Memmott et al. 2006, 2008). However, further research into fish trap quantification, variation, and utilisation is required to better characterise their place within Kaiadilt culture.

During the 1960s and 1970s a number of studies undertook genetic analysis of the people residing in the Wellesley Islands (Curtain et al. 1966, 1972; Simmons et al. 1962, 1964). Results emphasised differences in genetic markers of populations from the North and South Wellesley's, characterising the Kaiadilt as an aberrant genetic population. This reinforced ideas expounded by Tindale (1962a, 1962b, 1977) who suggested long-term occupation of the South Wellesley Islands by an isolated population, regarding the Kaiadilt as the ancestors of a relict group that had remained *in situ* and isolated since the most recent marine transgression. However, this theory can be easily tested against recent archaeological, anthropological, and linguistic evidence (Evans 1995, 2005; Memmott et al. 2006, 2016; Peck 2016; Ulm et al. 2010). A combination of linguistic modelling and archaeological evidence places the earliest human presence in the South Wellesley Islands at c.3500 BP (Memmott et al. 2016; Peck 2016; Ulm et al. 2010), significantly later than Tindale's theory. Moreover, White (1997) demonstrated that rates of genetic mutation within small founding populations are relatively fast, with changes occurring over generations rather than millennia. With current evidence suggesting a significantly more recent occupation and potential for relatively quick genetic mutation, Tindale's notion of long-term occupation can be safely discarded.

Figure 3.11 A Kaiadilt fish trap complex located at the mouth of Catfish Story, Bentinck Island (Photograph: Sean Ulm, 2013).

Local organisation systems (e.g. kinship and land tenure) in the North and South Wellesley's exhibit many commonalities. In particular, Memmott et al. (2006) highlights the presence of patriclans, patrilineal rights, birthplace attachments, and totemic affiliations, however in some cases the two diverge considerably. The Lardil display a strong patrilineal ideology, thus lands are commonly held by patriarchs with ownership passed on from male ancestors (Memmott 1982b; Memmott and Trigger 1998). For the Kaiadilt, land tenure is augmented with a more flexible birthplace-based system that incorporates patrilineal rights as a secondary mechanism (Evans 2016; Memmott 1982b). Moreover, Tindale (1962a, 1962b, 1963, 1977) suggests that the Kaiadilt could be divided into eight family groups or *dolnoro* consisting of 10 – 30 individuals headed by a patriarchal head or *dolnorodangka* (a term later revised by Evans (1995) to *dulmarra dangkaa*). Each group claims rights over a separate estate of land and resources on Bentinck Island. Strict rules of access were applied to these pieces of land and their constituent resources with permission of the estate's owner required prior to hunting or fishing (Evans 1995).

Variations in ceremony, particularly male initiation, are evident throughout the Wellesley Island region. Many similarities are shared between Lardil, Yangkaal, and adjacent mainland ceremonies that involve ritual circumcision and subincision (Memmott et al. 2006). These include taboos that restrict gender access to the ceremony itself, the symbolic use of fishing net and spear, imparting of secret knowledge, and participation in sacred song cycles (Memmott 2010; Memmott et al. 2006). Conversely, Kaiadilt initiation does not include subincision (Memmott 1982b; c.f. Tindale 1977), elaborate ceremonial components or secretive aspects, and is performed in public allowing both male and female participation (Memmott et al. 2006; Tindale 1963, 1977).

While numerous differences are evidenced between Aboriginal groups from the North and South Wellesley's, it is important to note that the similarities between them strongly suggest a common origin (Memmott et al. 2006, 2016). Moreover, the assumption that the Kaiadilt lived in total isolation from other Aboriginal groups is an oversimplification of local exchange networks. While Tindale (1962a, 1962b, 1977) cites the danger of open water crossings as a key factor in Kaiadilt isolation, more recent evidence indicates people may have undertaken such a voyage five or six times during their lifetime (Evans 2005; Memmott 1982b). These voyages were often for the purpose of cultural exchange with ethnographic accounts indicating that Allen Island was used as a gathering place for the dispersal of ideas and techniques and is identified as where the Kaiadilt learnt to cut boomerangs (Memmott 1982b). While it is now clear that Kaiadilt did interact with other Aboriginal groups on a semi-regular basis, it is likely that they experienced significantly less contact than their northern neighbours owing simply to the expansive open water crossing required to do so. However, this was to change with the commencement of Macassan and European visitation.

3.3.2 Foreign Contact

Contact with non-Aboriginal groups (e.g. Macassans or Europeans) is frequently cited as a key facilitator for significant behavioural and cultural change in Aboriginal populations. Ethnohistorical records and archaeological evidence suggest the South Wellesley Islands were at various times visited and on occasion permanently occupied by Macassan and European parties (e.g. Flinders 1814; Laurie 1866; Memmott 1982b; Oertle et al. 2014). Thus, it is essential that relationships between non-Aboriginal groups be explored to understand any possible impacts these may have had on Kaiadilt lifeways.

For many environments and populations along the north Australian coast engagement with Macassan voyagers was the catalyst for profound change. Originating from the port of Macasser in Sulawesi, Macassan praus often travelled along north Australian coasts during the 19th century to harvest timbers, tortoise shell, and bêche-de-mer (edible sea cucumber also known as trepang) (Macknight 1972, 1986; Memmott 1982b; Oertle et al. 2014). Trepang were harvested and processed, often by smoking, as the praus progressed around the coast facilitating many often prolonged instances of contact between Macassans and Aboriginal groups on Australia's north coast, generating a complex long-distance network of material and cultural trade (Macknight 1972, 1986; Memmott 1982b; Oertle et al. 2014). Numerous authors have described changes in subsistence, exchange networks, art, and language as key responses to Macassan contact (e.g. Faulkner 2013:5; Macknight 1972, 1986; Rosendahl et al. 2014a). However, evidence of direct association or interaction between Kaiadilt and Macassans is absent despite clear indications of Macassan presence in the region (Oertle et al. 2014). No loan words have been detected within the Kayardild language and there appears to be no adoption of material culture items (Evans 1992, 2005; Memmott 2010). Based upon this evidence it can be assumed that visitation by Macassan voyagers was sporadic and low-intensity with little to no contact with the Aboriginal population (Oertle et al. 2014).

Conversely, a long history of contact between Kaiadilt and European parties extends from at least the early 1800s to the late 1940s (see Memmott 1982b; Tindale 1962a for detailed reviews). It has been suggested a Dutch captain, Carstensz, was the first to come into contact with the Kaiadilt during the 1600s (Cawte 1972:9; Tindale 1962a), however there is little evidence to support this claim (Memmott 1982b). Similarly, Abel Tasman was likely the first European to sight the Wellesley Island group in 1644 (Emery 1973:33-34), although it is doubtful contact was made owing to a propensity for Dutch sailors to remain relatively far offshore (Memmott 1982b). A meeting between Matthew Flinders and an Aboriginal party on Horseshoe Island has been cited as initial contact (Flinders 1814:138), however some doubt remains as descriptions of the group and their toolkit suggest they may have belonged to a mainland population (Memmott 1982b). Later, while exploring Bentinck and Sweers Islands, Flinders found evidence of Kaiadilt occupation, although the people themselves remained elusive (Flinders 1814:145). This sporadic, indirect contact continued for a number of decades with Europeans often sighting Kaiadilt parties fishing and gathering from afar, although few allowed them to approach (see Boyd 1896; Chimmo 1857; Stokes 1846).

In 1866 the township of Carnarvon was established on Sweers Island by William Landsborough as a sanatorium during an outbreak of "Gulf Fever", an epidemic that swept through the southern Gulf region (Tindale 1962a, 1962b). This sparked a period of relatively regular, direct contact with Kaiadilt groups recorded by Landsborough (see Laurie 1866). While many previous observations characterised the Kaiadilt as timid and elusive, Landsborough's journal documents a number of meetings initiated by Kaiadilt as well as some aggressive actions by those same groups. On at least three occasions Kaiadilt parties were openly aggressive towards Europeans (Laurie 1866), however it is difficult to determine whether these attacks were without provocation owing to the tendency of ethnohistorical texts to reflect cultural biases and perspectives of the author (see Hiscock 2008:3-4). Although, in one instance the Kaiadilt were unquestionably incited towards violence with the abduction of one of their children by the Europeans (Laurie 1866). At the very least these interactions suggest that the widely cited timidity of the Kaiadilt be reconsidered. However, it must not be assumed that all violence was perpetrated by the Kaiadilt with oral histories describing at least one massacre by European parties c.1918 (Kelly and Evans 1985; Stubbs 2005; Tindale 1962a, 1962b). While these events may paint a bleak picture of European-Kaiadilt interaction, these assumptions must be tempered by the fact that violent clashes were not the norm with several friendlier or uneventful contacts also documented (see Bleakley 1961; Memmott 1982b; Roth 1901, 1903; Tindale 1962a).

While there is little evidence of how this extended period of direct contact may have impacted the Kaiadilt, it can be assumed that the effects were profound. Particularly with the loss of access to Sweers Island and massacre event subsequent to the abandonment of Carnarvon (Kelly and Evans 1985; Stubbs 2005). Moreover, several glass artefacts have been identified across Bentinck Island (Ulm et al. 2010), suggesting the incorporation of European materials into the Kaiadilt toolkit. However, the greatest period of change for the Kaiadilt occurred well after Europeans had abandoned the South Wellesley's with environmental and cultural factors leading to the forced evacuation of the Kaiadilt population to Mornington Island.

Between 1945 and 1948 a series of events significantly altered the cultural and demographic landscape of the Kaiadilt. During this time the region suffered a prolonged period of drought, potentially placing the Kaiadilt population under resource strain. Tindale (1962b) suggests this was implicit in increased internal conflict that led to the drowning of 14 people as they fled from Bentinck to Allen Island. However, Kaiadilt informants maintain that subsistence resources remained plentiful throughout this period and that it was disagreements over women that triggered infighting (Memmott 1982b). In August 1947, the Mission Superintendent J.B. McCarthy removed 42 people from Sweers Island, taking them to Mornington Island where a Dr Spalding reported a number of the children showed signs of malnutrition (Tindale 1962b). Five months later (February 1948) the remaining Kaiadilt population experienced a tidal surge that reached +3.6m above the usual high tide mark and inundated all but the highest points of

Bentinck Island (Tindale 1962b). This coincides with two tropical cyclones effecting the area within 42 days of one another (Figure 3.12). On 16 October 1948 a European party arrived on Bentinck Island to remove the remaining Kaiadilt. They found the usual camps deserted and freshwater sources fouled, prompting McCarthy to write 'Bentinck Island is in an appalling condition. There is no drinkable water on the north of the island' (quoted in Tindale 1962a:271). The surviving Kaiadilt were subsequently relocated to Mornington Island, thus ending the traditional occupation of the South Wellesley Islands.

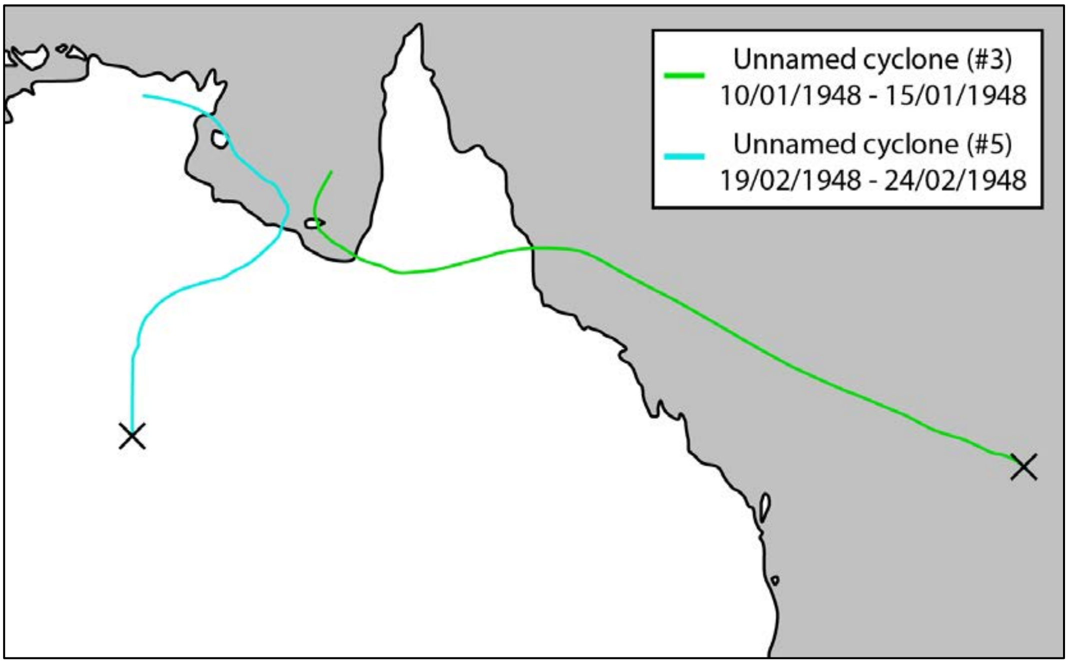

Figure 3.12 Two tropical cycles coincide with the reported tidal surge in February 1948 (BOM 2015c).

3.3.3 Seasonality

Ethnographic and archaeological evidence from across Australia has demonstrated close ties between seasonal fluctuations and changing occupation, subsistence, mobility, and demographic patterning (e.g. Argue 1995; Border 1999; Cosgrove et al. 2007; Davies 1985; Flood 1980; Meehan 1977, 1982; Memmott 2010; Memmott et al. 2006; O'Connor 1992, 1994; Pike-Tay and Cosgrove 2002; Sullivan 1982; Sutton 2010; Thomson 1939; Tindale 1962a). Similar relationships are evident in the Wellesley Islands, where seasonality appears to be deeply engrained within cultural systems. Thus, characterising relationships between seasonal change and Kaiadilt behaviour is integral to forming nuanced interpretations of short-term patterns.

While information pertaining to seasonal shifts in Kaiadilt behaviour is currently limited, detailed analyses of Lardil seasonality have been undertaken by several authors (see Memmott 2010; Memmott and Horsman 1991:24-25; Rosendahl 2012:56-58, 60). Findings indicate the Lardil delineate seasons by resource availability, precipitation, wind direction and strength, mosquito density, and temperature/humidity, including several intermediate seasons in addition to the broader concepts of the wet season and the dry season (Table 3.1). Given the close geographic proximity and similarities in climate, environment, and culture, it is likely the Kaiadilt made decisions based on similar seasonally-derived parameters. Further, some ethnographic texts hint at seasonally derived behavioural change (e.g. Tindale 1962a, 1962b, 1963, 1977). When these observations are coupled with what we know of the Lardil and other similar coastal groups, tentative approximations of Kaiadilt seasonality can be established.

Tindale (1962a) cites access to some resources and hunting grounds as susceptible to regular sub-annual shifts in climate and environment. For instance, the strong southeasterly winds that typify the early-to-mid dry season delay hunting expeditions to offshore sandbars, where turtle and dugong are plentiful, until after their peak in June (Tindale 1962a). The Lardil are similarly impacted as dry season winds force groups to intermittently abandon preferred coastal camps for the relative shelter of inland locales (Memmott 2010:21). Further, it has been suggested that the positioning of fish traps on the lee or windward sides of Bentinck Island may impact the timing of use owing to shifting wind direction rendering some traps unusable at certain points of the year – e.g. traps on the northwest coast are exposed during the wet season and vice versa (Tindale 1962a). Tindale (1962a) goes on to suggest during periods of trap disuse populations were increasingly reliant on estuarine and mangrove resources, potentially signalling a short-term shift in diet. However, this interpretation is called into question by information provided by a Kaiadilt man (Arthur Paul, dec.) who described fish trap walls as windbreaks that provide shelter to schools of fish during rough surface conditions allowing them to be speared with ease (Memmott et al. 2008). This suggests fish traps on both the lee and the windward sides of the island remain functional throughout the year.

Table 3.1 Lardil seasonal descriptions of weather, resources, and campsites accompanied by relevant Kaiadilt descriptions (adapted from Rosendahl 2012:60; Kaiadilt descriptions from Evans 1992).

Month	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Season	**Wet season**			**Hot-Wet-Dry-Transition**	**Cool Dry Season**				**Warm Dusty Season**		**Hot-Dry-Wet Transition**	
Summary of climatic characteristics	• Monsoonal rainfall, thunderstorms, cyclones • Rain falls heavily in short periods lasting a few days, mostly at night with intermittent breaks of hot calm weather • High humidity, profuse insect life, flooding, erosion occurs			• Thunderstorms • Monsoonal conditions cease • Wind direction begins to shift SE • Hot	• Southeast winds peaking in June • Wind strength varies in cyclic patterns • Lunar cycles intensify (June/July) • Diurnal cycles strongest from early morning to midday, cold and uncomfortable, but calm in evenings • Little (if any) rain				• Southeast winds subside • Soils blow away, dust storms/whirlwinds • Temperature rises • Most groundwater has evaporated • Morning glory clouds		• Wind direction begins to shift NW • Scattered afternoon thunderstorms of increasing intensity • High temperature and humidity	
Lardil climate descriptions	• First monsoonal rain – *kuburka* • Period of heavy perpetual cyclonic rain – *birrinju* • Mosquito time – *ngukajilalke* • Northwest winds – *jirrkarampen wanngal* • Intermittent northwest winds – *lilumpen wanngal* • Rain depressions (big rains) – *muthamangar* • Waterspouts sighted – *thandaman*, *thandabi*				• Southeast wind time – *larumpen wanngal* or *ngyelukan* • Cold wind time – *kuntha wanngal* • First southeast wind – *yelmiyal* • At times the east wind also blows – *liyalin*				• Time of the 'month fish' (*dunul*) – *jirrkaraalin* • Time of the ripening pandanus nut – *kuriyal* • Northwest wind – *jirrkaram* • Morning glory cloud – *weel*		• First rain time – *wurrkur wunda* • Time when the country is hot – *ngawan nyerrwe*; the ground is hot – *kiyawinwarka*; when people perspire – *darrathalan*; of the lightening – *binban* • Water running on ground after first rain – *wurrkur*	
Applicable Kaiadilt climate descriptions	• Wet season – *wunda* or *ngaruwarra wunda* • First rains of the wet season – *milda wunda* or *milwanda wunda* • Cyclone – *dirra yaruda*, *minjirrinda*, *wunda yarbuda* • Waterspout – *thandamanda* • Steady rain – *jathaldinda* • Rain storm - *mangara* • North wind - *jirrkurubudiinda*			• Gusty wind that keeps changing direction – *burldinburldinda*	• Cool southeast wind – *warrmara* • Cold weather – *ngurrinda* • Very cold – *kunthaa* • East wind – *rilunganda* or *rulunganda*				• Morning glory cloud – *wirilda* • Wind dies down/diminishes – *kunyawatha*		• Hot weather – *ngithalkuru* • Rain storm – *mangara* • Gusty wind that keeps changing direction – *burldinburldinda*	
Seasonal foods (Note – some of these resources are not present in the South Wellesley Islands)	• Wallabies • Turtle hunting, schools of fish and prawns netted • Frogs • Wild bee honey (sugarbag) • Goannas • *Wardirr* fruit consumed after processing • Mud crabs less plentiful • Many vegetables harvests begin including the mangrove fruit *marrin*, the wild plum tree *murrben*, the hunts of the *bilkurr* tree, the *wulun* fruit and *thalarr* seeds • The *nyulangka* fruit, the crow fruit *dangakur*, the fruit of the *bambularr*				• Best dugong hunting • Freshwater turtle and fish from interior water holes • Water lilies harvested • *Nyungar* root, *taltjir* roots, wild potato *yarrpa* • Turtle hunting • *Panja* from the swamp rush *kurka* • 'Dog-ball' fruit *dirriyurru*				• *Dulnhu* fish caught • *Jirdal* fruit and wild fig *kirrirr* • Pandanus nut *kuriyal*		• Wild bee honey *wankabel* • Frogs • Cycad fruit *wardirr* • Wild grape *benda* • Snakes	
Seasonal shelter, settlement and movement	• Wet weather camps on high sand ridges • Use of mosquito camps • Wet weather shelters • Reduced movement • Plentiful water resources			• Mosquito camps on beach or high dunes • Wet weather shelters transformed into shades	• Wind breaks • Abandonment of coast when winds peak • Dugong camps along the beach • Camps near water lily gathering sites • Dingo pups obtained • Wells dug in some camps				• Windbreaks on the beach • Frequent use of shades • Camps near *dulnhu* fish sites • Camps near pandanus • Wells dug		• Use of shades in the day • First mosquito camps • Shades transformed into wet weather shelters • Use of wells and rock holes as water sources	

Owing to sustained monsoonal downpours during the wet season, much of Bentinck Island experiences extensive annual flooding. Low-lying sections of the island quickly become inundated, essentially dividing the island along the central salt flat. Evidence from the North Wellesley's suggests that the combination of flooding and prolonged periods of heavy rainfall encourage a temporary shift towards a more sedentary lifestyle that sees the typically highly mobile Lardil establish 'wet weather camps' that are used for up to six weeks (Memmott 2010:21). It is currently unclear whether Kaiadilt populations experience a comparable decrease in mobility, however given the severity of wet season flooding across Bentinck Island disruption to mobility is likely. There is also the possibility that the availability of some resources may be impacted by wet season conditions, for example numerous authors cite freshwater influxes adversely impacting some shellfish populations (Bayne 1973; Meehan 1977, 1982; Morrison 2003; Yurimoto et al. 2014a). However, it must be noted that copious moisture could lead to an abundance of other, primarily floral, resources. Observations made on Bentinck Island demonstrate a significant increase in floral activity with many savannah species flowering and fruiting (personal observation, March 2014). Further, the Lardil characterise the wet season as a time when many vegetables and fruits are harvested and consumed (Table 3.1).

The availability of freshwater has been characterised as an important factor in patterns of hunter-gatherer occupation (e.g. Gale and Carden 2005; Nutley 2005). In the Wellesley Islands, ethnographic observations of the Lardil suggest that proximity to a freshwater source is implicit in selecting a camp site location (Memmott 2010:20-21). Monsoonal rainfall recharges freshwater sources, such as ground water lenses, which then gradually deplete during the following dry season. Thus, while freshwater sources remain plentiful following the wet season a wide range of locations are used, but as the year progresses water sources are exhausted and the number of desirable camp sites decreases sharply (Memmott 2010:20). Ethnographic sources from the adjacent mainland indicate a similar pattern for Ganggalida sites with the sporadic use or abandonment of some camps as water sources dwindle (Robins et al. 1998). The loss of smaller water sources could potentially signal a temporary demographic change whereby numerous groups converge on reliable freshwater sources, a pattern that has been observed elsewhere along the mainland coast (see Meehan 1982:32-34). Kaiadilt occupation was likely influenced by similar seasonally derived water availability. Camps supplied by ground water lenses and soaks may have seen seasonally dependant cycling of use and abandonment tied to water availability, while those with more permanent freshwater potentially saw intensified use during the late dry season. However, this is yet to be directly demonstrated.

The cyclonic conditions the South Wellesley Islands are frequently subjected to during the wet season (see Section 3.2.2) have the potential to significantly disrupt regular seasonal cycles of occupation and subsistence behaviour. Extremely rough seas, intense rainfall events, and destructive winds have been known to destroy important resource sites along Australia's mainland coast forcing adaptations in subsistence economies (see Meehan 1977, 1982:162-165). On Bentinck Island palynological records from Marralda Swamp indicate a rapid shift from brackish mangrove to freshwater swamp systems associated with a severe storm event (Moss et al. 2015). Likewise, records suggest the 1948 tidal surge that polluted freshwater sources across Bentinck Island and was implicit in the eventual removal of the Kaiadilt was the outcome of tidal banking caused by cyclonic winds coinciding with a peak king tide (BOM 2015c; Memmott 1982b; Tindale 1962a, 1962b). A number of similar surge events have been postulated for the region throughout its lifespan (see Memmott et al. 2016). Thus, trajectories associated with the onset of wet season conditions may be further punctuated by more extreme shifts in environment, climate, and behaviour (Table 3.2). While it appears that seasonality is fundamentally entwined with many behavioural trajectories within the Wellesley islands, it remains unclear how these notions may apply specifically to Kaiadilt populations. However, ethnographic accounts provide numerous hints of the trajectories that may emerge from high-resolution datasets centred on the South Wellesley's. The collection and analysis of such data will allow researchers to better understand interactions between seasonal environmental change and the Kaiadilt, thus providing an avenue to approach interpretations related to mobility, demography, and changing patterns of occupation permanency.

Table 3.2 Number of tropical cyclones per decade (1906 – 2006) in the South Wellesley Islands (BOM 2015c).

Years	No. of cyclones within 100 km	No. of cyclones within 200 km	No. of cyclones within 400 km
1906 – 1910	2	3	3
1911 – 1920	1	3	6
1921 – 1930	0	4	7
1931 – 1940	3	5	8
1941 – 1950	4	7	10
1951 – 1960	5	6	8
1961 – 1970	2	6	10
1971 – 1980	5	8	17
1981 – 1990	3	5	12
1991 – 2000	4	9	13
2001 – 2006	3	5	9

3.4 Summary

This chapter provided an overview of the physical and cultural background of the study area. The South Wellesley Islands were contextualised within broader patterns of environmental, climatic, and behavioural development allowing the validity and accuracy of local archaeological interpretation to be improved. Processes of palaeoenvironmental and landscape development constitute an integral component for understanding when and why Aboriginal populations began utilising the South Wellesley Islands as they underpin the development of numerous resources. The dialogue between environment and culture was demonstrated within Kaiadilt responses to their highly seasonal environment with similar patterns likely to emerge as occupation permanency is characterised. However, this interpretation was reached using indirect evidence from ethnographic and ethnohistoric sources. The complex systems of the South Wellesley Islands likely manifest within the archaeological record, although in ways and at scales not commonly explored. Thus, the incorporation of high-resolution techniques such as sclerochronology can provide the data required to accurately characterise these trajectories, allowing researchers to approach nuanced interpretations of how changing human-environment interactions impacted Aboriginal use of island environments.

Chapter 4 Biological and Ecological Overview of Target Shellfish Taxa

4.1 Introduction

Molluscs are fundamental components of aquatic ecosystems throughout most environmental zones worldwide. Such ubiquity has seen prolonged human exploitation of shellfish as an optimal, targeted resource to fill numerous niches in economic systems, including a supplementary form of protein, seasonal food source, fundamental resource, or raw material source (e.g. Attenbrow 2011; Bell 2009; Erlandson 1988, 2001; Faulkner 2013; Garvey 2015; Manne and Bicho 2011; Marean et al. 2007; Meehan 1982; Moss 1993; Rosendahl et al. 2014a). Mollusc remains are consequently one of the most common (often dominant) inclusions in coastal archaeological deposits, with the analysis of such material an integral component of much coast-centric archaeological research. Shellfish are highly sensitive to ambient conditions with fundamental aspects of biology, physiology, and behaviour responding to slight environmental variations. When these relationships are characterised and incorporated into analytical frameworks, the accuracy and validity of interpretations made through the lens of molluscan remains can be markedly improved.

In the South Wellesley Islands, molluscs constitute an important component of past and present Kaiadilt subsistence, evidenced by shellfish remains dominating both stratified deposits and surface scatters (Peck 2016; Rosendahl et al. 2014a; Ulm et al. 2010). Taxa from numerous environments were exploited by Kaiadilt populations, including intertidal flats, mangrove systems, estuaries, and rocky platforms, resulting in a wide variety of species accumulating within the archaeological record. Three archaeologically prevalent bivalve taxa *Gafrarium pectinatum*, *Marcia hiantina*, and *Polymesoda coaxans*, were selected for further analysis. These species are not only prominent in the archaeological record of the South Wellesley Islands but are fundamental components of shell-bearing features throughout the broader context of the north Australian coast (e.g. Bailey et al. 1994; Faulkner 2013; Meehan 1977, 1982; Morrison 2003; Rosendahl et al. 2014a, 2015; Sim and Wallis 2008). Moreover, these taxa provide a cross-section of commonly exploited environments throughout the Australian tropical region, with the potential to extend throughout much of the Indo-Pacific region. While other bivalves are prevalent throughout the archaeological record some are no longer extant (e.g. *Tegillarca granosa*), making it difficult to generate accurate modern interpretative analogues. Numerous species of gastropods are also found throughout the region, however they are not a focus here owing to dietary preferences producing less systematic correlations with ambient environmental conditions (Petchey et al. 2012). This chapter presents the biology, ecology, behaviour, and environmental relationships of these economically important shellfish taxa, thus forming the foundation for later discussion and interpretation.

4.2 *Gafrarium pectinatum*

4.2.1 Distribution and Economic Role

Gafrarium pectinatum (Bivalvia: Veneridae) (Roding 1798) is an intertidal bivalve common along tropical and subtropical shores throughout the Indo-Pacific with key habitats located in India, Japan, Southeast Asia, and Australia (Figure 4.1). Occupying a shoreline position close to the lower limit of the neap tide, *G. pectinatum* populations appear largely independent of sediment granularity residing in substrates ranging from sandy to muddy (Baron and Clavier 1992) as well as intertidal rocky platforms and associated rock pools (personal observation, March 2014, July 2014). Juveniles prefer sandy environments with low mud content, limiting their distribution and suggesting movement between growth stages (Baron and Clavier 1992). Often referred to by its synonym *Gafrarium tumidum* (Linnaeus 1758), *G. pectinatum* is commonly known as the venus clam (Jagadis 2011; Jagadis and Rajagopal 2007a, 2007b) or tumid venus clam (Jagadis and Rajagopal 2007b). In Kayardild this species is known as *bijurra* (Evans 1992).

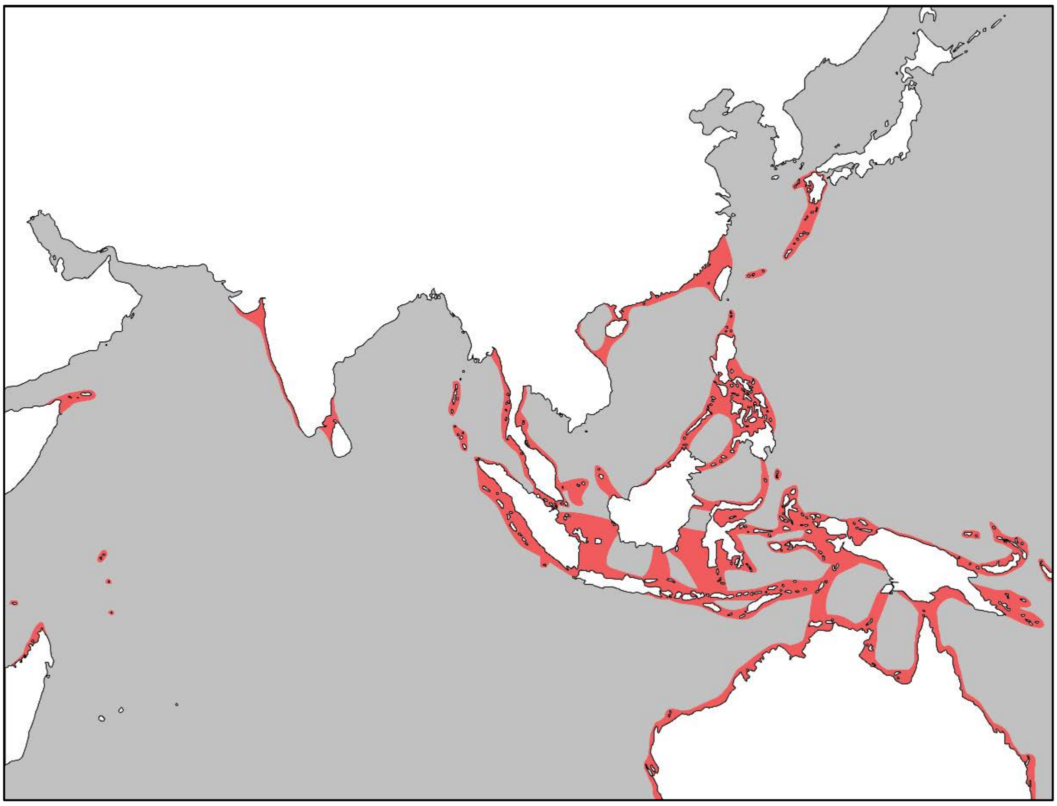

Figure 4.1 Distribution of *G. pectinatum* across the Indo-Pacific (after GBIF 2013a; SeaLifeBase 2012a).

While *G. pectinatum* is recognised as an important component of numerous modern diets throughout the Indo-Pacific (Davies 1985; Jagadis 2011; Jagadis and Rajagopal 2007a, 2007b; Kurihara 2003; Nayar and Rao 1985; Nielsen 1976; Purchon and Purchon 1981) as well as being highlighted as having potential commercial value in both Taiwan (Hsieh et al. 1981) and New Caledonia (Baron 1992; Jimenez et al. 2011), research focused on the biology and ecology of this species remains limited (Figure 4.2). A majority of available published data originates from two sources, work undertaken on the southeast coast of India (Jagadis 2011; Jagadis and Rajagopal 2007a, 2007b) and in New Caledonia (Baron 1992; Baron and Clavier 1992). A small dataset is also available from Japan, however this research focuses solely on adaptations against predation and desiccation (Kurihara 2003). While these studies explore various aspects of *G. pectinatum* ecology, including reproduction, settlement, larval and shell growth, and the impact of environmental conditions on distribution, caution must be exercised when applying these findings to geographically distant contexts.

Figure 4.2 *In situ* live *G. pectinatum* specimen at Raft Point, Bentinck Island, South Wellesley Islands (Photograph: Daniel Rosendahl, 2014).

Archaeologically, little work has focused on *G. pectinatum* beyond inclusions in species diversity lists and dietary reconstructions. However, when considered in combination, this body of research indicates that the exploitation of *G. pectinatum* was common across much of Australia’s north and northeast coasts (e.g. Beaton 1985; Brockwell et al. 2009, 2011; Faulkner

2008, 2013; Sim and Wallis 2008). In the Wellesley Islands, *G. pectinatum* is a regular inclusion within archaeological deposits and as part of surface scatters (Figure 4.3). Abundances of *G. pectinatum* suggest that it was subjected to relatively stable although low-level exploitation throughout much of the occupation of the island group with associated dates for exploitation extending to 1959 cal BP (Peck 2016).

Figure 4.3 A mixed shellfish scatter including *G. pectinatum* on Sweers Island (Photograph: Daniel Rosendahl, 2012).

Beyond more traditional archaeological analyses, isotopic assay of *G. pectinatum* undertaken by Petchey et al. (2013) suggests this species has the potential to act as a high-resolution palaeoenvironmental proxy as well as being a candidate for ^{14}C radiocarbon dating. However, caution is advised in areas with limestone bedrock and limited exchange with ocean water as results indicate *G. pectinatum* may prefer high intertidal estuarine environments, which put them at risk from terrestrial carbon interference (Petchey et al. 2013). As these factors are not present within the South Wellesley Islands, these same results suggest *G. pectinatum* is suitable for seasonality determinations via sclerochronological analysis of stable oxygen and carbon isotopes.

4.2.2 Biology and Ecology

4.2.2.1 Environmental Tolerances and Responses

Given its intertidal positioning, *G. pectinatum* is subjected to regular shifts in salinity and temperature as well as periods of aerial exposure. Unfortunately, there has been little research aimed at characterising the influence of environmental conditions on this species. The literature reveals only one experiment investigating the impacts of temperature, demonstrating that *G. pectinatum* can survive extended periods (at least 24 hours) of exposure to 34°C heat (Kurihara 2003). However, responses beyond mortality were not explored. Relationships between environmental mechanisms and *G. pectinatum* growth regimes, behaviour, and community structure therefore remain largely unknown. While associated responses potentially mirror those of bivalve species that share similar geographical distribution and environmental preferences direct evidence is required to validate this assumption.

There is a similar paucity of work exploring the effects of aerial exposure on *G. pectinatum*, however the study undertaken by Kurihara (2003) highlights adaptations developed to counteract the desiccation and predation common to intertidal communities. A short syphon allows *G. pectinatum* to inhabit shallow burrows in the substrate while continuing to respire, yet this species often prefers to remain on the sediment surface (Kurihara 2003). Thus, other approaches are utilised to mitigate desiccation and predation. Laboratory tests subjected live *G. pectinatum* to conditions common during aerial exposure, including elevated temperatures (27 – 34°C) and desiccation (simulated in a drying oven). After 48 hours, no mortalities were observed (Kurihara 2003). It is therefore postulated this species primary defence against these conditions is its thick, globose shell. Its shape and robustness also makes it difficult for predators to reliably access the organism via drilling or crushing. These same characteristics protect *G. pectinatum* from sharp increases in temperature by slowing heat conduction (Kurihara 2003). This likely diminishes the impact of short-term aerial exposure and associated thermal fluctuations, however reduced conduction may also hinder cooling and increase the probability of desiccation or heat coma during long emersions.

While basic measurements of growth rates have been undertaken, understandings of ties with environmental conditions remain underdeveloped. An observed decrease in growth rates during January (winter) in a Japanese population suggests links to temperature (Kurihara 2003), however as precise environmental conditions were not presented this cannot be confirmed. As with a majority of other molluscs growth slows substantially through ontogeny. For Indian populations, Jagadis and Rajagopal (2007a) suggest that *G. pectinatum* live for up to three years and grow approximately 24.4mm in their first year. This slows to 7.5mm during their second year and 5.9mm in the third year. This was confirmed by a similar pattern of growth found in a Japanese population (Kurihara 2003).

4.2.2.2 Reproductive Cycles

G. pectinatum mature into separate male or females forms, although they are indistinguishable externally. Results from geographically distant populations agree that sexual maturation occurs between 20 – 22mm (Baron 1992; Jagadis and Rajagopal 2007b). While the age at which this occurs has not been directly confirmed, comparisons with growth regimes suggest individuals mature sometime during their first year (Jagadis and Rajagopal 2007a). The tropical climate inhabited by a majority of *G. pectinatum* populations encourages protracted spawning throughout the year, peaking in November and to a lesser extent March and April (Baron 1992; Jagadis and Rajagopal 2007b). These correspond to the hottest temperatures (31.1 – 34.3°C) and highest salinities (above 30 PSU) (Baron 1992; Jagadis and Rajagopal 2007b), strongly suggesting a correlation between reproductive cycles and environmental conditions. Periods of sexual regression coincide with decreases in temperature, leading Baron (1992) to postulate that temperature was a key determining factor in the timing of *G. pectinatum* spawning. Further, instances of breeding cessation during periods of heavy rainfall (e.g. monsoonal systems) have been documented, indicating potential links between reproductive cycles and salinity (Jagadis and Rajagopal 2007b).

The paucity of research focused on exploring the biology and ecology of *G. pectinatum* severely limits our understanding of relationships between this species and the environment. While interest in commercial cultivation and harvest of *G. pectinatum* in Taiwan (Hsieh et al. 1981) and New Caledonia (Baron 1992; Jimenez et al. 2011) may encourage future researchers to undertake more detailed investigations of *G. pectinatum*, we are currently restricted to extrapolating estimates from the information currently available.

4.2.2.3 Shell Structure and Features

Little work has been undertaken on the physical and geochemical structure of *G. pectinatum* shell beyond confirming that it is constructed from aragonite (Glover and Taylor 2010). Likewise, there have been few attempts to characterise and understand internal growth features and their relationship with environmental factors. Visual analysis of *G. pectinatum* shell cross-sections generated as part of this research (see Chapter 5 for procedures) reveal few growth features are macroscopically visible (Figure 4.4), prompting the question of whether accurate sclerochronological analysis of this species is possible. It is therefore imperative that research exploring associated mollusc-environment relationships is carried out to increase our knowledge of how changing components of local habitats impact physical and geochemical attributes of *G. pectinatum* shell and test its efficacy as a medium for sclerochronological analysis.

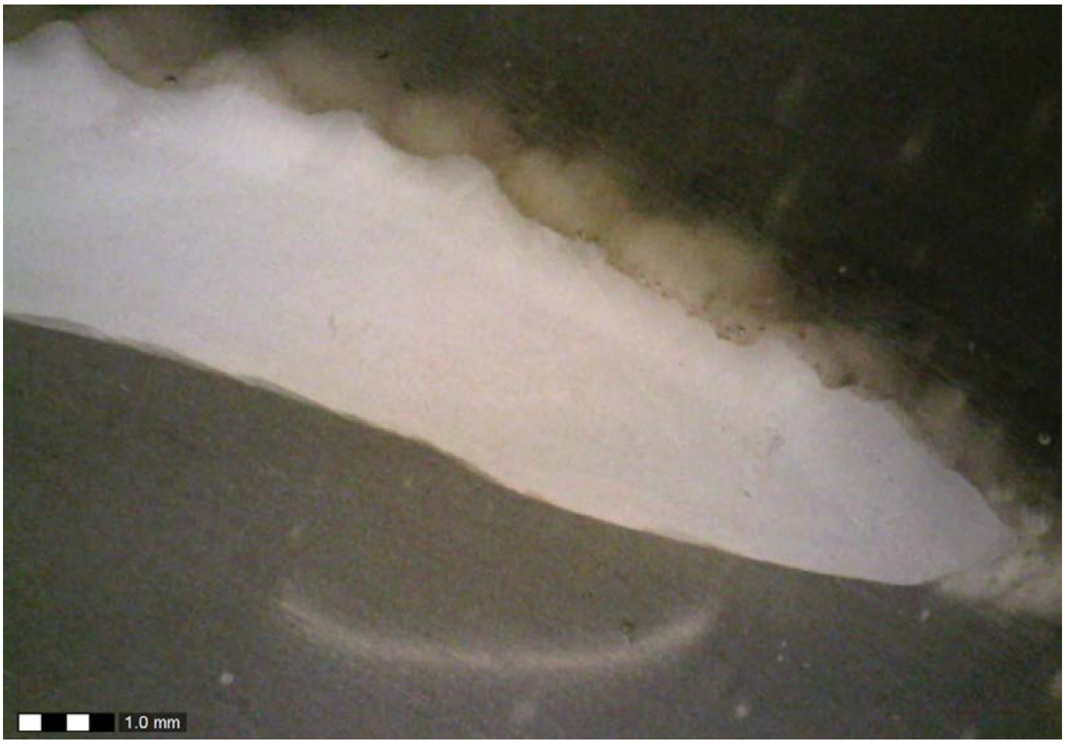

Figure 4.4 Section of a *G. pectinatum* live-collected from the South Wellesley Islands. Note the lack of easily visible growth features.

4.3 *Marcia hiantina*

4.3.1 Distribution and Economic Role

Marcia hiantina (Bivalvia: Veneroidea) (Lamarck, 1818) is a marine bivalve found throughout the Indo-West Pacific. This species inhabits an area stretching between the Gulf of Aden in the west, Papua New Guinea in the east, southern Japan in the north, and the Queensland coast in the south (Figure 4.5). Preferring sheltered areas, *M. hiantina* inhabits a variety of sandy and muddy substrates in the low intertidal and subtidal zones up to a depth of approximately 20m. This species frequently burrows up to 8cm into the substrates, employing a relatively long siphon as a snorkel (Carpenter and Niem 1998). Often referred to by a number of synonyms, including *Tapes hiantina* (Meehan 1982), *Paphia hiantina* (Davies 1985), and *Katelysia hiantina* (Lamarck 1818), *M. hiantina* is more commonly known as the hiant venus or gaping clam (Carpenter and Niem 1998) and is known in Kayardild as *bardawuluwulu* (Daniel Rosendahl pers. comm. 2015).

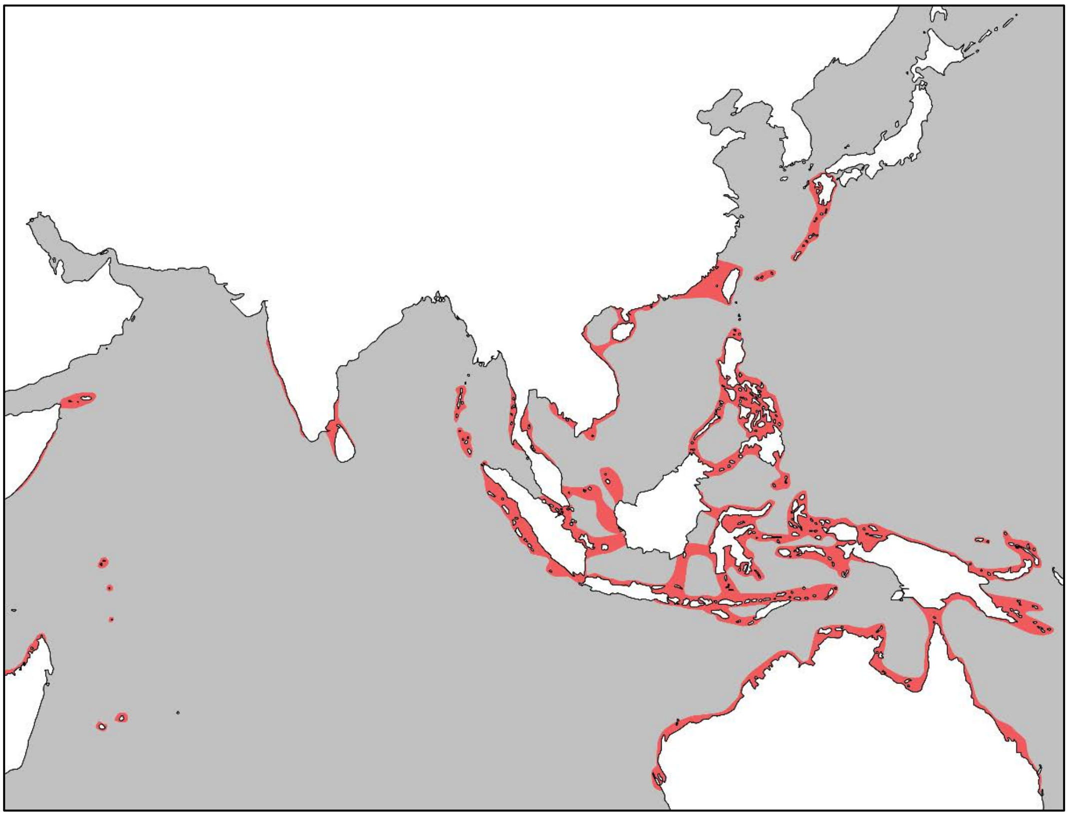

Figure 4.5 Distribution of *Marcia hiantina* across the Indo-Pacific (after SeaLifeBase 2012b).

While *M. hiantina* is an important component in a number of modern economies, particularly in the Philippines and Sri Lanka where it is commercially harvested (Kithsiri et al. 1994, 2000, 2004; Toral-Barza and Gomez 1986), very little research has examined the biology and ecology of this species. The majority of current datasets are largely tied to commercially farmed populations (Kithsiri et al. 1994, 2000, 2004). As commercial mollusc cultivation frequently produces high density populations with modified feeding, growth, and reproduction regimes (see Broom 1985; Mirzaei et al. 2015; Pathansali and Soong 1958), it can be difficult to apply associated findings to natural *in situ* communities (Figure 4.6). Moreover, akin to other species discussed in this chapter, a majority of the available data originates from a limited range of geographic locations, in this case Sri Lanka and to a lesser extent the Philippines, demanding caution when extrapolating findings to other populations.

Archaeologically, *M. hiantina* are common throughout many coastal archaeological sites along Australia's north and east coasts (e.g. Faulkner 2013; Morrison 2003, 2013; Rosendahl et al. 2014a; Sim and Wallis 2008; Ulm et al. 2010). Such widespread ubiquity throughout the archaeological record suggests *M. hiantina*'s importance to many coastal subsistence economies. This notion is reinforced in ethnographic observations of the Anbarra people of Arnhem Land where *M. hiantina* (referred to here by a synonym *Tapes hiantina*) are an important component of wet season diets (Meehan 1977, 1982). A similar pattern of seasonal exploitation was documented in the nearby Castlereagh Bay region (Davies 1985). Moreover, *M. hiantina* dominated shell mounds and extensive middens have been reported near Weipa, Queensland (Cochrane 2014; Morrison 2003, 2013). A number of other studies have documented the inclusion of *M. hiantina* in the archaeological record, including numerous areas along the Arnhem Land coast (e.g. Bourke 2004; Faulkner 2008, 2013), Kimberley coast (O'Connor 1996), and islands in the Gulf of Carpentaria (Rosendahl 2012; Rosendahl et al. 2014a; Sim and Wallis 2008; Ulm et al. 2010).

Figure 4.6 Populations of *M. hiantina* commonly inhabit sandy substrates located in subtidal and low intertidal zones (Photograph: Daniel Rosendahl, 2014).

Owing to their ubiquity throughout the archaeological record, *M. hiantina* shell is commonly used in the development of geochronologies based on radiocarbon (e.g. Brockwell et al. 2009; Faulkner 2008; Faulkner and Clarke 2004; Rosendahl et al. 2014a; Sim and Wallis 2008; Ulm et al. 2010). Approximately 72 chronologies situated along the Australian coast have incorporated a total of 102 unique radiocarbon determinations derived from *M. hiantina* shell (Ulm and Reid 2000; Williams et al. 2014). While isotopic assay undertaken by Petchey et al. (2013) does not include *M. hiantina*, similarities between this species and *G. pectinatum* suggest its use for radiocarbon dating and isotopic analysis might be warranted. While outside the scope of this research, further analysis of *M. hiantina* to confirm its suitability for radiocarbon dating should be encouraged, especially given its widespread use.

In the South Wellesley Islands, *M. hiantina* is the most abundant shellfish taxa throughout much of the archaeological record. The exploitation of this species is evident across a majority of the islands in the archipelago and can be seen throughout numerous deeply stratified deposits as well as variably sized surface scatters (Figure 4.7), suggesting its widespread and long-term incorporation into economic systems (Peck 2016). Modern populations of *M. hiantina* appear to have dwindled throughout the South Wellesley Islands in comparison to what appears to have been a highly available resource in the past. However, it is currently unclear as to why this may be the case with the potential paucity of modern *M. hiantina* populations not approached within the literature (see Chapter 9 for further discussion).

Figure 4.7 An extensive *M. hiantina* surface scatter located along the margins of the central saltpan on Bentinck Island.

4.3.2 Biology and Ecology

4.3.2.1 Environmental Tolerances and Responses

Some authors have described *M. hiantina* as a short-lived, fast growing species (Kithsiri et al. 2004), however very little data are available regarding the lifespan and growth rates of this taxa. Likewise few studies have explored interactions between environmental conditions and *M.*

hiantina populations. Yet, given what is known regarding the preferred habitat of this species and the ecology and biology of similar bivalve taxa, some basic approximations can be reached.

As the preferred shoreline position of *M. hiantina* places it at or just beyond the interface of tidal and subtidal influences, fluctuations in salinity, temperature, or extended periods of desiccation owing to aerial exposure are lessened. Therefore, *M. hiantina* is likely not as well equipped to successfully negotiate environmental variability as other more intertidal taxa such as *G. pectinatum*. Lowered environmental tolerances may cause heightened responses to slight change, increasing instances of growth and/or feeding cessation. This notion is strengthened by comparisons between two Sri Lankan habitats, Puttalam Lagoon (high salinity fluctuations, unfavourable substrates, and low mean depth) and Dutch Bay (stable salinity, sand/clay substrates), that found salinity and substrate impacted mortality and growth rates (Kithsiri et al. 2004). Conversely, research undertaken in the Philippines suggests *M. hiantina* populations may have a high tolerance for variable salinities with individuals surviving values ranging between 10 – 36 PSU with little impact on mortality (Toral-Barza and Gomez 1986), although there is no indication of how long these conditions persisted or whether growth rates were impacted. The same population was subjected to relatively stable temperatures (ranging between approximately 24 – 32°C) (Toral-Barza and Gomez 1986), making it difficult to ascertain the impact of temperature on mortality or growth.

As *M. hiantina* populations are positioned further towards the subtidal zone than the other species discussed in this chapter, environmental factors not present in the intertidal may impact the biology and ecology of this species. For instance, authors have suggested that aquatic plant coverage may affect the community dynamics of *M. hiantina* populations (Kithsiri et al. 1994, 2004). Dense concentrations of seagrass appear to enhance the deposition of larval spat fall, protect individuals from burrowing predators, and increase local productivity, thus facilitating significant increases in population density and recruitment (Kithsiri et al. 1994, 2004). Likewise, population density may also be impacted by changing salinity conditions (Kithsiri et al. 2000).

Unfortunately, the paucity of *M. hiantina* focused research makes it difficult to accurately characterise the impacts of environmental conditions on the biology and ecology of this species. While it is likely that temperature and salinity do impact growth rates, behaviour, and morality, as they do with other marine bivalve species, accurate characterisations require increasingly robust datasets generated from a combination of laboratory and *in situ* studies.

4.3.2.2 Reproductive Cycles

Despite several other species of venerid clams – particularly *Mercenaria mercenaria* (e.g. Ansell 1967; Craig et al. 1988; Dickinson et al. 2013; Zarnoch et al. 2015) – being subject to extensive research, very little is known about the reproductive activities of *M. hiantina*. A literature review revealed a single study of a population in Bacoor Bay, Sri Lanka, focusing on this topic (see Toral-Barza and Gomez 1986). Thus, only a limited overview of *M. hiantina* reproduction is presented.

M. hiantina is a dioecious species, maturing into distinct male and female forms. Little is known regarding the age and size at which sexual maturation occurs, however bivalve species with similar lifespans often exhibit accelerated growth rates to reach maturity within their first year (see Broom 1982a, 1982b; Jagadis and Rajagopal 2007a, 2007b; Narasimham 1969; Pathansali 1966). Like many other tropical mollusc taxa reproductive activity occurs continuously throughout the year, with the intensity fluctuating between distinct peaks and troughs. For the Sri Lankan population, a single peak occurred between June and September during the first year of observation, however the second year saw a significant decrease in overall spawning behaviour (Toral-Barza and Gomez 1986). This may be further complicated as Kithsiri et al. (2004) report variability in recruitment patterns between geographic locations, although no temporal information is provided.

The reproductive cycles of numerous marine bivalve species are tied to environmental conditions, particularly shifts in temperature, salinity, and productivity, thus intra- and inter-annual as well as geographic fluctuations observed in *M. hiantina* are potentially tied to similar factors. Toral-Barza and Gomez (1986) observed that slow gametongenic activity coincided with low temperatures, increasing as temperatures began to rise throughout the year. While decreased activity also corresponded with high salinity values, a lack of instantaneous responses to abrupt decreases owing to heavy freshwater inputs from typhoons, rainfall, and terrestrial runoff suggest that salinity fluctuations do not stimulate spawning (Toral-Barza and Gomez 1986). Yet, it was suggested that high salinities may inhibit spawning rather than gametogenesis. This has led Toral-Barza and Gomez (1986) to suggest that temperature is more critical to gametogenesis while salinity may regulate spawning to some extent. Similarly, Kithsiri et al. (2004) link geographic variability in the timing of recruitment peaks to differences in overall environmental conditions between the two locations.

While the work of Toral-Barza and Gomez (1986), and to a lesser extent Kithsiri et al. (2004), provide a broad overview of the impact key environmental conditions may have on reproductive cycles, factors not explored here, such as population density, substrate type, productivity, and shoreline positioning, can significantly impact the timing and periodicity of molluscan spawning (e.g. Broom 1985; Faulkner 2013; Yurimoto et al. 2014b). Moreover, elucidating the age and size at which sexual maturity is reached would greatly improve fundamental understandings of *M. hiantina* reproduction. Approaching these and other questions outlined in this section requires an increase in the number of studies focused on *M. hiantina* as a species. Increasing our knowledge of this species would provide more nuanced data related to biology and ecology while also allowing other disciplines, such as archaeology, to better interpret their own findings.

4.3.2.3 Shell Structure and Features

Little analysis of shell growth structures and their potential relationships to environmental stimuli has been undertaken, as is also the case for other aspects of *M. hiantina* biology and ecology. Moreover, there exists a comparable paucity of research into the geochemical attributes of *M. hiantina* shell. Low-power microscopic analysis of sectioned *M. hiantina* shell undertaken as part of this research (see Chapter 5 for procedures) reveals closely spaced micro-growth features that regularly alternate between lines and increments (Figure 4.8). This may indicate a substantial tidal influence on the growth patterning of this species, however further research is required to confirm this notion.

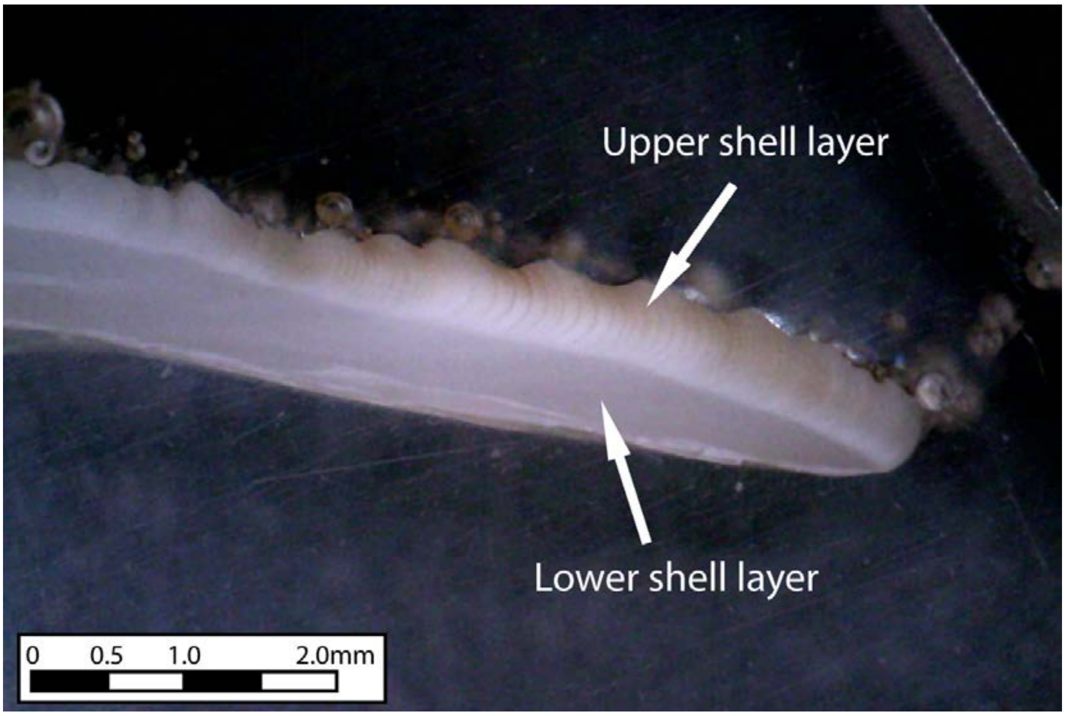

Figure 4.8 Growth features in *M. hiantina* shell are extremely closely spaced.

4.4 *Polymesoda coaxans*

4.4.1 Distribution and Economic Role

The large bivalve species *Polymesoda coaxans* (Bivalvia: Corbiculidae) (Gmelin, 1791) is distributed across tropical and sub-tropical zones throughout the Indo-Pacific, stretching from Sri Lanka in the west to the Solomon Islands in the east, and from Japan in the north to northern Australia and New Caledonia in the south (Figure 4.9). This infaunal species prefers shallow pools/burrows of water in the firm mud substrata surrounding the roots and stems of mangroves. Regular shifts in salinity, temperature, and periods of aerial exposure inherent to these tidally fed environments suggest that *P. coaxans* is a hardy species that possesses several specialised adaptations. Variably identified by a number of synonyms, including *Gelonia erosa* (Stephens et al. 2008), *Gelonia coaxans* (Beaton 1985), and *Polymesoda erosa* (Clemente and Ingole 2009; Gimin et al. 2004, 2005; Morton 1976), this species is more commonly referred to as 'mud clams' or 'mangrove cockles' (Gimin et al. 2004, 2005) and is known as *thubaldah* in Kayardild (Evans 1992).

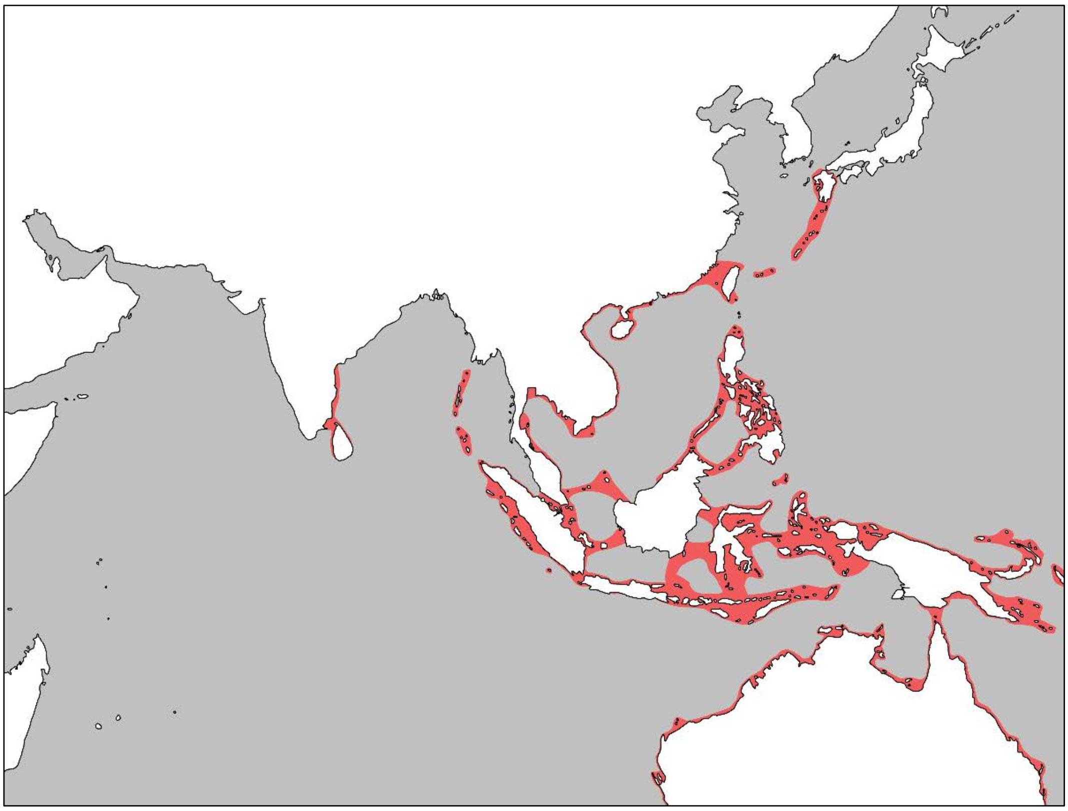

Figure 4.9 Distribution of *P. coaxans* across the Indo-Pacific (after GBIF 2013b; SeaLifeBase 2012c).

Modern *P. coaxans* populations in Southeast Asia, India, and along Australia's north coast are frequently exploited by nearby communities as part of traditional subsistence economies or as a supplementary protein source (e.g. Davies 1985; Gimin et al. 2005; Meehan 1982; Morton

1976). In various regions along Australia's north coast, *P. coaxans* has been identified as one of the most prominent non-fish groups in the indigenous catch (Coleman et al. 2003; Willan and Dredge 2004). Ethnographic observations by Davies (1985) and Meehan (1982) have documented the collection of *P. coaxans* along the Arnhem Land coast for subsistence purposes (Figure 4.10). Similarly, Roth (1904) observed *P. coaxans* valves being used as tools in the Princess Charlotte Bay region, Queensland. In the South Wellesley Islands, modern Kaiadilt people continue to exploit *P. coaxans* when present on country (Amy Loogatha, Netta Loogatha, Ethel Thomas, and Duncan Kelly, Kaiadilt residents of Mornington Island, pers. comm. 2014). Yet, despite its wide abundance, hardy nature, and relative ease of exploitation, *P. coaxans* is not commercially cultivated or harvested in any of the geographic zones it inhabits. This has led some researchers to suggest aquaculture of this taxa as an avenue to increasing food security in some coastal regions or as a commercial enterprise for indigenous communities (Clemente 2007; Clemente and Ingole 2009; Gimin et al. 2005).

Figure 4.10 *P. coaxans* is found in its preferred mangrove habitat across much of the Indo-Pacific region.

Given the widespread inclusion of *P. coaxans* in ethnographic reports of traditional subsistence economies, it is unsurprising that archaeological remains of this species are common throughout many of the same regions. In Borneo, *P. coaxans* were excavated from the Great Cave of Niah as part of excavations during the 1950s and 1960s (Harrisson 1970). These same shells were later geochemically assayed by Stephens et al. (2008) as part of palaeoenvironmental reconstruction efforts (see Chapter 2 and 7). Further evidence from Borneo suggests *P. coaxans* were employed beyond subsistence, forming an important component of expedient toolkits (Pyatt et al. 2010). Similar interpretations of *P. coaxans* use have been posited for Australia's north coast. Authors such as Beaton (1985), Schall (1985), and most recently Harris et al. (in press) have suggested *P. coaxans* shell tools were also present in Princess Charlotte Bay, a claim that was repeated in other areas such as the Alligator Rivers region (Schrire 1982) and the Kimberley coast (O'Connor 1999a).

Archaeological inclusions of unmodified *P. coaxans* are common along Australia's tropical coastline, including in Blue Mud Bay, Arnhem Land (Faulkner 2009, 2013), the Whitsundays (Barker 2004), and the Wellesley Islands (Peck 2016; Rosendahl 2012; Rosendahl et al. 2014b, 2014b, 2015). The wide availability of this species within the archaeological record has encouraged radiocarbon dates and palaeoenvironmental reconstructions to be obtained from *P. coaxans* (Brockwell 2006a, 2006b; Brockwell and Ackerman 2007; Brockwell et al. 2009; Hinton 2012; Rosendahl 2012; Sim and Wallis 2008; Stephens et al. 2008). However, Petchey et al. (2013) raises concerns regarding the reliability of radiocarbon dates derived from *P. coaxans* shell owing primarily to the presence of a strong terrestrial carbon signal (see Chapter 7 for further discussion).

Archaeological *P. coaxans* from the Wellesley Islands are frequently recovered from variably sized surface scatters (Figure 4.11), although are also rarely found in stratified deposits. While directly dating this species is problematic, owing to physiological challenges associated with its infaunal nature (see Petchey et al. 2013), current evidence suggests that many dense *P. coaxans* scatters on Bentinck Island (such as Mulla Island) were deposited within the last 400 years. This indicates a relatively recent commencement of *P. coaxans* exploitation that may be tied to cultural, behavioural, and/or environmental shifts occurring during the late Holocene. Preliminary research by Hinton (2012) used isotopic analysis of modern and archaeological *P. coaxans* shells as environmental markers for the South Wellesley Islands, however given concerns raised since then (Petchey et al. 2013) it is imperative that further evidence is collected to determine the viability of this species as an environmental proxy (see Chapter 7 for further discussion).

Figure 4.11 An expansive *P. coaxans* scatter on Mulla Island, south Bentinck Island, located in the centre of the large mangrove forest surrounding Mirdidingki Creek.

4.4.2 Ecology and Biology

Despite evidence indicating the importance of *P. coaxans* to various populations through time, research endeavouring to better characterise biological and ecological traits of this species remains geographically restricted. Laboratory-based experiments undertaken by Clemente (2007) and Clemente and Ingole (2009, 2011) in Goa, India, provide the most detailed accounts of environmental tolerances, reproduction, and associated behaviour available. Other researchers have explored the biology and ecology of *P. coaxans* in northern Australia (Gimin et al. 2004, 2005) and Southeast Asia (Dolorosa and Dangan-Galon 2014; Morton 1976, 1984, 1985, 1988), however these have focused exclusively on morphology and reproduction. Due to the geographically variable nature of molluscan responses to environmental stimuli, caution should be exercised when applying these findings to geographically distant populations until further localised research becomes available.

4.4.2.1 Environmental Tolerances and Responses

Given *P. coaxans* preference for landward habitats, populations are commonly subjected to the extremities of local conditions. The shallow pools of water they inhabit (Figure 4.12) are often only inundated during peak high tides, thus broad fluctuations in salinity, pH, and temperature are common (Clemente 2007; Clemente and Ingole 2011; Gimin et al. 2004). Moreover, processes of evaporation and drainage can leave communities aerially exposed for several days or weeks, until such time as water is replenished via tidal flushing. Adult *P. coaxans* rely on a variety of survival mechanisms to negotiate their harsh environment, however these do not develop until late in the juvenile stage. Thus, the distribution of this taxa is largely delineated by growth stage. Newly recruited larval settlers prefer either low-tide or mid-tide zones, juveniles are largely confined to low-tide areas (although small numbers have also been recorded in the mid-tide zone), while adults almost exclusively inhabit high-tide habitats (Clemente and Ingole 2011). This pattern likely hastens the growth of juveniles, allowing them to take advantage of the relatively stable conditions of the low-to-mid intertidal zones to quickly reach sexual maturity and equip them with the characteristics required to survive as adults.

Figure 4.12 A typical *P. coaxans* habitat consisting of shallow pools of water in depressions surrounding mangrove roots (Photograph: Daniel Rosendahl, 2014).

The massive aragonitic shell exhibited by adult *P. coaxans* is the most noticeable and easily recognisable defence against harsh mangrove conditions. It has been suggested that environmental conditions partially dictate the maximum size of *P. coaxans* shell (Morton 1988), diminishing the survivability of some individuals, however more research is required to better understand relationships between environment and shell robustness. The organism within the shell is comparatively small, exhibiting poor relationships between shell size and soft tissue weight (Clemente 2007), suggesting that *P. coaxans* directs significantly more energy to shell formation than soft tissue growth. The diminutive animal size allows this species to maintain a sufficiently large volume of water inside the shell to support its metabolic needs during long periods of emersion (Clemente 2007). Moreover, the robust nature of *P. coaxans* shell protects the animal from predators as well as the highly acidic mangrove mud (Morton 1985). The impact of low pH levels is commonly seen in significant dissolution of shell material near the umbo (Figure 4.13).

Figure 4.13 The low pH levels common to mangrove habitats can cause dissolution of *P. coaxans* shell, particularly around the umbo.

Like many other bivalve species, *P. coaxans* respond to aerial exposure by tightly sealing their valves to isolate the organism from ambient conditions (Clemente 2007). Similar behaviours are adopted by individuals subjected to freshwater (0 PSU) conditions. Continued exposure to greatly diminished salinities can lead to death with six days, while *P. coaxans* can survive typical brackish (18 PSU) and marine (30 PSU) salinities indefinitely (Clemente 2007). Likewise, direct sunlight increases mortality rates in emersed specimens (Clemente 2007), likely owing to rising internal temperatures and rates of desiccation. Emersion also sees the expulsion of water from the mantle cavity to allow aerial respiration through the mantle (Clemente 2007; Morton 1976).

Provided the animal was not subjected to direct sunlight and temperatures remain within an optimal range (24 – 30°C), completely exposed individuals can survive for up to five weeks under stable laboratory conditions (Clemente 2007). Natural *in situ* populations are capable of surviving much longer periods of aerial exposure, up to three months, owing to their ability to feed on subterranean water and detrital nutrients (Morton 1985). Under laboratory conditions

P. coaxans exposed to elevated temperatures (above 30°C) perish after three weeks, while cooler temperatures (down to approximately 5°C) cause death within four weeks (Clemente 2007). Natural *in situ* populations exhibit similar increases in mortality that coincide with seasonal drops in temperature (Morton 1988).

While Morton (1988) suggests environmental parameters influence *P. coaxans* growth rates, little research has explored the impact of changing environmental conditions on growth regimes. However, using broad understandings of bivalve physiology it is possible to reach some basic estimations. As valve closure signals the slow down or cessation of growth in many bivalve taxa (Schöne 2008), periods of aerial exposure, decreased salinity, or temperatures outside of an optimal range likely impact growth rates in *P. coaxans* (Thomas Stieglitz, pers. comm., 2015). Periods of altered growth are therefore likely common, potentially impacting the archiving of the environmental conditions within shell chemistry. However, given the extreme nature of its habitat, this species may have developed a higher tolerance for environmental variability than its intertidal counterparts.

As with other species, ontogenetic age plays a role in determining growth rates, with older specimen's precipitating shell at significantly slower rates than their younger counterparts. According to Clemente (2007), in the 6 months subsequent to recruitment, *P. coaxans* grow at a rate of approximately 10mm per month. During this time individuals reach sexual maturity causing energy to be redirected to the development of gonads and production of gametes, consequently growth gradually slows to 3.3 – 5mm a month. Similarly rapid growth rate has been observed in natural populations with individuals reaching 70mm within their first year (Dolorosa and Dangan-Galon 2014). Once specimens reach 80 – 90mm in length, growth again diminishes to approximately 2.5mm per month. Thus, animals reach their maximum size of 100 – 110mm in 3 – 4 years (Clemente 2007; Dolorosa and Dangan-Galon 2014). However, the lifespan of *P. coaxans* is difficult to determine with Clemente (2007) and Dolorosa and Dangan-Galon (2014) suggesting between 3 and 4 years, while Morton (1988) advocates life spans of up to 8 to 10 years. Inter-population comparisons indicate that environmental conditions likely play a role in determining the lifespan of individual *P. coaxans* (see Morton 1988), however the substantial difference between Indian/Philippine and Malaysian populations suggests that further analysis is required to better determine the longevity of this species.

4.4.2.2 Reproduction

P. coaxans are dioecious, displaying distinct male and female forms (Gimin et al. 2005). Reports of size at sexual maturation differ geographically with Indian and Philippine populations seeing sexual differentiation at 30 – 35mm and maturity between 40 – 46mm (Clemente 2007; Dolorosa and Dangan-Galon 2014), while *P. coaxans* from Hong Kong mature at 35mm (Morton 1985). While this variation seems relatively minor, it may be linked to inconsistency between the regions.

As with the other taxa discussed in this chapter tropical mollusc species typically breed continuously throughout the year with distinct peaks in spawning activity (Urban 2001), however the wide distribution of *P. coaxans* suggests it may employ a variety of reproductive strategies (Cardenas and Aranda 2000; Gimin et al. 2005). Morton (1985, 1988) documented spawning activity occurring in a single protracted event from September to May, suggesting that changes in salinity and temperature were key triggers. Indian *P. coaxans* exhibit a comparable extended peak from July to October triggered by changes to salinity from monsoonal rains, seasonal temperature shifts, or food availability (Clemente 2007; Clemente and Ingole 2009). Observations of a population in the Philippines indicate two recruitment peaks in April and September (Dolorosa and Dangan-Galon 2014). Similarly for northern Australia, target *P. coaxans* populations display a pattern of seasonally timed peaks with two major breeding periods, a short season in September and an extended period between February and May (Gimin et al. 2005). However, unlike *P. coaxans* from Hong Kong and India there is no evidence to link spawning in Australian populations with shifts in temperature or salinity (Gimin et al. 2005).

Contrasting these three *P. coaxans* populations reveals that there are indeed clear geographic differences in reproductive timing. The highly seasonal spawning regimes of *P. coaxans* suggests that if breeding cycles also influence growth rates evidence would manifest at specific times of the year, e.g. late in the wet season in Northern Australia. However, further research is required to link reproductive cycles with changes in growth patterns in *P. coaxans*.

4.4.2.3 Shell Structure and Features

Similar to other bivalve species, changes in growth rates linked with environmental conditions and physiological cycles are reflected through macroscopic physical changes within *P. coaxans* shell. Previous studies of the internal shell structures of this species have revealed the presence of well-defined growth lines and increments (Figure 4.14) as well as regular bundles of thin dark lines linked with tidal flushing of estuarine systems (Hinton 2012:74, 91). However, it is not yet possible to accurately link growth structures to exogenous and endogenous stimuli.

Correlations between oscillating stable oxygen and carbon isotopes ratios and alternating shell growth features have been characterised in numerous studies, suggesting similar growth structures return comparable values (e.g. Andrus and Crowe 2000; Jones and Quitmyer 1996).

However, a majority of this research has focused on temperate species where seasonal temperature fluctuations are the primary drivers behind growth stoppages, rather than the dual influences of salinity and temperature seen in tropical environments with strong monsoonal influences. For *P. coaxans* inhabiting tropical Australian environments, Hinton (2012:74) found no correlation between growth structures and stable isotope ratios with negative and positive $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values obtained from both lines and increments. Such variability indiscriminate of growth structure, suggests that factors beyond water salinity and temperature are influencing growth rates in *P. coaxans* populations. In particular, long periods of aerial exposure owing to *P. coaxans* infaunal nature and preference for landward habitats as well as irregular tidal inundations of mangrove environments are likely closely linked with periodic growth stoppages.

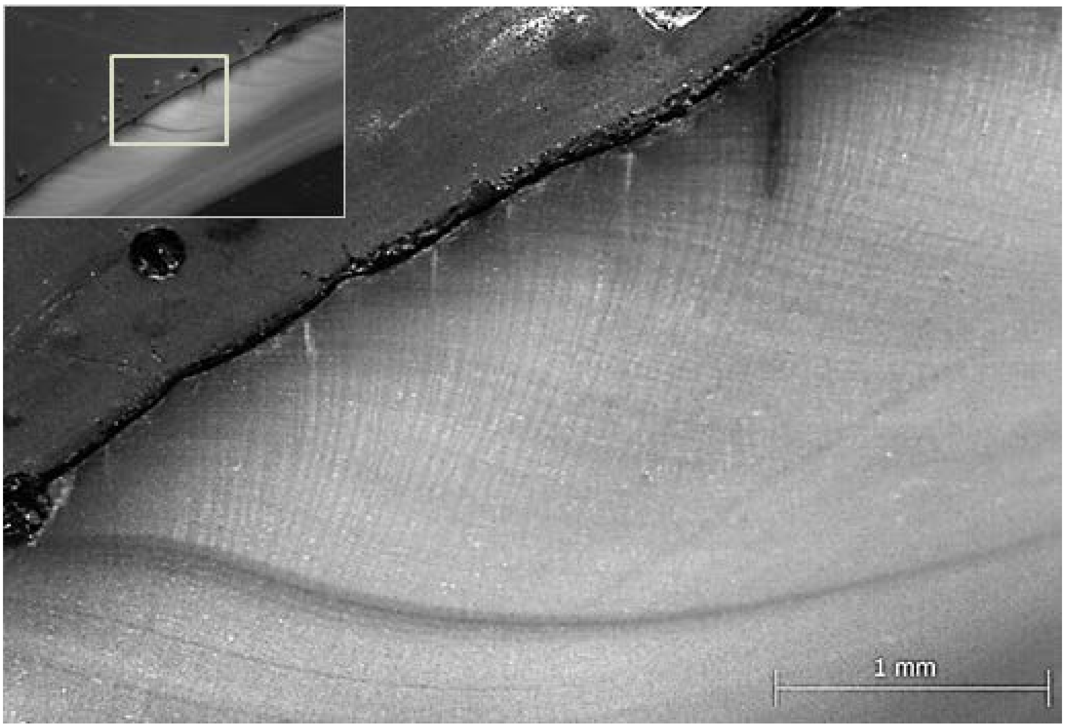

Figure 4.14 Both growth lines and increments are present within the internal shell structure of *P. coaxans.*

4.5 Summary

The biological and ecological overviews of *G. pectinatum*, *M. hiantina*, and *P. coaxans* presented in this chapter illustrate various relationships between these taxa and their environments. These interactions provide a framework capable of affording context integral to interpretations of modern and archaeological data. Species-specific biological and ecological factors also inform the suitability of shellfish taxa for geochemical assay while also drawing attention to potential issues. While much of this information originates from regions geographically distant to the South Wellesley Islands, it provides a foundation from which cautious extrapolations and comparisons can be made. However, it is also evident that numerous aspects of mollusc-environment relationships remain underdeveloped. Further research is required to more accurately characterise the impact of regular environmental changes on the behaviour, growth, and reproduction of constituent shellfish populations. Moreover, additional studies focused on the geochemical archives found in the shells of these taxa would assist in elucidating their efficacy as proxies for palaeoenvironmental reconstruction and seasonality analysis.

Chapter 5 Field and Laboratory Methods

5.1 Introduction

A range of analytical techniques were employed to characterise relationships between the geochemistry of target mollusc taxa shell and ambient environmental conditions as well as mid-to-late Holocene site-use, mobility, and demography in the South Wellesley Islands. Associated patterns are linked with sub-annual environmental and cultural factors, requiring high-resolution field and laboratory methods to identify localised short-term change. Further, unlike temperate zones, where a majority of sclerochronological research originates, seasonal environmental cycles prevalent along Australia's tropical north coast are driven by a combination of temperature change and hydrological shifts associated with the Australian monsoonal cycle. Methods are therefore tailored to account for these unique circumstances. This chapter outlines procedures adopted for the collection of modern environmental baseline data, live-collection of shellfish specimens, excavation of archaeological material, and laboratory analyses.

5.2 Field Methods

Four field seasons totalling 75 days were conducted by the author across the South Wellesley Islands during both wet (2014 and 2016) and dry (2013 and 2014) seasons. During this time environmental data as well as modern and archaeological specimens were collected from sites across the island group, with a focus on Bentinck Island. Modern observation and sampling was carried out over all field seasons, while archaeological excavation occurred primarily during the 2013 season (June – July). Further material not collected by the author, including water samples and modern shellfish specimens collected during 2012 (June – July) and 2015 (September) as well as archaeological material excavated between 2010 and 2012, is also incorporated.

5.2.1 Modern Environmental Data and Shellfish Collection

To accurately parse and interpret isotopic values derived from archaeological specimens a comparative framework formed via modern observations must first be established (e.g. Andrus and Crowe 2000; Bailey et al. 1983; Burchell et al. 2013b; Hallmann et al. 2009; Mannino et al. 2003). Analysis of modern live-collected molluscs combined with characterisations of local environmental conditions provide insight into interactions between the two and can be used to guide interpretations of archaeological results. To facilitate this, the impact of local environmental cycles on constituent mollusc populations was examined. A water sampling strategy designed to determine end-member values for $\delta^{18}O_{water}$, $\delta^{13}C_{DIC}$, and salinity was deployed in conjunction with continuous instrumental monitoring of temperature fluctuations at key sites. Third-party instrumental data from nearby Bureau of Meteorology (BOM) and Australian Institute of Marine Science (AIMS) stations located on Sweers Island and Karumba, respectively, were also incorporated. Live-collections of target mollusc taxa were undertaken during wet and dry season conditions, with sclerochronological analysis providing seasonal end-members for $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values.

5.2.1.1 Data Collection Sites

A majority of environmental monitoring was undertaken in the Mirdidingki Creek system and adjacent tidal zones. This area was targeted as it encompasses populations of target mollusc taxa and contains archaeological evidence of use by Kaiadilt populations. Moreover, Mirdidingki and the surrounding area provides a cross-section of environments common across the South Wellesley Islands and greater Gulf region, including clay pans, mangrove forests, tidal estuaries, intertidal flats, and subtidal zones. A detailed overview this area can be found in Chapter 6.

Other sites around Bentinck Island also underwent sampling (Figure 5.1). In particular, shellfish were live-collected from Raft Point (southeast coast of Bentinck Island) and Ngathald (west coast of Sweers Island). Where possible, water samples accompanied each live-collection of shellfish with additional water samples collected from the open marine system adjacent to Thundiy on the north coast of Bentinck Island.

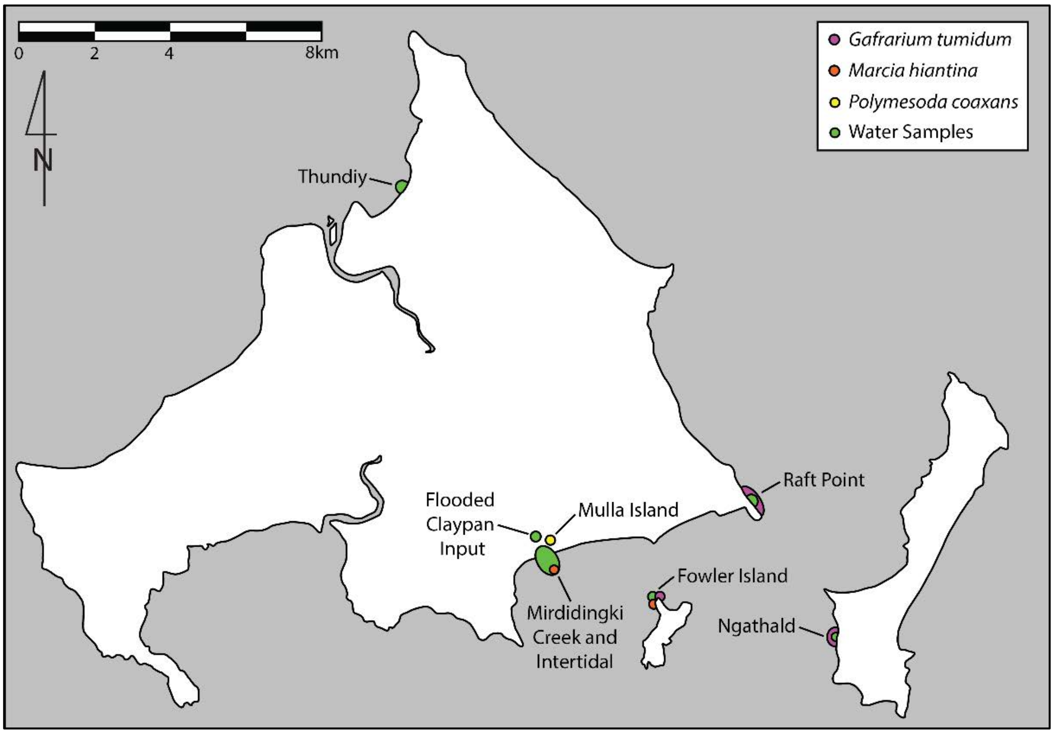

Figure 5.1 Water sample and live-collection sites were concentrated along the south coast of Bentinck Island, Sweers Island, and Fowler Island with ancillary collections occurring at Thundiy on the north coast.

5.2.1.2 Water Sampling

Water samples were collected to characterise daily/tidal and seasonal fluctuations in $\delta^{18}O_{water}$, $\delta^{13}C_{DIC}$, and salinity. The South Wellesley Islands are extremely isolated and are therefore particularly difficult and expensive to access. This meant the commonly employed strategy of continuous daily or monthly sampling over the course of a full year (e.g. Kennett and Voorhies 1995) was not feasible. Instead, end-member tidal cycles during wet and dry seasons were sampled extensively to establish seasonal hydrological ranges. Sampling was principally undertaken over two dry seasons (2013 and 2014) and one wet season (2014) with auxiliary sampling taking place during 2015 (September) and 2016 (February) in conjunction with live-collection of shellfish specimens. Collection sites throughout Mirdidingki Creek were selected to provide examples of environments common both on Bentinck Island and throughout the Wellesley Islands. As such, samples were taken from the end of the creek system, at its mouth, and in the intertidal and subtidal zones (Figure 5.2). The positioning of each intertidal zone sample was dictated by tidal height. Additional sampling was also undertaken in the mangrove forest surrounding Mirdidingki Creek.

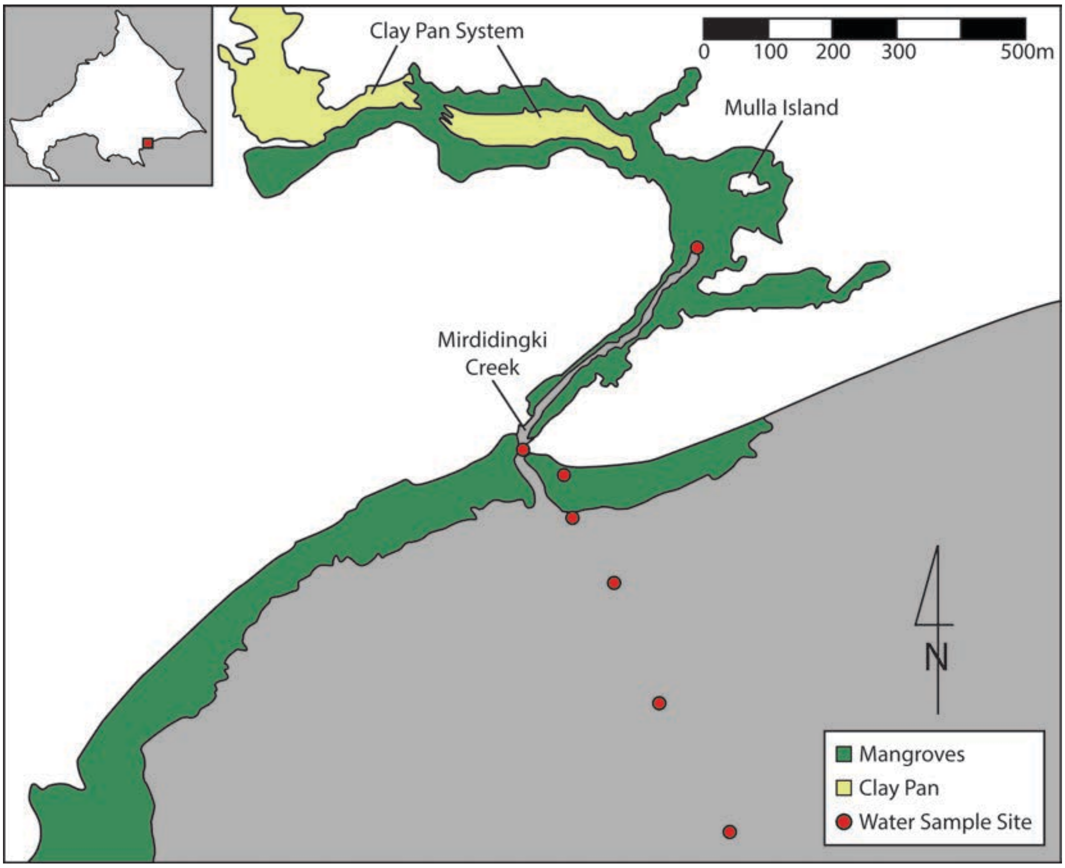

Figure 5.2 Example of water sampling over a single tidal cycle (wet season 2014, spring tide). Dark green indicates extent of mangroves.

While no laboratory preparation was required for $\delta^{18}O_{water}$ and salinity sampling, vials for $\delta^{13}C_{DIC}$ samples were prepared prior to each field season. Exetainer vials (12mL) were acidified with 2mL of 85% phosphoric acid (H_3PO_4) before being capped with rubber septa. Acidified vials were flush filled with helium (He) using a ThermoFisher Gas Bench III. Preparation occurred as close to the commencement of field seasons as possible to minimise gas leakages that can occur through pierced septa.

In the field, water was drawn from sample sites using a container such as a bucket. All samples were recovered from this container to ensure a homogenous sample set. Between each sample set the container was thoroughly rinsed to avoid cross-contamination. Vials for $\delta^{18}O_{water}$ (1x 12mL centrifuge vial) and salinity (2x 50mL centrifuge vials) were submerged then filled and capped while still immersed. Care was taken to ensure no air bubbles were trapped within the sample, thus reducing the chance of evaporation and interaction with atmospheric conditions during storage and transport. For $\delta^{13}C_{DIC}$ samples 2mL of He was removed by syringe and replaced by 2mL of sample water.

A record of all samples was kept in the form of a field specimen (FS) log. Each sample (for salinity both vials are counted as a single sample) was assigned a field specimen number (FS#). All vials were labelled with FS#, date, time, location, tide (spring or neap), and sample type before having their lids secured with electrical tape for transport. Where possible water samples were refrigerated until being transported to the laboratory.

Additional water sampling was undertaken during the 2014 dry season (July) along the north coast of Bentinck Island adjacent to Thundiy (Figure 5.3). This serves as a comparative dataset to test for variability in water composition between north and south coasts. Unfortunately, it was not possible to undertake similar sampling during the wet season as extensive seasonal flooding and inclement ocean conditions restricted access to Thundiy. Sampling methodology remained consistent with that undertaken at Mirdidingki with three sample sets ($\delta^{18}O_{water}$, $\delta^{13}C_{DIC}$, and salinity) recovered from a single sampling location in the tidal zone. Thundiy sample sets were collected at the beginning and end of July 2014.

While a further course of water sampling was planned for 2015, targeting mangrove environments within the Mirdidingki area, no water was present in associated systems owing to limited inundations by low average tidal heights (see Chapter 7). Thus, this sampling plan was abandoned. To assist in characterising hydrological differences between the open marine system and high shore rock pools (see Chapter 8), water samples were collected from the rocky platform located at Ngathald, Sweers Island. This coincided with the live-collection of *G. pectinatum* specimens from the same coastline (see Section 5.2.1.5).

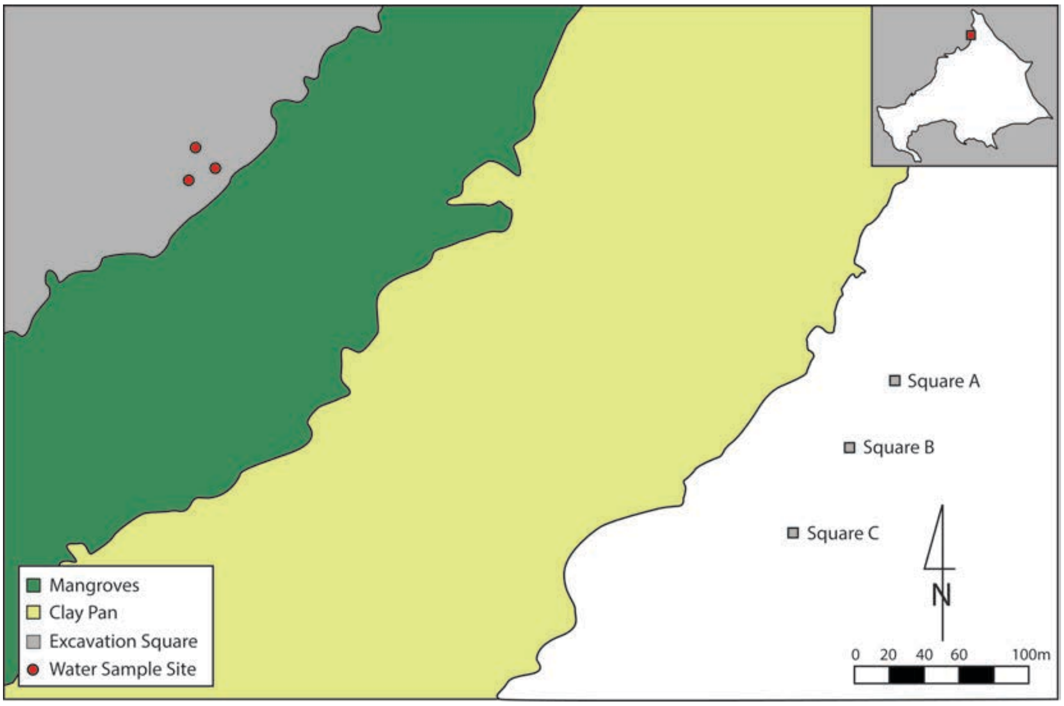

Figure 5.3 Thundiy water sampling sites shown in context with excavations undertaken in 2010.

A series of three water sample sets were collected during the 2016 wet season in conjunction with the collection of modern *G. pectinatum* and *M. hiantina* specimens. Samples originate from intertidal zone off the south coast of Bentinck Island, the north coast of Fowler Island, and the mangrove forest fringing Mulla Island.

5.2.1.3 Environmental Sensors

A series of environmental sensors were deployed throughout Mirdidingki Creek and its surrounds to provide a continuous record of environmental and hydrological changes over a full annual cycle (minimum of 388 days). These included five temperature loggers (HOBO Pendant) and one combination temperature/salinity logger (Star-Oddi DST-CT). Salinity data from the combination logger is not used within this research and so will not be discussed. HOBO Pendant sensors logged temperature readings every 90 minutes (16 data points per day), while the Star-Oddi DST-CT recorded once every 3 hours (8 data points per day). Sensors were distributed across six stations (Table 5.1) located at the end of Mirdidingki Creek (STN2), mid-creek (STN3), mouth of the creek system (STN1), intertidal (STN4) and subtidal zones (STN6), and a *P. coaxans* habitat (STN5) (Figure 5.4). Each sensor was secured to robust mangrove roots or star pickets using cable ties and electrical tape. GPS coordinates were recorded to allow easy relocation and collection. Water samples were collected adjacent to each station at the time of installation to assist with calibration. Sensor stations were observed over the course of each field season to ensure they had not become fouled and were cleaned if necessary. Instruments were recovered during the 2014 dry season (mid-to-late July).

Table 5.1 Sensor stations were deployed throughout the Mirdidingki Creek system and adjacent inter- and sub-tidal zones for a full annual cycle.

Station	Sensors	Location	Deployment	Comments
STN1	1 x Combination Salinity/Temperature	Mouth of Mirdidingki Creek	20/06/2013 – 13/07/2014	NA
STN2	1 x Temperature	End of Mirdidingki Creek	20/06/2013 – 20/07/2014	NA
STN3	1 x Temperature	Approximate mid-point of Mirdidingki Creek	20/06/2013 – 08/07/2013	Relocated (STN6) after approx. two weeks of deployment
STN4	1 x Temperature	Approximate mid-point of intertidal flats	20/06/2013 – 14/07/2014	Owing to its intertidal position, this sensor was likely exposed during some low tides
STN5	2 x Temperature	*P. coaxans* habitat	20/06/2013 – 20/07/2014	Sensors in *P. coaxans* habitat and nearby tree
STN6	1 x Temperature	Subtidal	09/07/2013 – 20/07/2014	Sensor relocated from STN3 to subtidal

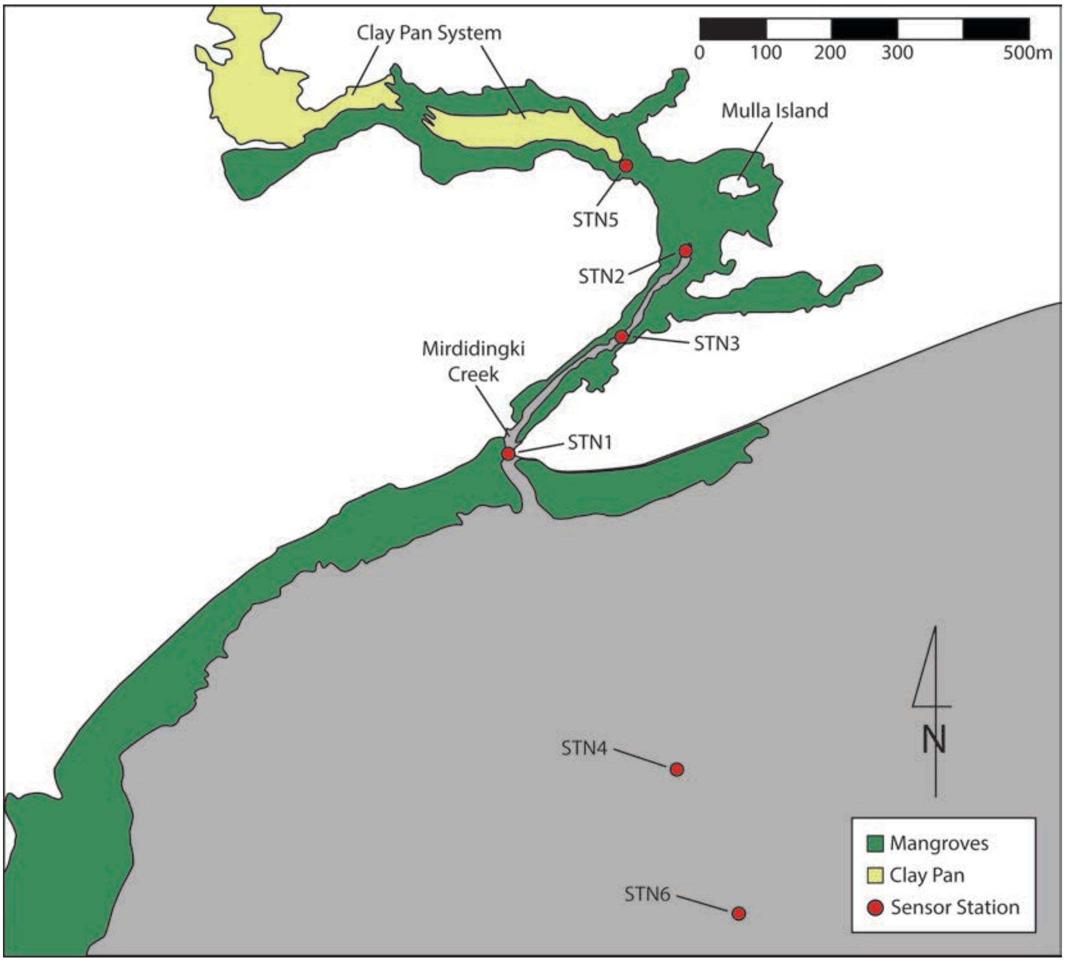

Figure 5.4 Positions of sensor stations deployed throughout the Mirdidingki Creek system, adjacent inter- and subtidal zones, and a *P. coaxans* habitat.

5.2.1.4 Third-Party Data

Third-party environmental data was obtained from the Australian Bureau of Meteorology (BOM) station located on Sweers Island (ID: 029139), approximately 10km southeast of Bentinck Island (Figure 5.5). Temperature, tidal, and rainfall data from 2001 to 2014 was accessed. It must be noted the short distance between Sweers and Bentinck Islands may result in some discrepancies, particularly with regards to rainfall, which can be highly localised in the Gulf of Carpentaria even during the wet season (personal observation, March 2014; Texas Battle, resident of Sweers Island, pers. comm., 2014). Despite this, Sweers Island represents the best source of long-term environmental data in the South Wellesley archipelago. Additional rainfall data from the Mornington Island BOM station (ID: 029039) was also accessed.

Sea surface temperature (SST) data was obtained from the Australian Institute of Marine Science (AIMS) station at Karumba (ID: KURFL1), located on the mainland coast approximately 150km southeast of Bentinck Island (Figure 5.6). This sensor was positioned on a reef flat (Lat: -17.49355, Long: 140.830183) at a depth of 0.0m and remained active from 18/11/1999 until

13/10/2006, although there are numerous breaks in the dataset (Table 5.2). Data was recorded at 30 minutes intervals before being averaged into daily and monthly means.

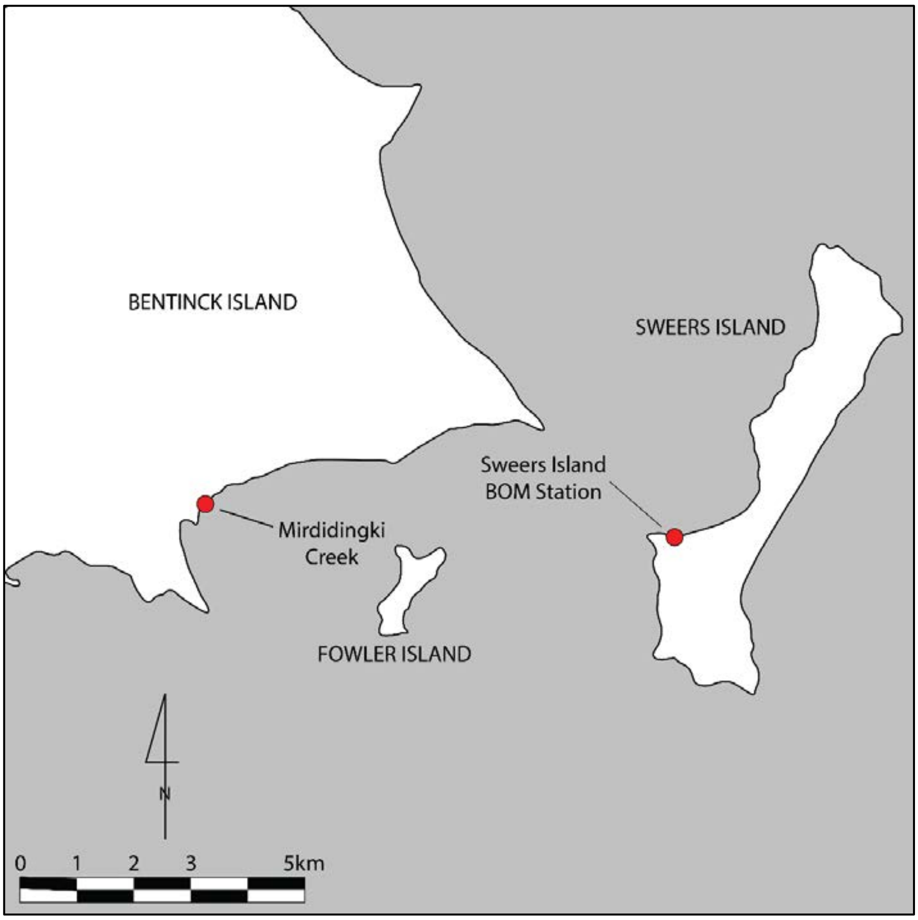

Figure 5.5 The Sweers Island BOM station and Mirdidingki Creek sensor stations sit approximately 10km apart.

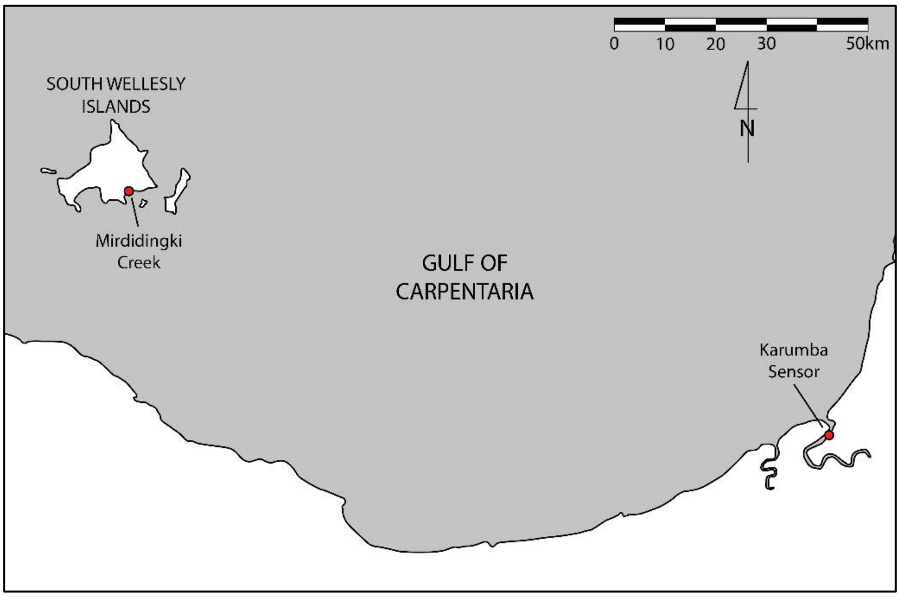

Figure 5.6 Sensors deployed in Mirdidingki Creek are approximately 150km west-northwest from the Karumba sensor station.

Table 5.2 Number of SST datasets recorded per month for the Karumba sensor over its 7 year deployment (AIMS 2015).

Month	No. of overall datasets
January	6
February	4
March	4
April	4
May	4
June	4
July	4
August	4
September	4
October	4
November	6
December	7

5.2.1.5 Live-Collected Mollusc Specimens

Live *P. coaxans*, *G. pectinatum*, and *M. hiantina* specimens were gathered during field seasons as modern control samples. Similar to water sampling, some authors advocate monthly collections of modern specimens over the course of a full year (e.g. Andrus and Crowe 2000). However, owing to the remote nature of the South Wellesley Islands an end-member sampling regime was undertaken with targeted live-collection of specimens occurring during wet and dry seasons. Local knowledge provided by Kaiadilt traditional owners (Netta Loogatha, Amy Loogatha, Ethel Thomas, and Duncan Kelly) was used in conjunction with known ecological preferences of each species (see Chapter 4) to target areas with the highest potential of concentrated populations. Water sample sets were collected at each shellfish gathering site to provide temporally and geographically localised environmental context. All mollusc specimens were assigned a FS# with details of date, time, location, and species. Mollusc specimens were euthanised by freezing as soon as possible subsequent to gathering.

Assemblages of *P. coaxans* were collected around Mirdidingki Creek near Mulla Island during 2013 and 2014 wet and dry seasons (Figure 5.7). Additional assemblages were collected at Mosquito Story to the west of Mirdidingki Creek in 2012 by Sean Ulm and Daniel Rosendahl as well as Mulla Island in 2015 by Texas Nagel, Anna Kreij, Daniel Rosendahl, and Sean Ulm. Cultural prohibitions forbid the counting of shells while collecting in mangrove habitats (Duncan Kelly, Kaiadilt traditional owner, pers. comm., 2013), thus it was only possible to approximate numbers during collection.

Figure 5.7 Top: The expansive mangrove forest fringing Mirdidingki Creek where live *P. coaxans* specimens were collected. Bottom: Example of an *in situ P. coaxans* specimen (Photograph: Daniel Rosendahl, 2014).

Live *G. pectinatum* were primarily sourced from the tidally exposed rocky shorelines and rock pools near Raft Point on the southeastern coast of Bentinck Island (Figure 5.8). While this area is geographically removed from Mirdidingki Creek, water sampling indicates similar water constitution. Thus, environmental observations remain applicable. Collections from Raft Point occurred during both wet and dry seasons during 2014. An additional cohort was collected in 2015 on the intertidal rock platform located at Ngathald on the west coast of Sweers Island.

Figure 5.8 Top: Typical rocky platform environment where *G. pectinatum* were live-collected (Photograph: Daniel Rosendahl, 2014). Bottom: *G. pectinatum* found in an intertidal rock pool (Photograph: Daniel Rosendahl, 2014).

While a large quantity of archaeological *M. hiantina* are found across Bentinck Island, indicating that this species was once plentiful and readily accessible, locating live populations of *M. hiantina* proved difficult. Thus, specimens were only collected during two field seasons, the 2014 dry season (*n* = 4) from the subtidal zone adjacent to STN6 (Figure 5.9) and the 2016 wet season (*n* = 4) from a sandbar off Raft Point and the intertidal zone around Fowler Island. While this assemblage is smaller than those associated with other target taxa, combining results with predictive modelling allows an understanding of how seasonal fluctuations are recorded within *M. hiantina* shell geochemistry to be approached. However, potential problems associated with the relatively limited nature of this assemblage must still be considered and discussed (see Chapter 9).

Figure 5.9 Top: Typical low intertidal flat environment home to *M. hiantina* (Photograph: Daniel Rosendahl, 2014). Bottom: Live *M. hiantina* specimen prior to collection (Photograph: Daniel Rosendahl, 2014).

5.2.2 Archaeological Material

5.2.2.1 Site Selection

As this research focuses on tracking changing patterns over through time, selection of target archaeological sites centres on chronological security and available time depth. The three sites explored in this research – Thundiy, Dangkankuruwuru, and Murdumurdu (Table 5.3) – exhibit well established, secure chronologies representative of changing phases of Kaiadilt occupation (ephemeral, low-level or seasonal, and permanent) proposed by previous research (Memmott et al. 2016; Peck 2016; Ulm et al. 2010). Detailed site descriptions and radiocarbon chronologies are presented in subsequent chapters.

Table 5.3 Archaeological shell matrix sites across Bentinck Island targeted for analysis.

Site	Site Type	Year Excavated	Site Area (m^2)	Area Excavated (m^2)	Sieve Size (mm)	Earliest Date (cal BP)
Dangkankuruwuru	Midden	2013	10500	1.25	2.3	1537
Murdumurdu	Midden	2012	3000	0.5	2.3	328
Thundiy	Midden	2009	600000	1	2.3	793

5.2.2.2 Excavation Methods

Excavations followed a predetermined recovery strategy designed to ensure consistency and facilitate comparisons of datasets from targeted sites. All excavations were limited to small test pits, being conducted as single or adjoining 50cm x 50cm squares orientated north-south/east-west. Additional squares were only excavated where cultural depositions continued below a depth obtainable in a 50cm x 50cm configuration (c.70cm) to minimise disturbance of the landscape. Where multiple adjacent squares were excavated they were labelled alphabetically (A, B, C etc) in a clockwise direction from the northeast square.

Excavation was undertaken by trowel in arbitrary c.2cm excavation units (XUs or spits) within identified stratigraphic phases. The southwest corner of each square was used as a reference point for horizontal (x, y) coordinates to plot objects and features. Five points of elevation (four corners and centre) were recorded for each excavation unit (XU) using a local datum, autoset level (Nikon AP-8), and stadia rod. Plan view photographs were taken at the completion of each excavation unit. Upon completion of the excavation, pits were cleaned by hand before photographs and section drawings of all sides were made. Information regarding photograph number, date, time, square, excavation unit, and any other details were recorded within a photographic log. A record of all samples (sieved/bulk samples and objects/special finds) recovered during excavation was kept in a field specimen (FS) log, where each item was assigned a unique field specimen number (FS#). Objects encountered *in situ* during excavation were assigned a FS#, plotted in three dimensions, labelled, and bagged separately, examples of objects include shell and charcoal samples for radiocarbon dating, articulated bivalves, and stone artefacts. The weight of excavated deposit was recorded to the nearest 0.25kg using a graduated 10kg bucket balance and 10L bucket.

Excavated sediment was dry-sieved onsite through 2.3mm mesh to reduce sample mass while minimising damage and loss of fragile elements such as fish bone. Sieving stations were situated on tarpaulins to prevent contamination of the underlying sediments. Retained material was labelled and bagged with an individual FS#. A sample (c.250g) of the <2.3mm sediment from each excavation unit was collected. Munsell Soil Color® Chart and pH tests were conducted in the field for every excavation unit. All information was recorded on a standardised form listing all associated FS#, plotted objects, photograph numbers, weight, and descriptions. Any deviations from the above protocols are addressed within relevant chapters.

5.3 Laboratory Methods

Laboratory methodology was designed to complement protocols deployed during fieldwork. Precise sample collection and analysis procedures are combined to generate robust datasets from which high-resolution interpretations of occupation patterns and population dynamics can be made.

5.3.1 Water Sample Analysis

All isotopic analysis of water samples was conducted at the Advanced Analytical Centre, James Cook University, Cairns, under the guidance of Dr Christopher Wurster, Dr Jen Whan, and Costjin Zwart. Salinity samples were processed by TropWATER, James Cook University, Townsville.

5.3.1.1 $\delta^{18}O_{water}$

A ThermoFisher Thermal Conversion Elemental Analysis Mass Spectrometer (TC/EA IRMS) was used to assess relative oxygen isotope abundance in water samples. Water samples of 1.5mL were pipetted into 2mL vials capped with rubber septa. Isotopic values were calibrated using Vienna standard mean ocean water (VSMOW) and Greenland ice sheet precipitation (GISP) standards, with a precision error of better than 0.1‰. Sample blocks were interspersed with sets of standards and blanks to ensure accuracy and precision. Cycles of three to five injections per sample were employed to negate memory effects.

5.3.1.2 $\delta^{13}C_{DIC}$

Stable carbon isotope ratios for water samples were determined using an online ThermoFisher Gas Bench III coupled to a ThermoFisher DeltaV^{PLUS} isotope ratio mass spectrometer (IRMS) through the ThermoFisher ConFloIV. Laboratory standards were prepared to calibrate isotopic values. Three carbonates ($NaHCO_3$, Na_2CO_3, and $CaCO_3$) with known isotopic values were used. Each standard was prepared by weighing between 200 and 500µg of carbonate into an exetainer vial and capped with rubber septa, flush filling the vial with He, and finally acidifying it with 6mL of a boiling 10:1 solution of deionised water and 85% phosphoric acid. A combination of standards and blanks were interspersed throughout sample blocks to monitor accuracy and precision. Precisions for internal standards were better than 0.1‰.

5.3.1.3 Salinity

Analysis of salinity samples was conducted at TropWATER, James Cook University, Townsville. Salinity and electrical conductivity measurements were conducted using a Cond 315i probe. The probe was calibrated for each analysis using internal potassium chloride standards. Salinity values were reported as practical salinity units (PSU).

5.3.2 Stable Isotope Analysis of Molluscan Carbonates

5.3.2.1 Selection of Specimens

Selection criteria for archaeological shellfish specimens are mediated by a number of important considerations including assemblage size and composition, potential for pre- or post-depositional alteration, specimen suitability, and labour and monetary constraints. Of particular concern to this research is recrystallisation of shell carbonates by extreme temperatures. Ethnographic accounts of Kaiadilt cultural practices indicate refuse is placed into the campfire subsequent to meals (Tindale 1963). Temperatures reached by campfires commonly exceed those required to initiate recrystallisation (Collins 2012; Milano et al. 2016; Robins and Stock 1990). Thus, it is essential that selection criteria are designed to accommodate this aspect of Kaiadilt culture.

Previous studies have outlined specimen selection criteria aimed at countering latent inaccuracies associated with post-depositional diagenesis. In particular, Burchell et al. (2013b:262) suggests a series of conditions that must be met for selection: 1) a portion of the ventral margin must be intact and preserved; 2) the upper shell layer must be intact and preserved; 3) absence of evidence indicating exposure to fire, e.g. burnt portions of shell or association within a hearth feature; and 4) size of the fragment is sufficient to provide an adequate sample of growth. Hinton (2012) utilised similar conditions as the basis for selecting suitable modern and archaeological *P. coaxans*.

While authors typically restrict analysis to whole valves, research has demonstrated that fragments can provide comparably reliable isotope values (Burchell et al. 2013a, 2013b; Hallmann et al. 2013; Kingston et al. 2008). However, it is important to ensure that fragments originate from different specimens to avoid erroneous results. This also applies to whole valves as sampling from both valves of a single specimen would provide unnecessary replication.

Selection criteria for modern live-collected mollusc specimens are relatively simple as there is little potential for geochemical alteration, unlike archaeological assemblages. Principally, specimens must have reached sexual maturity to: a) ensure at least one full annual cycle has been recorded within their shell structures; B) negate issues that may stem from different life stages inhabiting variable environments (see Chapter 4); c) allow juvenile growth rates to slow and stabilise; and d) negate differences in kinetic effects from different growth phases (see Schöne 2008). Other criteria include an intact ventral margin and upper shell layer that displays relatively little damage. This was particularly important for *P. coaxans* whose shell is often degraded by acidic mangrove mud (see Chapter 4).

Taking the above factors into consideration, this research has developed the following selection criteria for both archaeological and modern material (Table 5.4):

Table 5.4 Selection criteria applied to all specimens targeted for isotopic analysis.

Specimen Selection Criteria
• Identified either as one of a refitted valve-pair OR no conjoining valve was found • Past age of sexual maturation • Largely intact ventral margin – minimal macroscopic damage • Minimal wear on outer shell surface • No evidence of burning or exposure to fire – burnt sections or association with hearth features • Upper shell layer intact and preserved • Preferably whole valve, however fragments are also suitable provided they are of sufficient size to generate adequate carbonate sample from the ventral margin and have landmarks allowing minimum number of individuals (MNI) determination to identify specimens as individuals

To ensure assemblages provide a representation of species abundance, a percentage-based sampling approach was implemented. For material originating from stratified deposits, 5% (rounded to the nearest 10) of the total minimum number of individuals (MNI) for each target species was selected from each XU. For those XUs with MNI counts of less than five, one suitable specimen was sampled. If the number of suitable individuals totalled less than 5% of the XUs MNI, all usable specimens were selected.

5.3.2.2 Specimen Preparation

As specimens were sampled using a variety of carbonate collection techniques (see Section 5.3.2.3), specimen preparation differed depending on the chosen sampling protocol. Regardless of carbonate collection method, all valves were manually abraded with a wire brush to remove adhering particulates and loosely attached periostracum. Each valve was then immersed in an ultrasonic bath of deionised water for a minimum of 10 minutes. Valves were left to air dry for 24 hours. No further preparation was required for specimens undergoing targeted ventral margin sampling, this included all archaeological material and a majority of modern material.

Select modern specimens were analysed using high-resolution micro-milling to generate an ontogenetic isotope profile. Similarly, in species where micro-milling was not feasible (see Chapter 9) ontogenetic micro-drill spot sampling was undertaken. Numerous authors suggest that specimens undergoing ontogenetic sampling be reinforced with an epoxy to guard against catastrophic damage during sectioning or carbonate collection (e.g. Burchell et al. 2013a, 2013b, 2014; Hallmann et al. 2010, 2013). While numerous forms of epoxy are available, E180 was selected owing to its proven efficacy (see Hinton 2012) and ready availability. This two-part epoxy requires resin and hardener to be combined in a 5:1 ratio. Moulds were greased with petroleum jelly to ensure the epoxy did not adhere to its interior. A layer (1 – 2cm) of epoxy mixture was poured into each mould and allowed to partially harden for approximately 20 – 30 minutes. Mollusc valves were then gently placed dorsal side down in the still hardening epoxy and immersed with a further layer of mixture. This two-step process ensured each valve was surrounded by a thick layer of epoxy, providing maximum structural stability (Figure 5.10). The epoxy was left to cure at room temperature for a minimum of 48 hours.

Figure 5.10 A live-collected *P. coaxans* valve encased in epoxy prior to thick sectioning.

Encased specimens were thick sectioned and polished by José Abrantes at the Centre for Archaeological Science, University of Wollongong. Two ~3mm thick sections were produced per valve (Figure 5.11). Specimens were bisected along the axis of maximum growth using a Gemmasta trim saw fitted with a 9 inch diamond sintered blade. Excess material was ground from the exterior of the section until they were approximately 4 – 5mm thick. A series of increasingly fine emery papers (600 and 1200 grit) were used to smooth and polish each section by hand. After each stage of polishing the section was cleaned in an ultrasonic bath of deionised water to remove any remaining particulates.

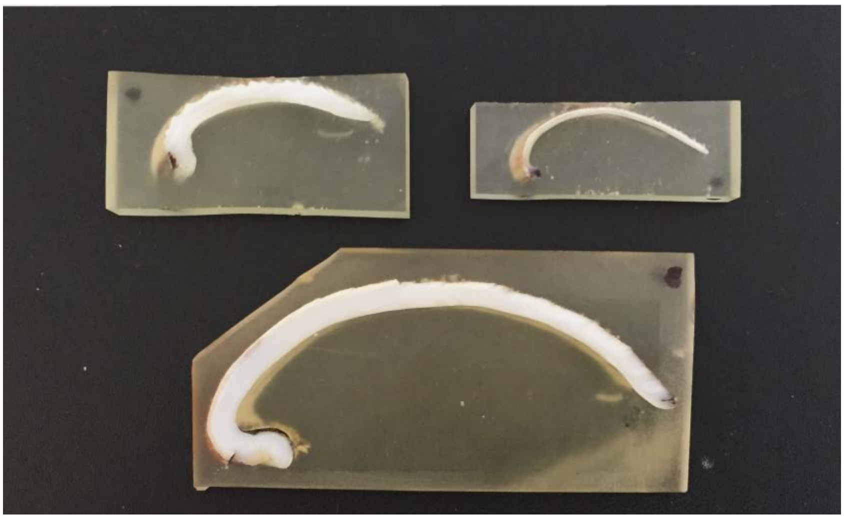

Figure 5.11 Thick sections of target specimens. Top left: *G. pectinatum*; Top right*: M. hiantina*; Bottom: *P. coaxans*.

5.3.2.3 Carbonate Sampling

Carbonate sampling procedures are an exceptionally important, although often overlooked, facet of sclerochronology. Attainable resolution, time investment, monetary costs, and quantity of analysable material are largely dictated by sampling regimes. This research employs a combination of techniques to balance these attributes and produce datasets suitable for the aims of the study.

High-Resolution Micro-Milling

As growth features of target mollusc taxa are macroscopically fine, small sample sizes can assist in characterising short-term environmental oscillations within shell carbonates. Micro-milling has been endorsed as a technique allowing high levels of accuracy, precision, and sampling resolution (Spötl and Mattey 2006; Stephens et al. 2008; Wurster et al. 1999). High-resolution micro-milling was undertaken on a select number of modern specimens with the intention of sampling carbonate deposited in both wet and dry season conditions. A lack of detailed information relating to growth rates and structural features of target species (see Chapter 4) caused difficulties in characterising full annual cycles prior to isotopic analysis. It was therefore decided c.50 transects would be milled from select specimens with known temporal (live-collected during wet and dry season conditions) and geographic provenance to provide seasonally targeted isotopic snapshots. This allowed intra-seasonal variations and seasonal averages to be characterised. Sampling was confined to the most recent annual cycle to allow comparisons between observed environmental conditions and live-collected shellfish, while simultaneously limiting the time and monetary costs of sampling and analysing individual specimens. The amount of time represented in micro-milled samples was dependent on species-specific shell precipitation rates. As such, ontogenetic profiles generated for larger, longer-lived species (*P. coaxans*) represent shorter periods of times at higher resolutions than small, shorter-lived taxa (*G. pectinatum* and *M. hiantina*).

A NewWave Micromill^{TM} system fitted with a 50µm conical drill bit was used (Figure 5.12). Thick sections were mounted to the stage with double-sided tape. Where possible scan lines were digitised to coincide with individual growth features under magnification (x45 – x75). However, accurately assessing growth feature placement in some portions of shell proved difficult. If growth features were not visible, scan lines were spaced at a resolution of approximately 150µm. Each transect measured approximately 80µm deep, 100µm wide, and traversed the width of the upper shell layer (where multiple layers were detected). An average of 58µg of powder was produced per transect, although this was highly dependent on transect length. Powder samples were collected using a pair of scalpels and placed in a vial, labelled, and recorded along with any associated comments (e.g. type of growth feature, issues with sample, relative size of transect). Between each sample the section, drill bit, stage, and scalpels were thoroughly cleaned with compressed argon (Ar).

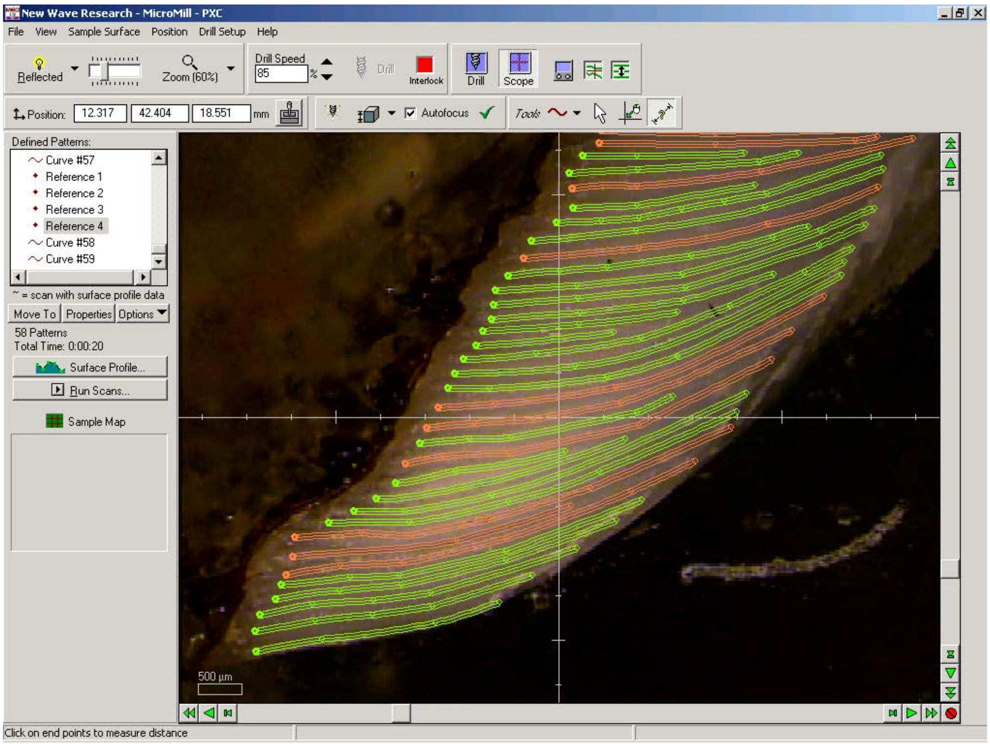

Figure 5.12 NewWave Micromill^{TM} interface showing the process of transect digitisation.

Targeted Ventral Margin Collection

Targeted ventral margin sampling permits the analysis of carbonates precipitated just prior to death. As this research is not attempting detailed palaeoenvironmental reconstructions, focusing rather on characterising variability between annual seasonal shifts and timing of material deposition, this procedure allows the expedient collection of relatively large sample sets without sacrificing resolution. Further, this technique minimises destruction of irreplaceable archaeological specimens, requiring only a small carbonate sample (between 40 and 80µg per specimen) without the need for sectioning.

Targeted ventral margin collection was applied to all remaining modern specimens as well as all archaeological material. As precise timing of collection is known for modern specimens, ventral margin collection allows comparisons between specimens collected during different seasons and associated environmental conditions with relative ease. For archaeological material, comparisons of ventral margin isotope values to modern analogues allow expedient seasonal determinations.

The stage of a reflected light microscope (Wild M3 Stereo Microscope) was cleaned with 100% ethanol and covered with a square of aluminium foil to collect carbonate powder. Carbonate was abraded from the ventral margin using a Dremel 3000 Rotary Tool fitted with a cylindrical diamond wheel (Dremel 2.4mm 7122 Point Diamond Wheel) under 6.4x magnification. A 10mm area surrounding the axis of maximum growth (5mm either side) was ground to remove a small carbonate sample (40 – 80µg). Powder was then collected and placed in a labelled vial. Between samples drill bits were cleaned in an ultrasonic bath of deionised water to avoid cross-contamination, the microscope stage and scalpels were cleaned with compressed air and ethanol, and the foil layer replaced.

Micro-Drill Spot Sampling

Sectioned *M. hiantina* specimens were deemed unsuitable for micro-milling as sample transects were limited by extremely thin upper shell layers, causing carbonate samples well below weights required for isotope analysis (see Section 5.3.3; further discussed in Chapter 9). Spot sampling was undertaken on these sections as it allows collection of larger carbonate samples with a minimal decrease in resolution.

Powder was extracted using a Dremel 3000 Rotary Tool fitted with a 0.3mm round tungsten carbide drill bit (Komet Dental H71-104-003). Samples were taken from sectioned material at an average resolution of approximately 345µm (centre to centre) under 20x magnification (Figure 5.13). A procedure similar to edge margin collection was employed. Bench space was cleaned using 100% ethanol. A square of aluminium foil was applied to catch any loose carbonate. Samples were extracted, collected into a vial, and labelled before the bench was re-cleaned and a new layer of aluminium foil was applied. A fresh drill bit was used for each sample and cleaned in an ultrasonic bath of deionised water to avoid cross-contamination.

Figure 5.13 Spot sampled *M. hiantina* thick section.

Further Sampling

Owing to concerns regarding recrystallisation in archaeological material (see Section 5.4.2.1), each shellfish was tested using fourier transform infrared spectroscopy (FTIR). Further details regarding the specifics of this procedure can be found in Section 5.3.2.4. A carbonate sample of at least 2mg (as this research is only interested in determining the carbonate polymorph precise carbonate weights are unnecessary) was collected from near the umbo of each specimen using the same Dremel Rotary Tool set-up as for ventral margin collection. The 2mg weight represents the minimum amount allowable for accurate FTIR analysis (1% of sample boat capacity), thus minimising damage to archaeological specimens. This carbonate material was collected subsequent to the completion of all other sampling and was stored in separate vials.

5.3.2.4 Testing for Recrystallisation

To test for recrystallisation, carbonate samples were analysed using a Bruker Alpha-T Fourier Transform Infrared Spectroscopy unit. To ensure readings reflected laboratory conditions, in-house standards were prepared using material known to be either calcite or aragonite. For the aragonite standard carbonate from a live-collected modern *Polymesoda coaxans* valve was used, while a laboratory calcite powder was employed to generate the calcite standard. Carbonate samples collected for FTIR testing were thoroughly combined with potassium bromide (KBr) using a mortar and pestle. The mixture was then packed into a FTIR sample boat, ensuring a smooth surface, and loaded for analysis. A series of 25 background readings were taken prior to analysis. Samples were then subjected to 25 runs to produce a wavelength plot. Data was normalised using the baseline normalisation function prior to interpretation. Plots for archaeological samples were compared to standards to gauge recrystallisation. Frequencies of 875-900 indicate calcite and suggest that recrystallisation may have occurred, while peaks of 857 indicate stable aragonite (Figure 5.14).

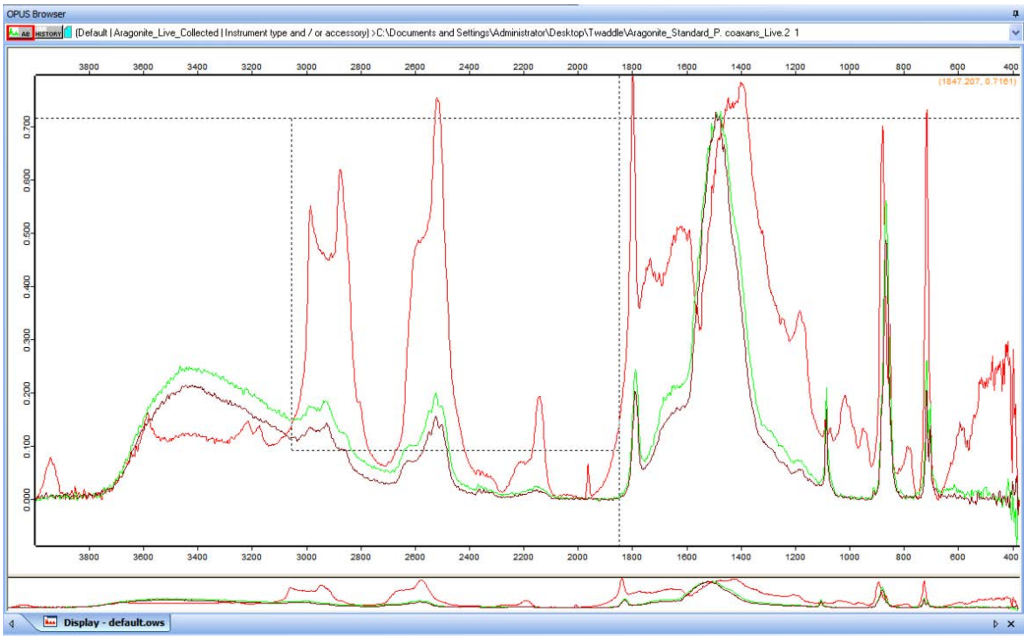

Figure 5.14 FTIR wavelength plot depicting an aragonitic shell (black line) in comparison to aragonite (green line) and calcite (red line) standards.

5.3.3 Stable Isotope Analysis

Sample preparation was undertaken by the author while stable isotope analyses were run by Dr Jennifer Whan and Dr Christopher Wurster at the Advanced Analytical Centre, James Cook University, Cairns. Samples were weighed to measure between 30 – 80µg before being transferred to exetainer vials and sealed with a rubber septa. Sample vials were flushed filled with helium before being acidified with 100% phosphoric acid and left to equilibrate for 18 hours at 25°C. Analysis of stable oxygen and carbon isotope composition was undertaken using a Thermo GasBench III connected to a DeltaV^{PLUS} (ThermoFisher) gas source mass spectrometer via a ThermoFisher ConFloIV. Each set of samples (*n* = 30) were accompanied by at least five standards (NBS-18 and/or L-SVEC) and three control samples (NBS-19) with similar mass to unknown samples. The results are reported with reference to the international standard Vienna Pee Dee Belmnite (VPDB) with precision better than 0.1‰ for both $\delta^{18}O$ and $\delta^{13}C$.

5.4 Modelling and Predictive Equations

Measured $\delta^{18}O_{shell}$ and $\delta^{18}O_{water}$ values can be used to calculate sea surface temperatures (SST) using the empirically derived temperature equation for biogenic aragonite proposed by Grossman and Ku (1986) with the correction for conversion of VSMOW to VPDB applied by Dettman et al. (1999) using Equation 5.1:

$$SST°C = 20.6 - 4.34\,(\delta^{18}O_{shell(VPDB)} - (\delta^{18}O_{water(VSMOW)} - 0.27)) \qquad \text{(Equation 5.1)}$$

Equation 5.1 was chosen as it has proven accuracy in many sub-tropical regions (see Mannino et al. 2008; Prendergast et al. 2013; Schöne 2013; Yan 2013). Furthermore, a study undertaken by Lécuyer et al. (2004) indicates that this equation is applicable across many temperate and tropical mollusc taxa. While SST values are rarely calculated in this study (see Chapter 9), this equation was instrumental in modelling seasonal $\delta^{18}O_{shell}$ value ranges. Measured $\delta^{18}O_{water}$ values were used to calculate $\delta^{18}O_{shell\text{-}predicted}$ for both wet and dry seasons in key mollusc habitats (subtidal, intertidal, estuarine, and mangrove). These were calculated using Equation 5.2, a rearrangement of Equation 5.1 to solve for $\delta^{18}O_{shell}$ (following Prendergast et al. 2013).

$$\delta^{18}O_{shell\text{-}predicted} = (20.6 + 4.34(\delta^{18}O_{water(VSMOW)} - 0.27) - T) \times 4.34^{-1} \qquad \text{(Equation 5.2)}$$

Measured seasonal $\delta^{18}O_{water}$ values from Mirdidingki Creek, its surrounds, Thundiy, and water samples associated with live-collections were used in these calculations ($\delta^{18}O_{water(VSMOW)}$). Temperature data (T) originated from sensor stations deployed in the Mirdidingki region. It should be noted that the $\delta^{18}O_{water}$ values are spot samples taken over discrete tidal cycles (single days) and so differ in resolution to $\delta^{18}O_{shell}$ values, which may represent longer periods. Seasonal maximums, minimums, and averages are calculated to act as estimated ranges for determining seasonality in archaeological material.

5.5 Summary

This chapter outlined field and laboratory methods and protocols enacted to allow the accurate characterisation of sub-annual patterns associated with Kaiadilt decision-making processes. As such, a multi-method approach provided a framework in which modern and archaeological data were recovered from local shellfish populations, archaeological sites, and key environmental contexts.

Chapter 6 Modern Environmental and Hydrological Cycles

6.1 Introduction

This chapter reports the results of environmental monitoring in the Mirdidingki Creek area on the south coast of Bentinck Island. Monitoring occurred over a full annual cycle, encompassing 388 days. Results are augmented by rainfall, tidal, and temperature data from the Bureau of Meteorology (BOM) weather station on Sweers Island (ID: 029139) as well as the Australian Institute of Marine Science (AIMS) environmental monitoring station at Karumba (ID: KURFL1). Environmental and hydrological data are synthesised to characterise conditions during both wet and dry seasons. Predictive models as to how these conditions impact shellfish populations are also generated. In later chapters these data are combined with stable isotope determinations from the shells of live-collected mollusc specimens with known temporal and spatial provenance to demonstrate how seasonal conditions are reflected within shell geochemistry to test the efficacy of each target taxa for the aims of this research (see Chapters 7 – 9).

6.2 Data Collection Areas

The majority of environmental observation was focused in and around Mirdidingki Creek located on the south coast of Bentinck Island (Figure 6.1). This area encompasses numerous environments and habitats common throughout the greater Wellesley Island and Gulf of Carpentaria region. The creek itself is heavily influenced by tidal forces, which partially flush the system during each tidal cycle. Dense mangrove forests (dominated by the rib-fruited mangrove *Bruguiera exaristata* and red mangrove *Rhizophora stylosa*) surround the creek, which terminates abruptly as an open body of water approximately 530m inland in a dense mangrove thicket. The muddy substrate and root systems associated with surrounding mangrove forests are home to a number of mollusc taxa, including *Polymesoda coaxans* (mud shell), *Telescopium telescopium* (long bum), *Pinctada* spp. (black lip oyster), and various species of *Nerita*. Peak high tides inundate the supratidal mangrove substrate on average every 1.5 to 2 weeks during most of the year, replenishing shallow pools of water inhabited by numerous mollusc taxa (including *P. coaxans*).

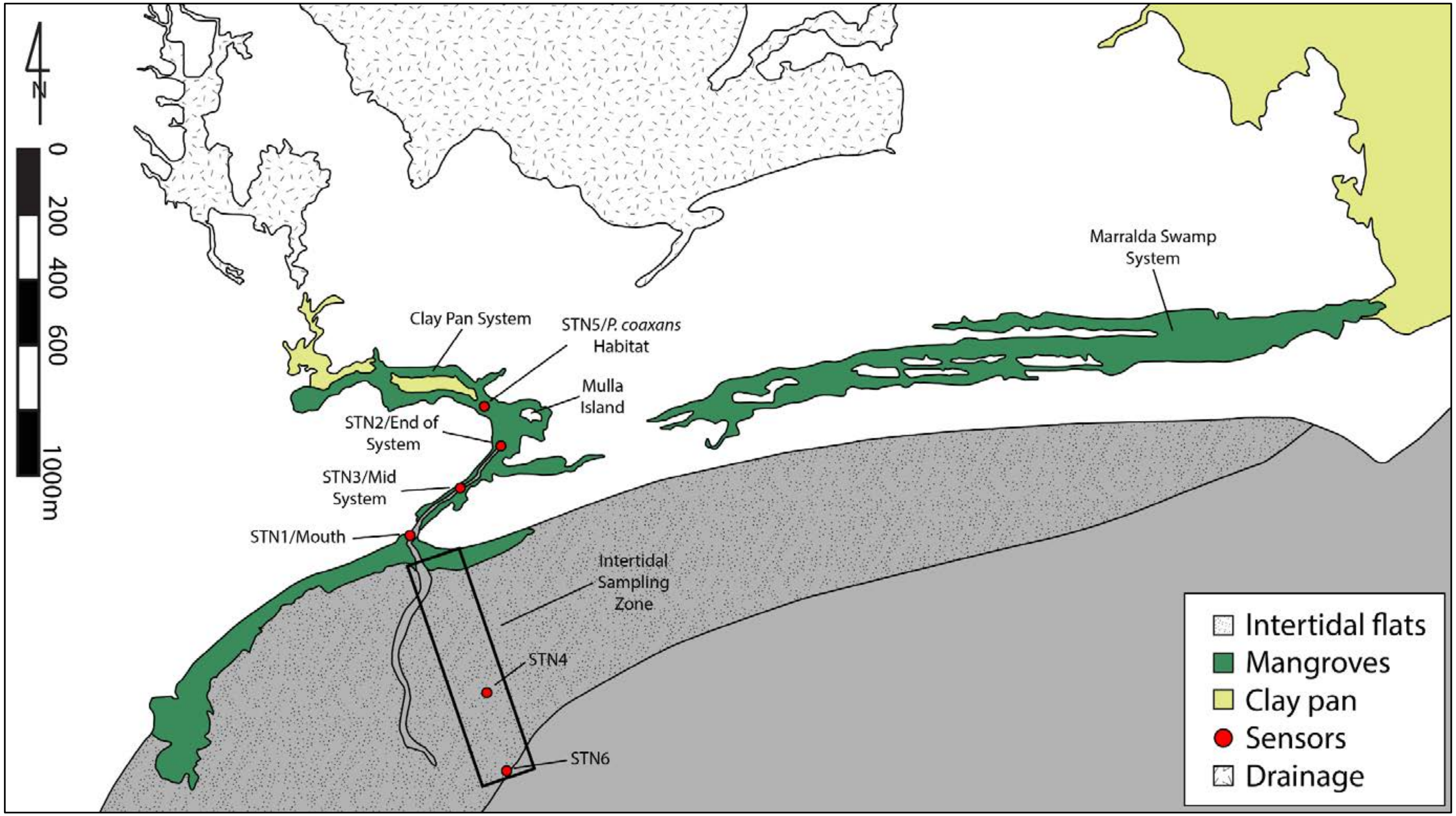

Figure 6.1 The area surrounding Mirdidingki Creek consists of mangrove forests, intertidal flats, low-lying drainage channels, and a numerous clay pans.

To the northwest of Mirdidingki Creek is a small unnamed clay pan system that consistently floods during wet season conditions, becoming a source of substantial freshwater input into the surrounding mangrove and estuarine systems (Figure 6.2). Nearby freshwater lenses in the beach ridge system bordering the estuary input small amounts of freshwater into the creek year round, although the impact of this on water constitution is likely negligible owing to low flow rate. Additionally, low-lying areas to the north are subject to extensive wet season flooding (personal observation, March 2014), which feeds into the clay pan via a series of drainage channels (Figure 6.1). A series of interconnected channels in the swales of a coastal dune field join Mirdidingki Creek with a freshwater swamp (Marralda Swamp) 500m to the east. Moss et al. (2015) suggest Marralda Swamp underwent a number of transitions between sheltered estuarine system (500 – 2400 BP), extensive well-established mangrove forest (500 BP – AD 1940s), and freshwater swamp (AD 1940s – present). Thus, exchange of waters between Marralda and Mirdidingki may have variably influenced past estuarine hydrology.

The adjacent intertidal zone consists of large, gently sloping tidal flats that stretch seaward for up to 600m during peak low tides (Figure 6.3). This isolates Mirdidingki Creek and its shallow intertidal channel from the open marine system, trapping water within the creek system and limiting the impact of tidal flushing. Numerous important cultural sites have been recorded in the surrounding area including a story place to the west, Mosquito Story, and dense *P. coaxans* scatters across the surface of Mulla Island and fringing banks of Mirdidingki Creek.

Further modern collection sites were scattered along the coast of Bentinck Island, including Raft Point and Thundiy, as well as Ngathald on Sweers Island and the northern tip of Fowler Island. Situated on the southeast extremity of Bentinck Island, Raft Point exhibits a gently sloping rocky laterite shore and numerous intertidal rock pools, both of which are home to a variety of mollusc taxa (Figure 6.4). Live shellfish specimens (*G. pectinatum*) and associated water samples were collected from Raft Point on two occasions – during the 2014 wet season and during the 2014 dry season (discussed further in Chapter 8).

The rocky platform at Ngathald is situated on the southwest coast of Sweers Island. This area exhibits similar characteristics to Raft Point with a gently sloping rocky laterite shore, numerous intertidal rock pools, and numerous shellfish taxa (Figure 6.5). Additionally, stone-walled fish traps are found in the area. Live *G. pectinatum* specimens and a single set of water samples were recovered from Ngathald during the dry season in 2015. Associated findings are further discussed in Chapter 8.

Figure 6.2 The clay pan system north of Mirdidingki Creek is inundated by fresh meteoric water during the wet season, which inputs into surrounding mangrove forests and the creek itself (Photograph: Daniel Rosendahl, 2014).

Figure 6.3 The intertidal zone adjacent to Mirdidingki Creek extends approximately 600m into the open marine environment owing to its gently sloping, prograded nature (Photograph: Anna Kreij, 2014).

Figure 6.4 The intertidal rocky platform at Raft Point is the most southeasterly landform on Bentinck Island (Photograph: Daniel Rosendahl, 2014).

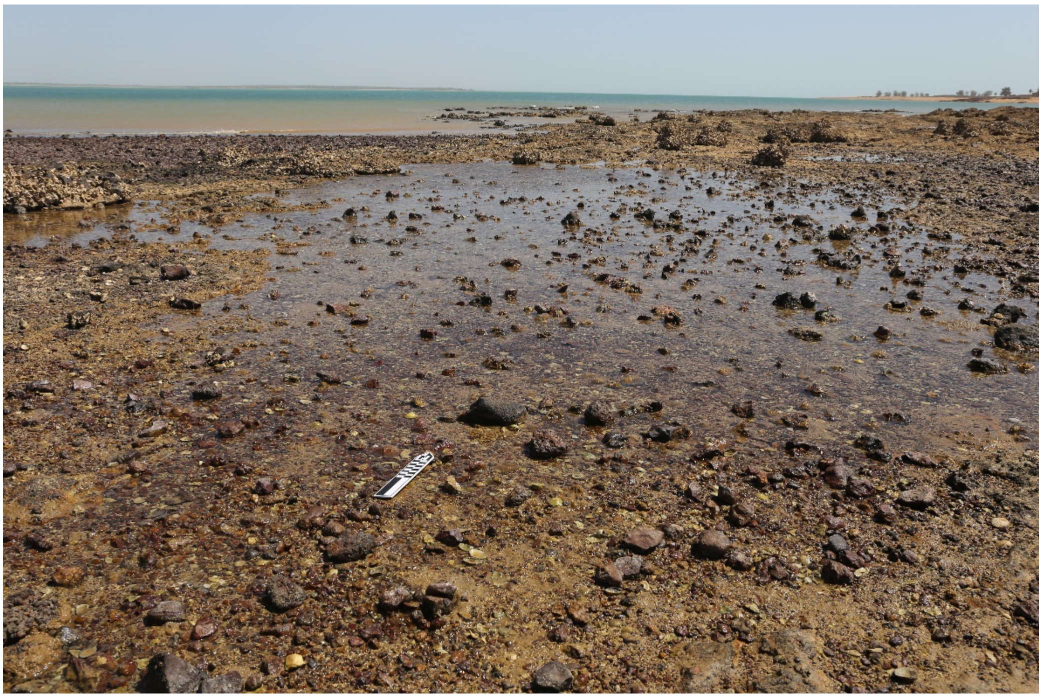

Figure 6.5 Water samples were collected from various rock pools and the open marine system at Ngathald, Sweers Island (Photograph: Sean Ulm, 2015).

Thundiy, an extensive shell midden complex, is located on the north coast of Bentinck Island. Fringing the nearby coastline is a dense mangrove corridor that is inundated at high tide with water from the open marine environment to seaward. The shoreline itself consists of muddy strata that gently slopes seaward. Water samples were collected from immediately beyond the mangrove fringe during the 2014 dry season. A detailed overview of the Thundiy complex can be found in Chapter 10.

Fowler Island is located c1.5km to the south of Bentinck Island (Figure 6.6). During the lowest low tides a sand bar connects the two islands, making Fowler Island accessible by foot. The surrounding intertidal zone is comparatively small compared to areas such as Mirdidingki, with a steep drop off into deeper subtidal waters. The shoreline of Fowler Island is comprised of intertidal flats, rocky cliffs, and dense mangrove fringes. Live shellfish specimens (*G. pectinatum* and *M. hiantina*) and water samples were collected from muddy sand that typifies the northern tip of the island.

Figure 6.6 Intertidal flats on the north coast of Fowler Island are home to *G. pectinatum* and *M. hiantina* populations (Photograph: Daniel Rosendahl, 2012).

6.3 Environmental Observations

6.3.1 Sensor Monitoring

6.3.1.1 Temperature

The BOM station on Sweers Island provided a continuous daily atmospheric temperature record stretching from August 2001 to December 2014 (totalling 4861 separate readings) consisting of daily maximums and minimums. Temperatures ranged from 9.1 to 39.5°C (Figure 6.7), with an average minimum of 23.3°C and an average maximum of 30.3°C, equating to a mean annual shift of 7.0°C. Differences between wet (November to March) and dry (April to October) seasons were minimal with wet season minimums averaging 26.4°C (range = 17.5 – 30.7°C) and maximums averaging 32.8°C (range = 25 – 39.5°C), while dry season minimums and maximums averaged 21.1°C (range = 9.1 – 28.5°C) and 28.6°C (range = 14.8 – 38.5°C) respectively. Comparisons of these averages reveal a 5.3°C change in mean minimum temperatures and a 4.2°C shift in mean maximums between the two seasons.

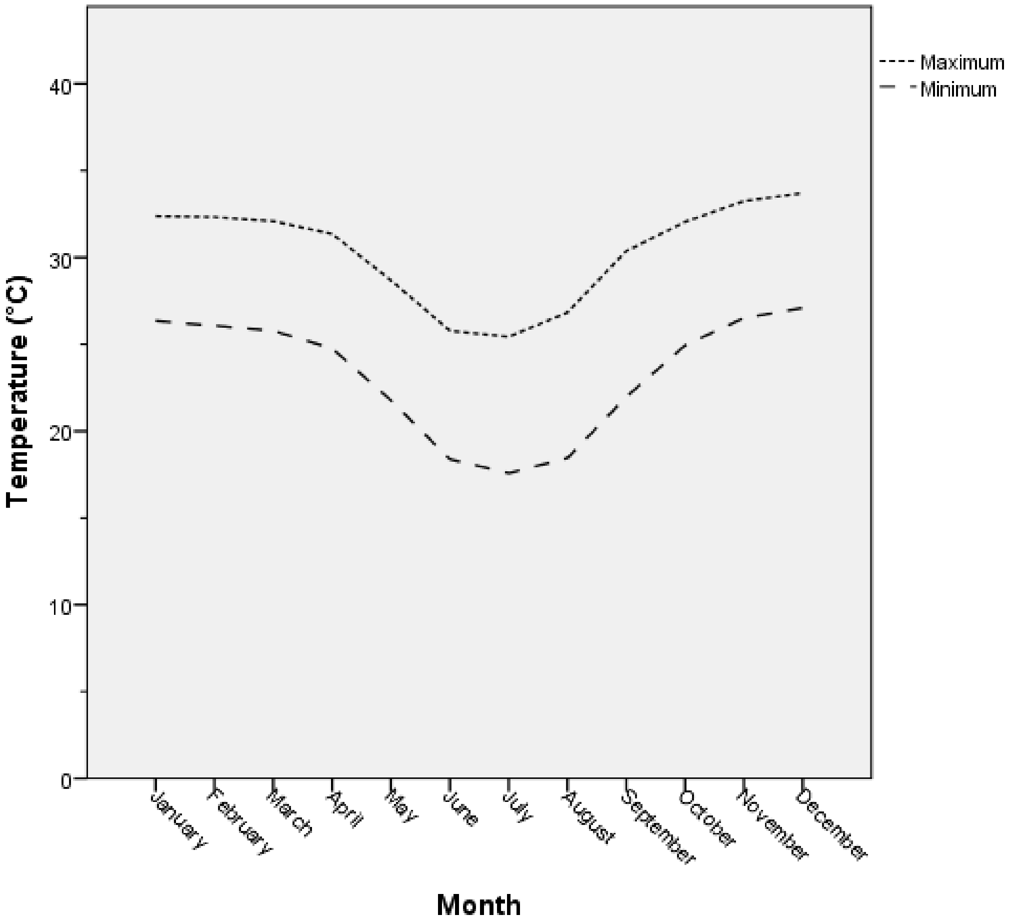

Figure 6.7 Monthly minimum and maximum temperature averages from Sweers Island (ID: 029139) 2001 - 2014 (BOM 2016).

Monthly sea surface temperature (SST) readings were accessed from the AIMS station at Karumba. These readings provide daily SST minimums, maximums, and averages between December 1999 and September 2006, although it must be noted that this dataset is not continuous (see Section 5.2.1.4). Monthly averages spanning the 8 year deployment of this sensor reveal water temperatures ranging between 16.5 and 33.7°C (average = 26.6°C) with an average minimum of 23.2°C and a maximum of 29.6°C (Figure 6.8). This produces a mean annual fluctuation of 6.4°C. Seasonal variability is slightly more pronounced in SST than BOM atmospheric data with wet season minimums averaging 27.8°C (range = 27.3 – 28.3°C) and maximums of 33.2°C (range = 32.1 – 33.7°C), while dry seasons average minimum temperatures were 20.0°C (range = 16.5 – 25.9°C) with maximums of 27.0°C (range = 22.3 – 31.8°C). This equates to a mean seasonal shift of 7.8°C and 6.2°C for minimum and maximum temperatures, respectively. Overall seasonal averages indicate wet season SSTs are stable ranging between 30.3 and 31.1°C (mean = 30.6°C), while the dry season sees more variability with a range of 20.0 to 28.4°C (mean = 23.7°C). The source of dry season temperature variability appears to be April (mean = 28.4°C), September (mean = 24.5°C), and October (mean = 28.2°C), which display elevated temperatures compared to the remainder of the dry season.

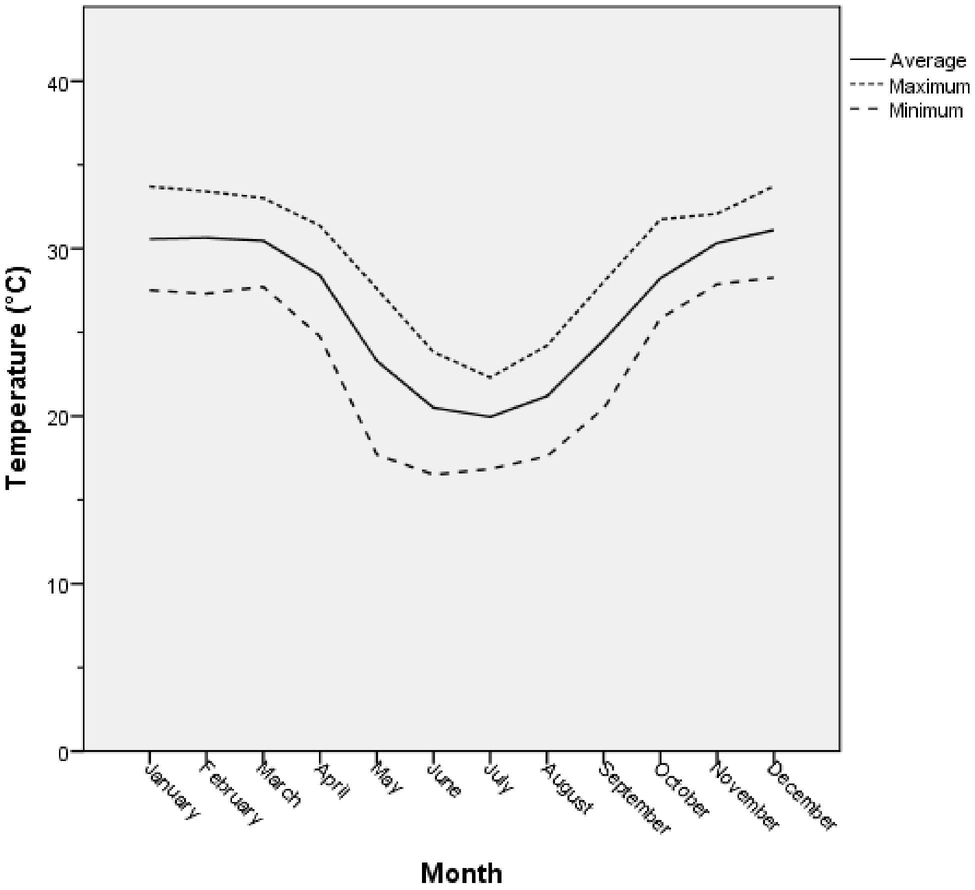

Figure 6.8 Monthly sea surface temperature means recorded over an 8 year period (1999 – 2006) at Kurumba, Queensland (AIMS 2015).

Localised water temperature data was collected at sensor stations STN1, STN2, STN4, STN5 (H and A), and STN6. As the instrument originally positioned at STN3 was relocated to STN6 after approximately 2 weeks, data associated with this short deployment is not included here. Instruments recorded readings every 1.5 hours returning over 6000 measurements each, allowing data to be expressed as daily, monthly, and seasonal averages, maximums, and minimums. The exception to this was STN1, which documented temperature every 3 hours. Temperature readings ranged between 10.5 and 56.8°C with an average of 26.7°C. Monthly averages displayed a distinctly narrower range of 17.3 to 33.1°C (mean = 25.9°C) (Figure 6.9).

Wet season (November – March) readings returned a mean temperature of 30.4°C (range = 20.1 – 53.0°C), while the dry season (April – October) saw an average of 24.4°C (range = 10.5 – 56.9°C). This equates to a mean seasonal fluctuation of 5.9°C. A majority of extreme maximum temperatures originate from STN5H owing to a combination of shallow water depth, dark sediments, and exposure to extended periods of direct sunlight. Overall, results typify patterns characteristic of wet tropical regions with relatively minor seasonal shifts.

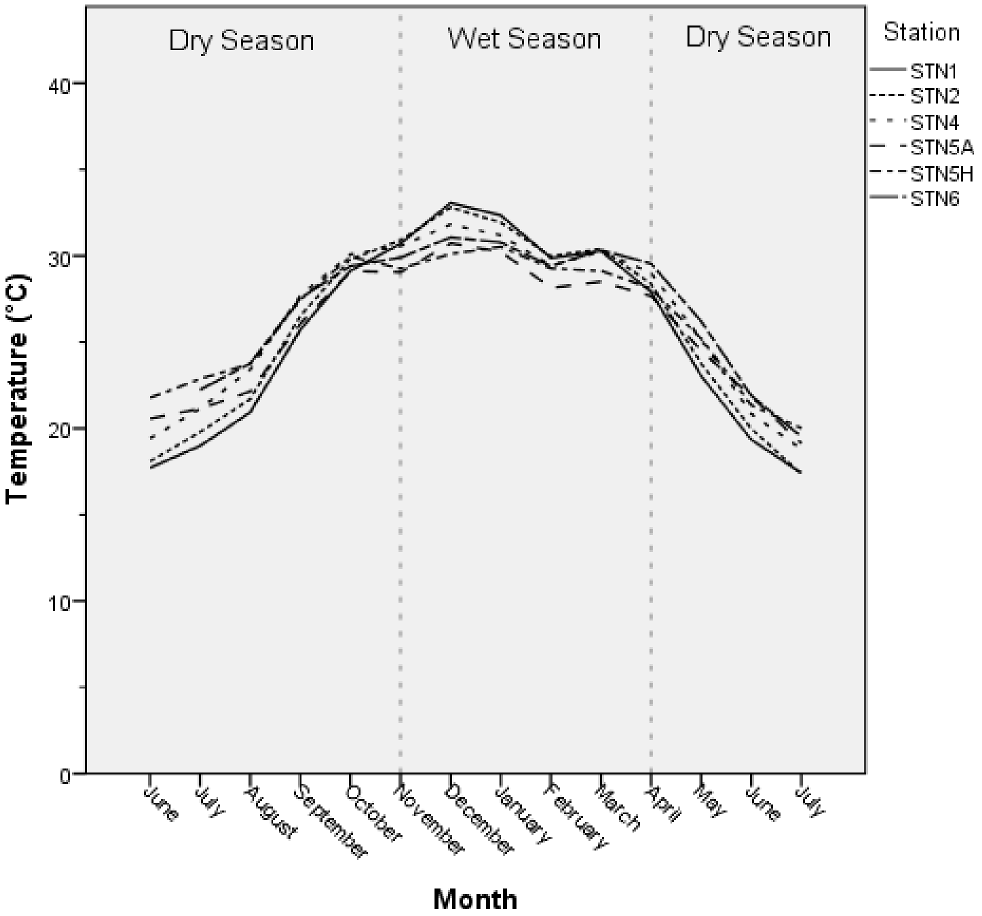

Figure 6.9 Monthly averages for all temperature sensors (June 2013 – July 2014).

Sensors recording the estuarine environment of Mirdidingki Creek (STN1 and STN2) suggest local temperatures correspond well to BOM records from the nearby Sweers Island, although increased fluctuation is evident. Daily means indicate annual minimums fell to 12.0°C while maximums reached 40.6°C. Seasonally, wet season temperatures averaged 31.2°C (range = 23.5 – 40.6°C), while the dry season saw an average of 21.4°C (range = 12.0 – 32.4°C). Thus, mean fluctuation between the two seasons was moderate at 9.9°C. Comparing monthly means reveals that temperatures reported by both stations remained consistent with one another, exhibiting only minor inter-sensor variability (Figure 6.10). While measures were taken to ensure these sensors remained submerged over the entire annual cycle it is unclear whether peak low tides caused limited aerial exposure, potentially accounting for heightened variability.

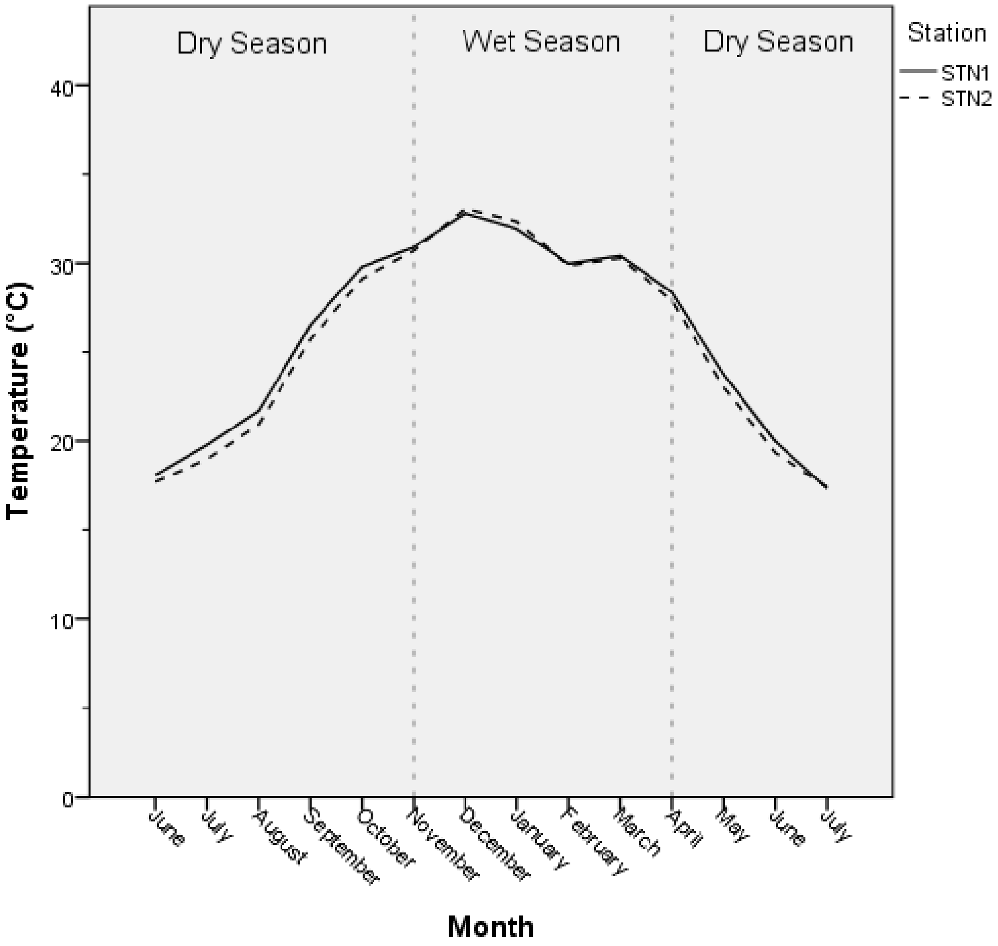

Figure 6.10 Mean monthly temperatures for STN1 and STN2 (2013 - 2014) located at the mouth and end of Mirdidingki Creek respectively.

Temperatures from the intertidal and subtidal zones were recorded by STN4 and STN6, respectively. Comparisons between monthly averages from the two stations reveal close connections, with means remaining within 2.0°C throughout deployment (Figure 6.11). When monthly ranges are considered, variability between the two stations becomes more pronounced. Intertidal readings tended to produce higher maximums, particularly during the hotter months with the STN4 average for January 6.3°C higher than the subtidal, while STN6 returned more pronounced lows. Seasonal averages indicate that subtidal temperatures fluctuated by 7.1°C with wet season averages ranging between 24.5 and 34.3°C (mean = 30.3°C) and dry season means oscillating between 13.3 and 30.1°C (mean = 23.2°C). Intertidal readings again saw slightly more variability with a mean shift of 8.61°C. Wet season averages ranged between 22.4 and 40.1°C (mean = 30.7°C), while the dry season saw fluctuations of 11.7 to 32.6°C (mean = 22.1°C). The intertidal environment in which STN4 was deployed is inherently changeable owing to the rise and fall of tides, thus this sensor was aerially exposed during some tidal cycles (personal observation, July 2013, March 2014, July 2014). This exposure is likely the source of heighted temperature readings from this instrument. As STN6 was installed beyond the interface of inter- and subtidal zones, it remained submerged throughout its entire deployment.

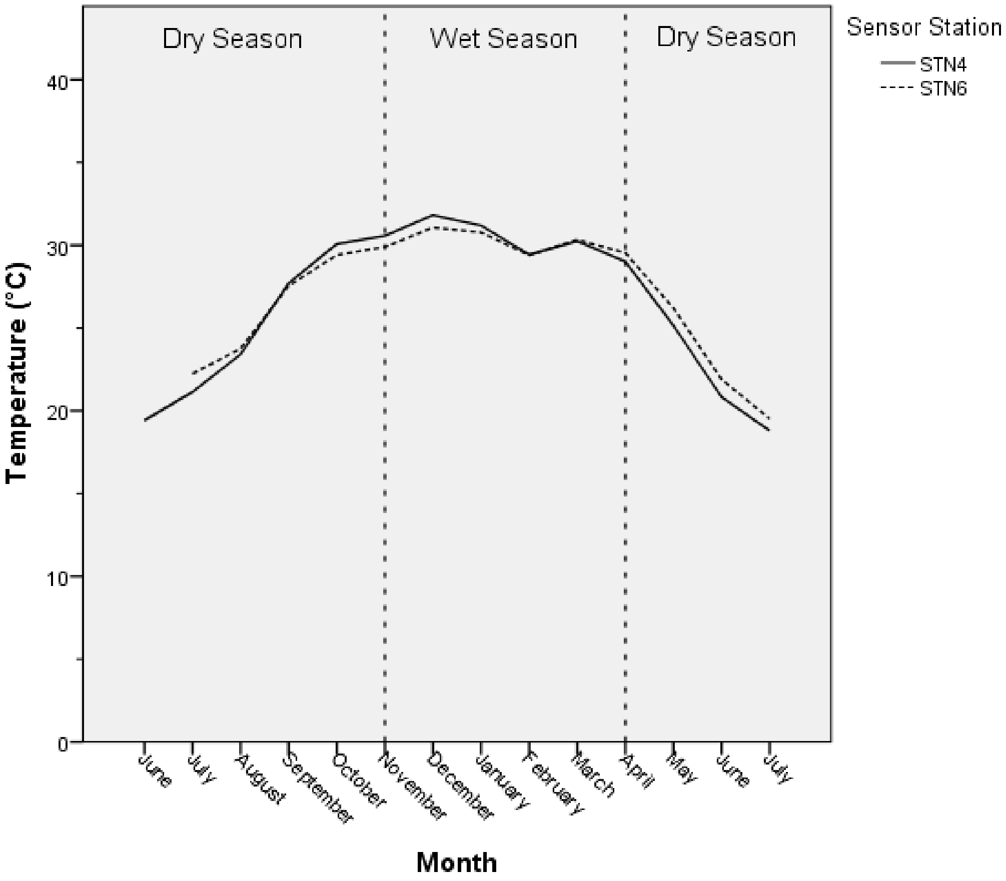

Figure 6.11 Mean monthly temperatures for intertidal (STN4) and subtidal (STN6) zones adjacent to Mirdidingki Creek (2013 - 2014).

Atmospheric temperatures were collected by a single sensor (STN5A) deployed in a tree as part of STN5. Daily means indicate a range of 10.5 to 43.4°C during deployment (mean = 26.1°C). Seasonal data show an average shift of 7.5°C between wet and dry seasons. Wet season temperatures ranged between 20.1 and 43.4°C (mean = 29.4°C), while the dry season fluctuated between 10.5 and 31.5°C (mean = 21.9°C) (Figure 6.12). When compared to BOM data it becomes apparent that STN5A shows more variability in both minimums (range of variability = 0 – 5.1°C) and maximums (range of variability = 0.1 – 6.9°C), although overall differences between the two are minor with minimums varying 2.0°C and maximums 1.7°C.

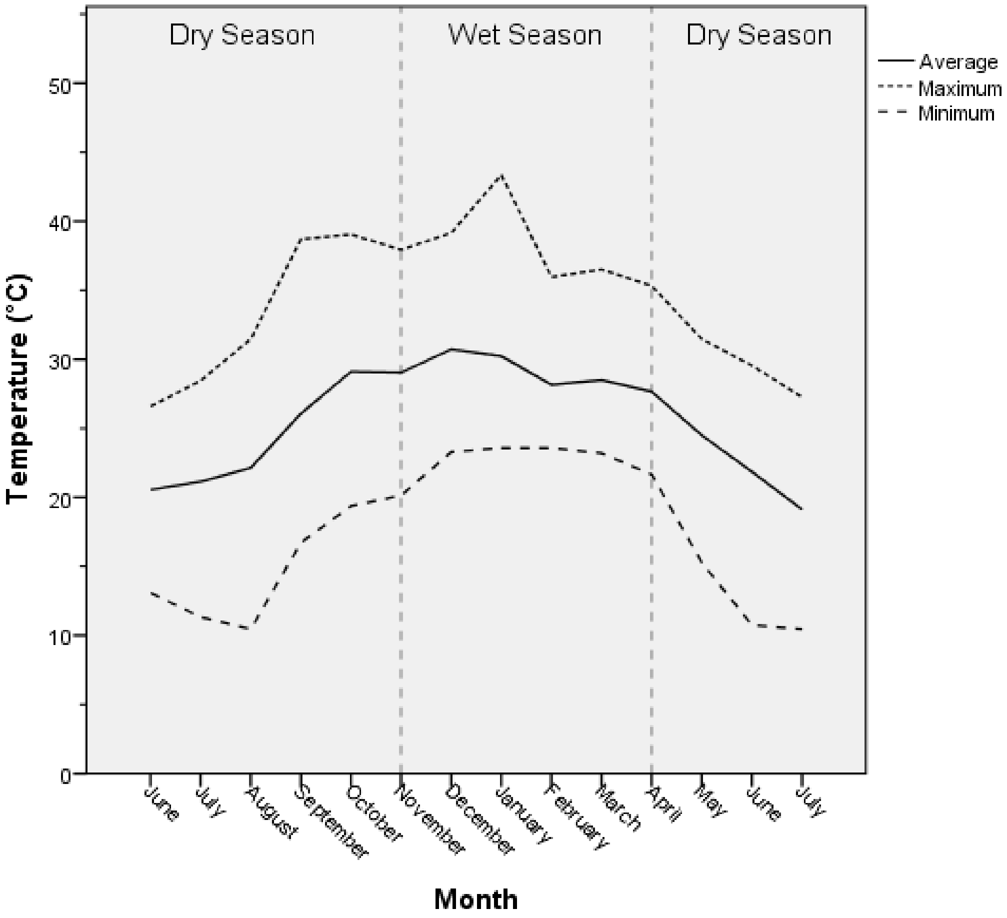

Figure 6.12 Temperatures from STN5A (2013 – 2014) show occasional spikes (e.g. January).

Water temperatures recorded in a *P. coaxans* habitat (STN5H) reveal significant fluctuations in temperature throughout deployment (Figure 6.13). Readings indicate a temperature range of 11.6 to 56.8°C (wet season range = 20.8 – 53.0°C, mean = 29.7°C; dry season range = 11.6 – 56.8°C, mean = 24.5°C) with numerous months registering maximum temperatures of between 45 and 56°C (2013: July – December). Biological studies of *P. coaxans* indicate that while this species can survive elevated temperatures for periods of up to three weeks, mortality rates increase above 30°C (Clemente 2007). Sensor data indicate that in the Mirdidingki mangrove forest temperatures did not exceed 30°C for more than c.16 hours in either wet or dry seasons, potentially limiting temperature induced mortality. Temperatures were likely mediated by other mechanisms, such as tidal cycles and cloud cover during the wet season. Despite exceptionally high maximums, monthly averages for STN5H remain similar to other sensors with a statistical comparison using an analysis of variance (ANOVA) demonstrating strong statistical similarity between sensors (*F*(5) = .213, *p* = .956).

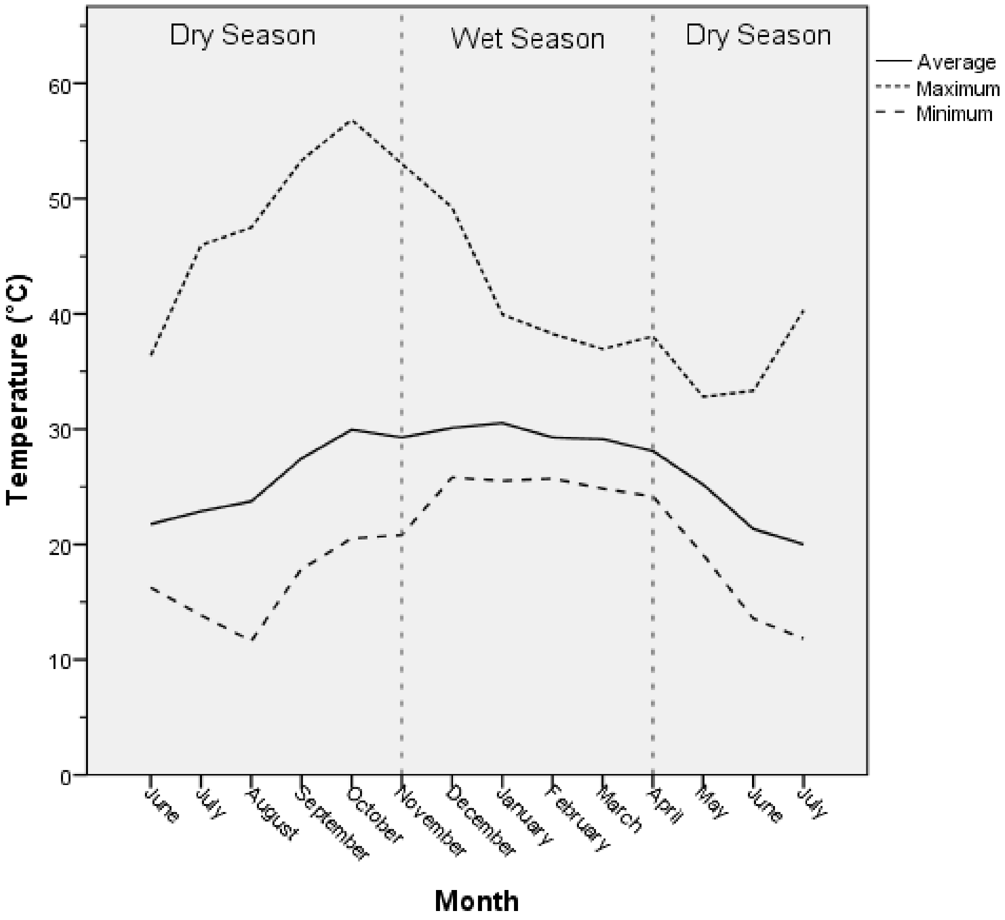

Figure 6.13 Monthly temperature averages from STN5H (2013 – 2014).

Comparisons of daily temperature averages amongst all monitored environments using ANOVA indicates significant statistical differences ($F(3) = 6.130$, $p < 0.001$). However, further analysis using a Tukey HSD post hoc test reveals most monitored environments are significantly similar with the exception of estuarine and subtidal data ($p < 0.001$). The strength of these similarities differ with estuarine data showing only weak connections with the intertidal ($p = 0.058$), while remaining comparisons reveal significances of increasing strength (subtidal and mangrove $p = .109$; estuarine and mangroves $p = .409$; intertidal and mangrove $p = .832$).

6.3.1.2 Tides

Tidal data was accessed from the Sweers Island BOM station and the Karumba AIMS station. All tidal data is relative to the lowest astronomical tide (LAT) in the current tidal datum epoch (TDE) as recommended by the Permanent Committee for Tides and Mean Sea Level (PCTMSL) (PCTMSL 2014). The Sweers Island dataset provides daily highs and lows over a short period (2013 – 2014), while Karumba provides an extended collection of monthly highs and lows from 1985 – 2014. Tidal cycles in the Gulf of Carpentaria primarily follow a daily diurnal pattern (one high and one low tide a day), with wet season means of 2.41m (range = 0.33 – 5.33m) and dry season averages of 1.91m (range = -0.38 – 4.58m). Increased heights in the wet season are linked with tidal banking caused by strong northwesterly winds (Memmott 1982b). Moreover, a secondary semi-diurnal ‘double tide’ is observed throughout the year every c.13 days (Figure 6.14), lasting between 1 and 4 days. Seasonal amplitudes remain relatively stable, displaying a 0.44m difference (wet season: mean = 3.64m, range = 3.07 – 4.36m; dry season: 3.39m (range = 2.48 – 4.08m).

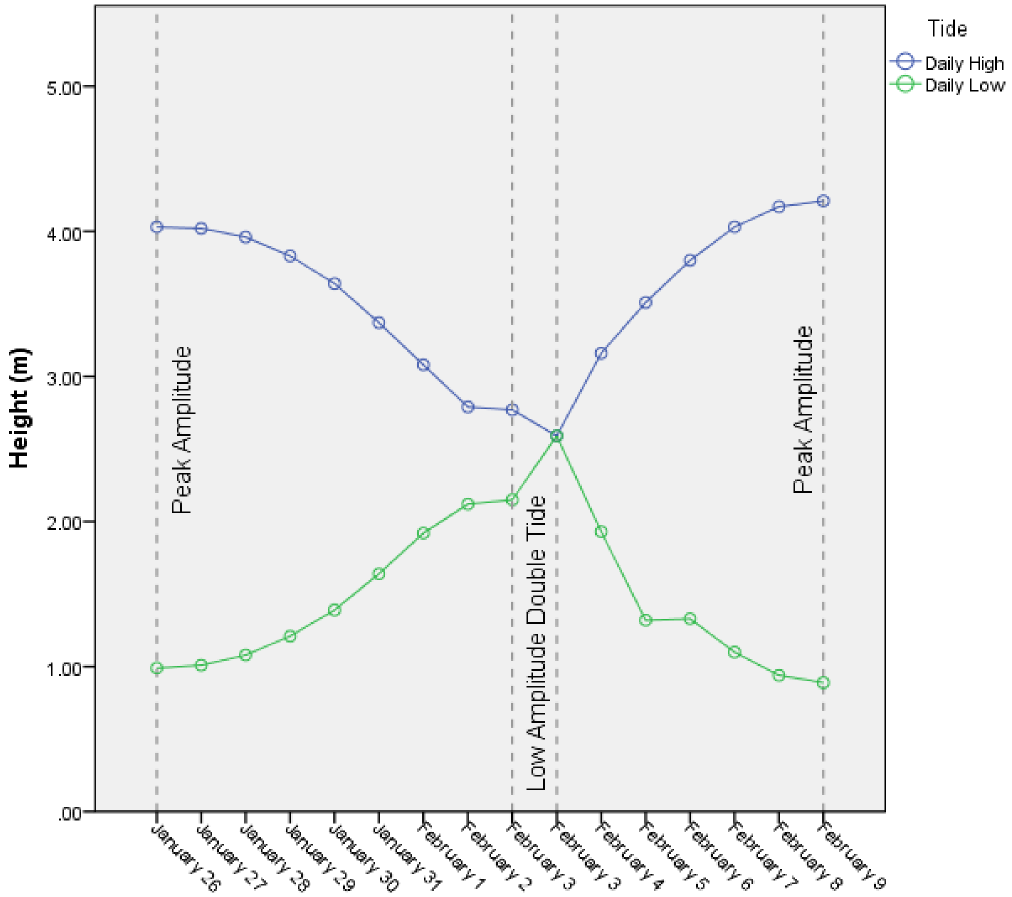

Figure 6.14 Wet season tidal cycles are typified by increased high and low tidal heights. Note the double low amplitude tide on 3 February 2014 (BOM 2014).

6.3.1.3 Rainfall

This research utilises rainfall data from the Sweers Island BOM station collected between 2001 and 2014 inclusive. Over this time wet season months saw an average of 236.05mm (range = 7 – 1066.5mm), while dry season months averaged 12.13mm (range = 0 – 349.1mm) (Figure 6.15). Thus, between 2001 and 2014 the dry season experiences, on average, approximately 5% of the yearly rainfall. This 5% primarily consists of rainfall from April and to a lesser extent October in years where the wet season may have commenced earlier or continued longer than usual (examples of this can be seen in 2006 and 2010). A majority of the remaining dry season months experience little to no precipitation. BOM data also indicate a decrease in rainfall intensity since

2012 with the lowest yearly precipitation since 2008, which is indicative of the recently declared El Niño phase (BOM 2015b). The possibility of this impacting isotopic values derived from molluscan shell carbonates is discussed in later chapters.

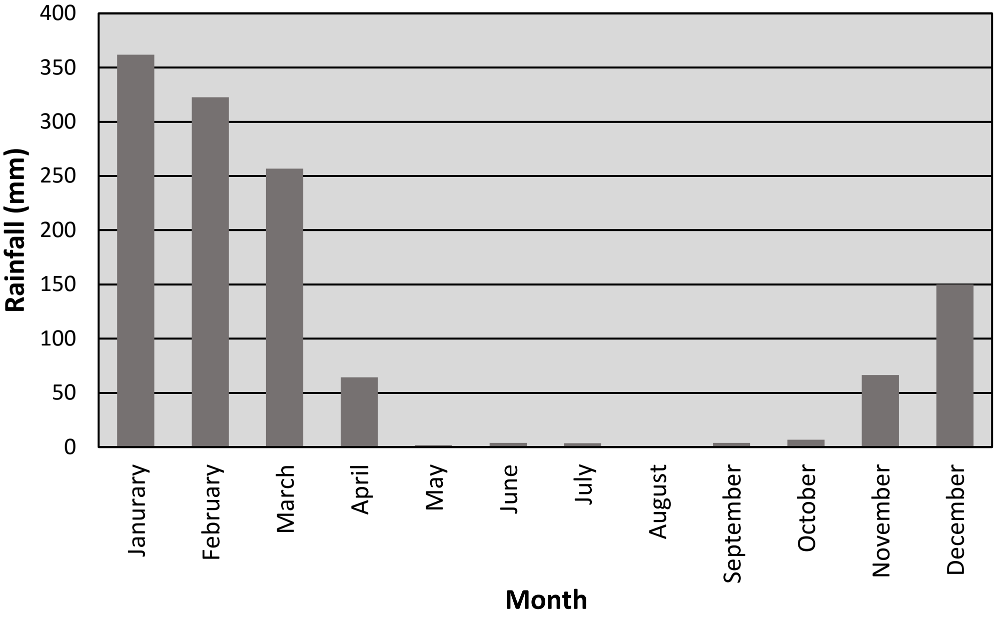

Figure 6.15 Monthly rainfall averages for Sweers Island (2001 - 2014) (BOM 2016).

6.3.2 Seasonal Water Sampling

To contextualise the following data it is important to remember that the $\delta^{18}O_{water}$ value of seawater is approximately 0.0‰ (Rohling 2013:917). This can be impacted by a variety of different processes, including evaporation and mixing with freshwater (Bemis and Geary 1996; Dansgaard 1964). Evaporation causes lighter ^{16}O isotopes to be preferentially removed, shifting remaining water towards more positive $\delta^{18}O_{water}$ values. Conversely, the introduction of freshwater (particularly meteoric waters) leads to increasingly isotopically negative values. Similar patterns are present in $\delta^{13}C_{DIC,}$ where carbon from marine sources tends towards more positive values typically above -4.0‰ while those from terrestrial sources are significantly more negative (Petchey et al. 2013)

6.3.2.1 Dry Season 2013

During the 2013 dry season, water sampling was undertaken over two tidal cycles – one high amplitude (spring) and one low amplitude (neap). Samples were collected from the mouth of Mirdidingki Creek (adjacent to STN1) and in the intertidal zone approximately 2m beyond the water's edge. Additional sample sets were collected at sensor positions during installation and at mollusc collection sites during live-collection, outcomes associated with shellfish collection are discussed together with shell carbonate results in later chapters (see Chapters 7 – 9).

Salinity

Salinity results from the Mirdidingki Creek area (*n* = 18) remained stable over the course of sampling (Figure 6.16), ranging between 34.4 and 36.2 PSU (mean = 35.5 PSU). Spring tide salinities (*n* = 10) were slightly increased (range = 35.9 – 38.8 PSU; mean = 36.7 PSU) in comparison to neap tide results (*n* = 18; range = 34.4 – 35.6 PSU; mean = 35.2 PSU). Differences between sampling locations were also minor with intertidal readings averaging 36.5 PSU (*n* = 9; range = 35.5 – 38.8 PSU), while creek mouth values returned a mean of 35.5 PSU (*n* = 9; range = 34.4 – 36.2 PSU). Salinity readings indicative of marine conditions typically range from 30 to 40 PSU (Sharqawy et al. 2010), thus values throughout the Mirdidingki area can be characterised as marine.

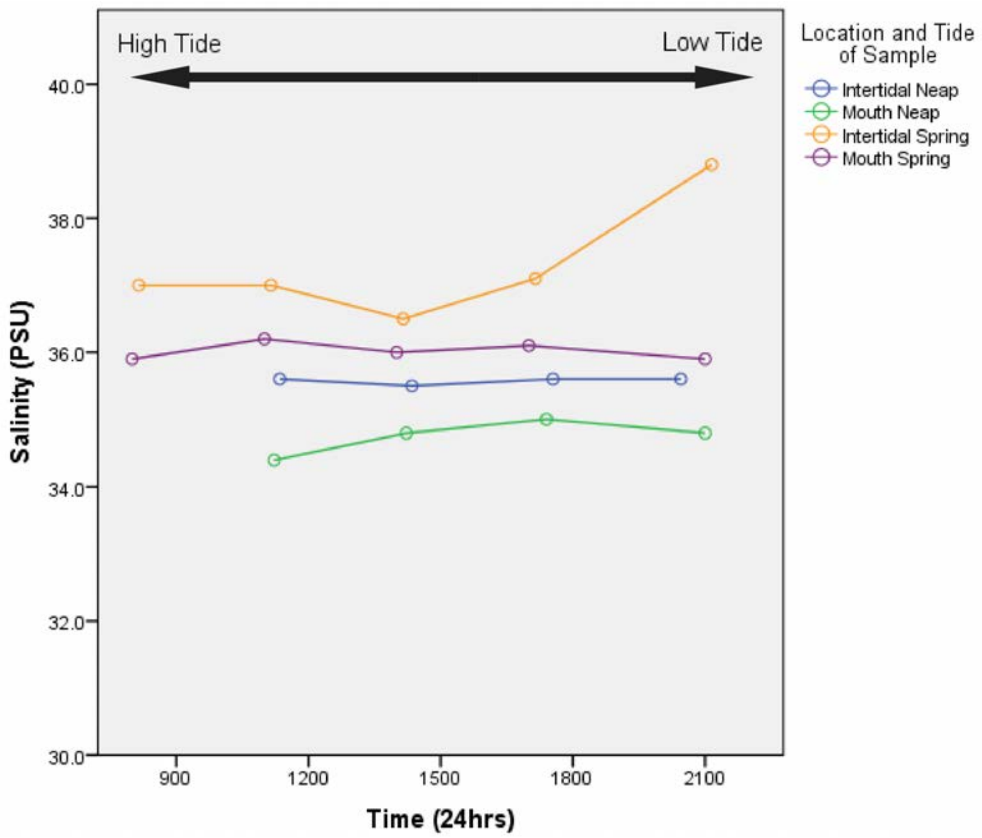

Figure 6.16 Salinity sample results from the 2013 dry season. Neap tide samples collected 16 July 2013, spring tide samples collected 16 July 2013.

Additional salinity values mirror those from neap and spring tides, remaining close to typical marine conditions (range = 34.1 – 36.1 PSU). Again, the only exception is from the *P. coaxans* habitat, which returned a significantly lower salinity reading (Table 6.1). This suggests a brackish environment is present within local mangrove forests during dry season conditions, although the definition of brackish conditions is expansive encompassing salinities between 0.5 and 30 PSU.

Table 6.1 Salinity values from additional water samples taken during sensor installation. Note a water sample set was not collected for STN4.

Date	Time	Station	Location	Salinity (PSU)
20/06/2013	1100	STN1	Mouth	34.4
20/06/2013	1130	STN2	System End	34.9
20/06/2013	1145	STN3	Mid System	34.1
20/06/2013	1400	STN5	*P. coaxans* Habitat	20.1
08/07/2013	1830	STN6	Subtidal	36.1

$\delta^{18}O_{water}$

Water oxygen isotope composition ($\delta^{18}O_{water}$) from Mirdidingki Creek ranged between +0.0‰ and +0.9‰ with a mean of +0.2‰ (Figure 6.17). Only minor variability was displayed across tidal cycles with both spring (*n* = 10; range = +0.0‰ – +0.9‰; mean = +0.4‰) and neap (*n* = 8; range = +0.1‰ – +0.6‰; mean = +0.2‰) tide values remaining relatively stable. Similarly, $\delta^{18}O_{water}$ values from the intertidal zone (*n* = 9; range = +0.1‰ – +0.9‰; mean = +0.4‰) and creek mouth (*n* = 9; range = +0.0‰ – +0.5‰; mean = +0.2‰) display few differences. These conditions are indicative of a stable marine environment experiencing very little input from freshwater sources.

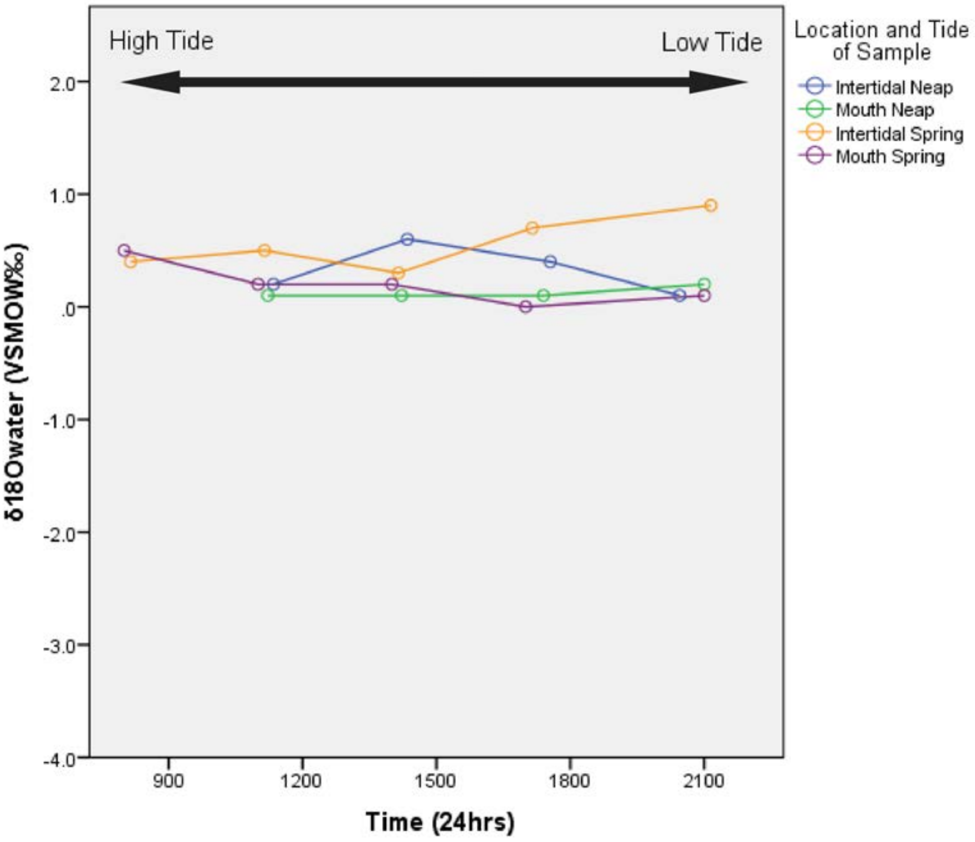

Figure 6.17 $\delta^{18}O_{water}$ sample results from the 2013 dry season. Neap tide samples collected 16 July 2013, spring tide samples collected 22 July 2013.

Additional water samples collected upon the installation of sensor stations are largely coincident with the more intensive sampling phase (Table 6.2). Measurements of $\delta^{18}O$ values from inside the creek system, taken at STN1, STN2, and STN3, are more negative (-0.3‰, 0.0‰, and -0.5‰, respectively) than those taken from at the subtidal STN6 (+0.5‰). Conversely, the sample retrieved from STN5 returned a significantly more negative oxygen value (-2.9‰), indicating the presence of inter-environment variability linked with freshwater input into the mangrove system as also evidenced by salinity.

Table 6.2 Oxygen values from additional water samples taken during sensor installation. Note a water sample set was not collected for STN4.

Date	**Time**	**Station**	**Location**	**$\delta^{18}O_{water}$ (‰)**
20/06/2013	1100	STN1	Mouth	-0.3
20/06/2013	1130	STN2	System End	-0.5
20/06/2013	1145	STN3	Mid System	+0.0
20/06/2013	1400	STN5	*P. coaxans* habitat	-2.9
08/07/2013	1830	STN6	Subtidal	+0.5

$\delta^{13}C_{DIC}$

The stable carbon isotope composition of dissolved inorganic carbon ($\delta^{13}C_{DIC}$) from Mirdidingki Creek ranged between -5.8‰ and +0.2‰ with a mean of -2.6‰ (Figure 6.18). Spring tide $\delta^{13}C_{DIC}$ values were similar to neap tide values, averaging -2.6‰ (range = -5.8‰ – +0.1‰; *n* = 9) and -2.6‰ (range = -5.5‰ – +0.2‰; *n* = 8), respectively. Intertidal $\delta^{13}C_{DIC}$ values (*n* = 9) showed a slightly larger range (-5.8‰ – +0.2‰) and more positive mean (-1.5‰) than readings from the creek's mouth (*n* = 8; range = -5.5‰ – +0.1‰; mean = -3.8‰), suggesting variable interaction with terrestrial carbon sources. Carbon values at both sample sites become increasingly negative throughout the spring tide (Figure 6.18) likely owing to the periodic introduction of terrestrial carbon by tidal waters interacting with the surrounding mangrove forest. This phenomenon is explored further in Section 6.4.1.

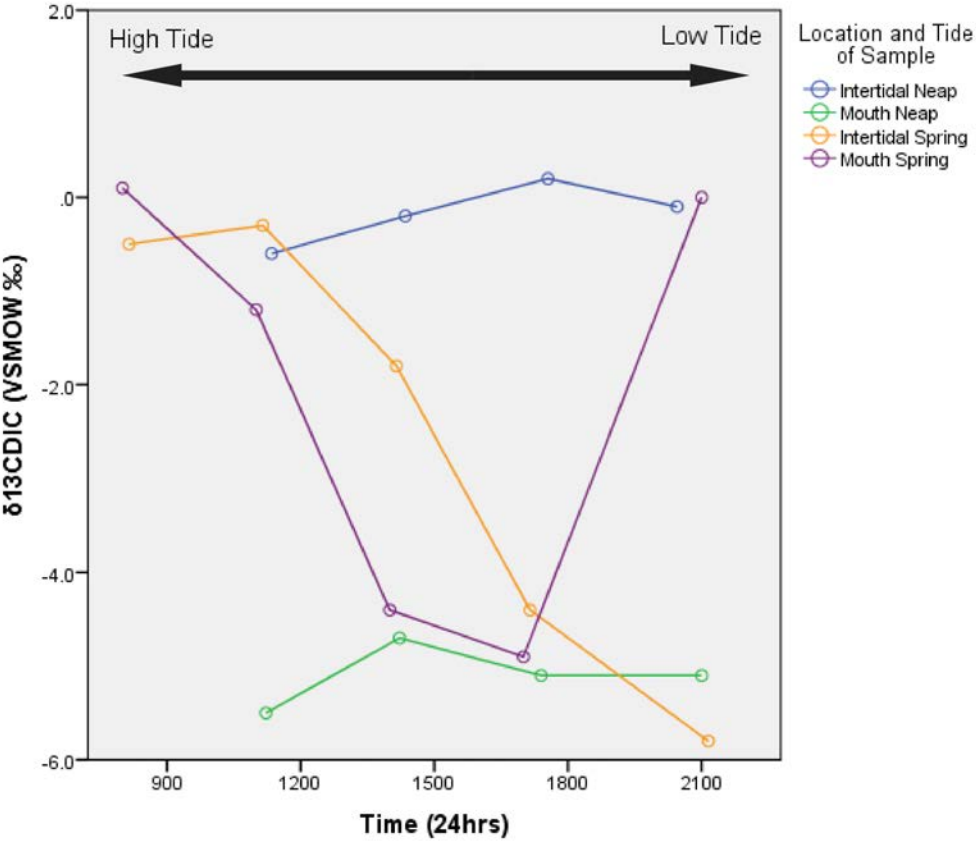

Figure 6.18 $\delta^{13}C_{DIC}$ sample results from the 2013 dry season. Neap tide samples collected 16 July 2013, spring tide samples collected 22 July 2013.

Water samples collected in conjunction with sensor station installation reveal similar results to tidal end-member sampling (Table 6.3). Samples taken from Mirdidingki Creek's estuarine environment are significantly more negative than that of the subtidal environment. The sample taken from the STN5 is significantly (c.9‰ – 10‰) more negative than the other environments, indicating almost exclusive C3 terrestrial source. Thus, dry season carbon values from mangrove environments are not representative of broader environmental trends.

Table 6.3 Carbon values from additional water samples taken during sensor installation. Note a water sample set was not collected for STN4.

Date	Time	Station	Location	$\delta^{13}C_{DIC}$ (‰)
20/06/2013	1100	STN1	Mouth	-5.6
20/06/2013	1130	STN2	System End	-6.1
20/06/2013	1145	STN3	Mid System	-6.0
20/06/2013	1400	STN5	*P. coaxans* Habitat	-15.0
08/07/2013	1830	STN6	Subtidal	-1.8

6.3.2.2 Wet Season 2014

As part of fieldwork undertaken in the 2014 wet season, water sampling occurred over two complete tidal cycles – one high amplitude and one low amplitude. Samples were collected from the mouth of Mirdidingki Creek (adjacent to STN1), the end of the creek system (adjacent to STN2), and in the intertidal zone approximately 2m beyond the interface between land and water. Further samples were collected from the flooded clay pan to the north of Mirdidingki Creek, a major input located at the end of the creek system, and adjacent to STN5.

Salinity

Salinity values fluctuated significantly over the course of wet season sampling (Figure 6.19), ranging between 0.1 and 24.5 PSU (*n* = 22). Moreover, average salinity readings indicate a substantial salinity depression compared to the 2013 dry season (mean = 10.3 PSU). Considerable variation occurs during both spring and neap tides with values ranging from 0.1 to 21 PSU (*n* = 13; mean = 6.12 PSU) and 6.1 to 24.5 PSU (*n* = 9; mean = 16.2 PSU), respectively. Comparisons between sampling positions demonstrate both mouth (n = 8; range = 0.6 – 19.3 PSU; mean = 8.0 PSU) and end of system (*n* = 6; range = 0.1 – 7.7 PSU; mean = 3.9 PSU) values are significantly lower than those from the intertidal (*n* = 8; range = 4.4 – 24.5 PSU; mean = 17.3 PSU). Variability is likely due to fluctuating inputs of freshwater from the clay pan, surrounding mangroves, and rain event. Thus, neap tide values can be viewed as a stable wet season environment and spring tide values as an extreme.

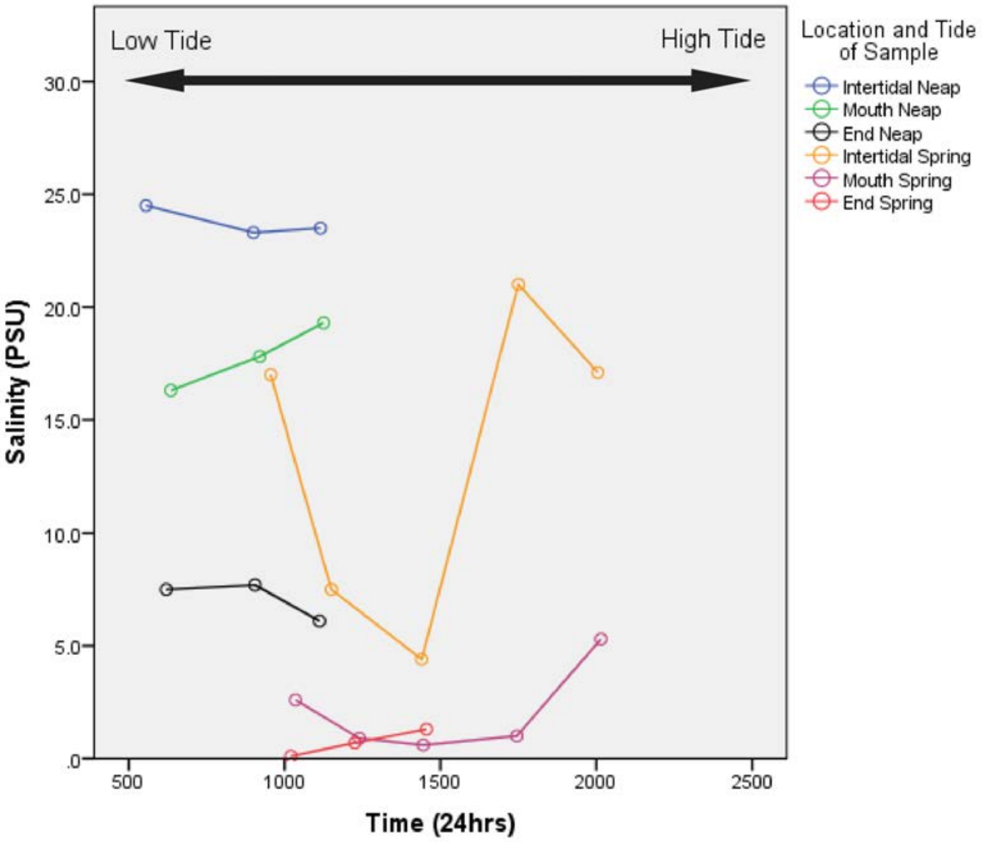

Figure 6.19 Salinity sample results from the 2014 wet season. Neap tide samples collected 05 March 2014, spring tide samples collected 28 February 2014.

Salinity samples from the inundated clay pan and terrestrial input both returned values of 1 PSU, indicating freshwater conditions (Table 6.4). This is unsurprising given both sources consist primarily of runoff from rainfall-derived flooding events. However, STN5 returned a brackish signal (15.2 PSU), indicating some saline input. When considered in combination the associated $\delta^{18}O_{water}$ value (Table 6.5), this result suggests a residual marine signal from a recent tidal inundation depositing salt on the supratidal flats. However, it is difficult to pinpoint the source with any greater accuracy.

Table 6.4 Salinity values for additional water sampling during the 2014 wet season.

Date	Time	Location	Salinity (PSU)
28/02/2014	0955	Input into Mirdidingki Creek	1.0
04/03/2014	1220	Mirdidingki Clay Pan	1.0
04/03/2014	1235	STN5	15.2

$\delta^{18}O_{water}$

Wet season $\delta^{18}O_{water}$ values for the Mirdidingki Creek area averaged -4.8‰ (*n* = 22; range = -5.9‰ – -3.1‰) (Figure 6.20). Intertidal values ranged between -5.5‰ and -3.1‰ (*n* = 8; mean = -4.0‰), while creek mouth values saw a mean of -5.1‰ (*n* = 8; range = -5.9‰ – -3.9‰). The end of the creek system returned the most consistent values, ranging between -5.7‰ and -5.2‰ (*n* = 6; mean = -5.6‰). Comparisons between spring and neap tides revealed some variability with values averaging -5.2‰ (*n* = 13; range = -5.9‰ – -3.5‰) and -4.3‰ (*n* = 9; range = -5.7‰ – -3.2‰), respectively. This was likely caused by strong freshwater input from the small clay pan system (*n* = 1; $\delta^{18}O_{water}$ = -6.4‰; salinity = 1.0 PSU) and surrounding mangrove forest (*n* = 1; $\delta^{18}O_{water}$ = -6.1‰; salinity = 1.0 PSU) in conjunction with a monsoonal rain event that occurred during spring tide sampling. These likely introduced a contribution of low ^{18}O meteoric water to sample sites, causing $\delta^{18}O_{water}$ values to become more negative. Between collection of the spring and neap tide sample sets (occurring approximately 7 days apart) little rainfall occurred while input from the clay pan and surrounding mangroves decreased considerably, allowing $\delta^{18}O_{water}$ values to stabilise. Thus, fluctuations between neap and spring tides demonstrate the variability that can occur during or subsequent to the regular monsoonal precipitation events that typify the South Wellesley Islands wet season.

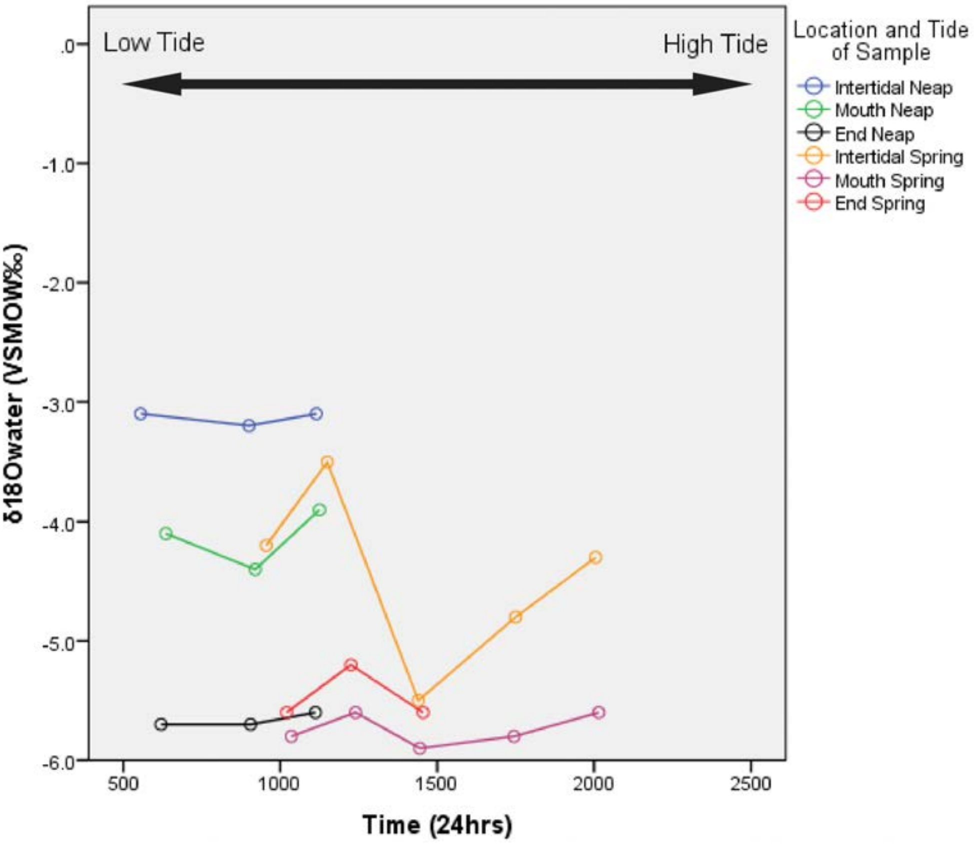

Figure 6.20 $\delta^{18}O_{water}$ sample results from the 2014 wet season. Neap tide samples collected 05 March 2014, spring tide samples collected 28 February 2014.

Results from $\delta^{18}O_{water}$ samples collected from the main terrestrial input into Mirdidingki Creek, the small inundated clay pan system to the northwest, and *P. coaxans* habitat show similarities to values from creek and intertidal sampling (Table 6.5). Both clay pan and mangrove input values (-6.4‰ and -6.1‰ respectively) are likely representative of recent rainfall $\delta^{18}O_{water}$ as they have not yet mixed with marine water. The STN5 sample resembles neap tide creek mouth signals (-4.1‰) suggesting some hydrological consistency. Salinity values from this sample set are also elevated, indicative of low-level marine influence likely originating from tidal inundation, although it is difficult to accurately identify its source. Whatever the origin of this variability, it is clear the mangrove environment at STN5 again deviates from broader trends.

Table 6.5 Oxygen values for additional water sampling during the 2014 wet season.

Date	Time	Location	$\delta^{18}O_{water}$ (‰)
28/02/2014	0955	Input from mangroves into Mirdidingki Creek	-6.1
04/03/2014	1220	Mirdidingki Clay Pan	-6.4
04/03/2014	1235	STN5	-4.1

$\delta^{13}C_{DIC}$

The mean $\delta^{13}C_{DIC}$ value (Figure 6.21) for the 2014 wet season was -8.9‰ (*n* = 21; range = -13.0‰ – -0.82‰). Both spring (*n* = 13) and neap (*n* = 8) tides display significant variation in $\delta^{13}C_{DIC}$ values with ranges of -13.0‰ to -2.8‰ (mean = -8.8‰) and -12.7‰ to -0.8‰ (mean = -9.0‰), respectively. Intertidal samples exhibit significantly more positive values than the creek system owing to the dilution of the strong terrestrial signal found in estuarine water in the open marine environment. Further, of the three sampling sites the intertidal zone shows the most variation with values ranging between -8.0‰ and -0.8‰ (*n* = 7; mean = -4.4‰). The creek mouth site varies by up to 3.8‰ with a range of -12.8‰ to -9.0‰ (*n* = 8; mean = -10.5‰), while the end of the system shows a similar variation of 2.8‰ and a range of -13.0‰ to -10.2‰ (*n* = 8; mean = -12.1‰). The wide range of values present in the intertidal is likely caused by the introduction and mixing of fluctuating amounts of runoff from flooding events and tidal cycles, while the relative stability of the creek system is linked with its enclosed space and consistent interaction with terrestrial carbon sources.

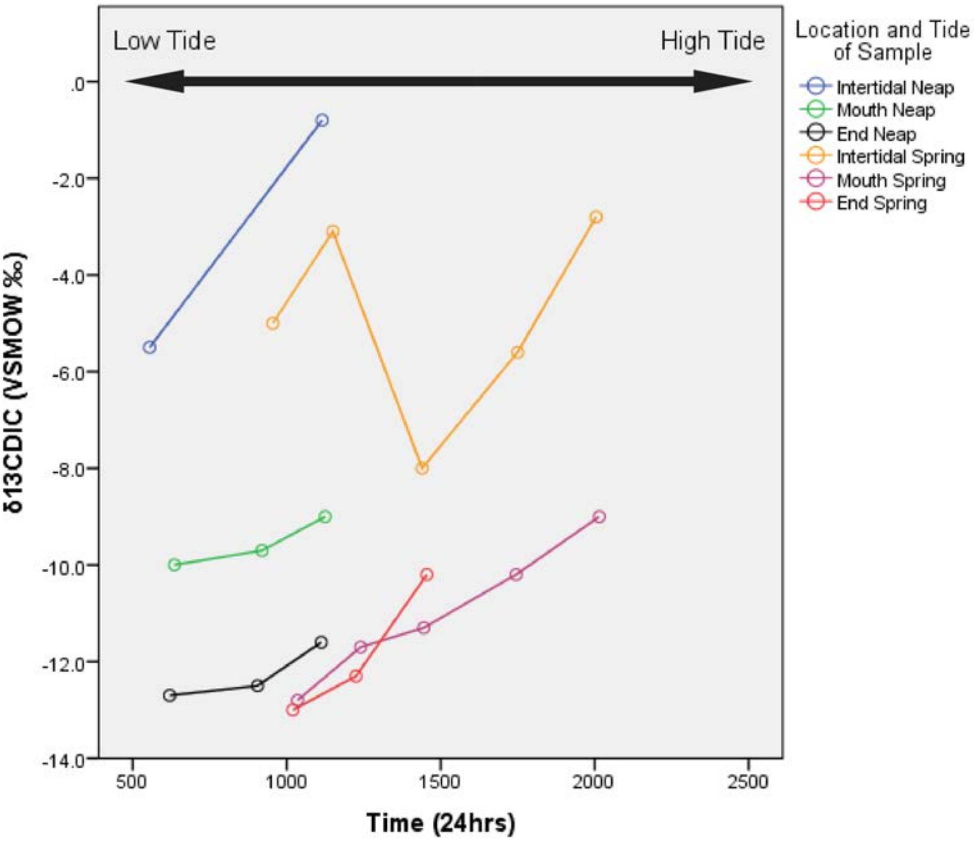

Figure 6.21 $\delta^{13}C_{DIC}$ sample results from the 2014 wet season. Neap tide samples collected 05 March 2014, spring tide samples collected 28 February 2014.

All additional carbon isotope values for DIC collected from a major run-off input into the end of Mirdidingki Creek, the small clay pan to the north, and STN5 are indicative of major terrestrial influence (Table 6.6), which is unsurprising as they have not yet interacted with marine waters. Interestingly, the STN5 signal remains in line with the other values suggesting that salinity and $\delta^{18}O_{water}$ variability may not be the result of marine mixing.

Table 6.6 Carbon values for additional water sampling during the 2014 wet season.

Date	Time	Location	$\delta^{13}C_{DIC}$ (‰)
28/02/2014	0955	Input into Mirdidingki Creek	-13.2
04/03/2014	1220	Mirdidingki Clay Pan	-11.6
04/03/2014	1235	STN5	-11.1

6.3.2.3 Dry Season 2014

Similar to previous sampling, water samples were collected during the 2014 dry season over two tides of variable amplitudes (high and low) at the end and mouth of Mirdidingki Creek, as well as in the open marine system just beyond the water's edge. Further water samples were collected from the open water adjacent to Thundiy on the north coast of Bentinck Island.

Salinity

As with dry season data from 2013, salinity remains relatively stable (n = 26; range = 29.8– 34.1 PSU; mean = 32.8 PSU), although is slightly depressed when compared to the previous year (Figure 6.22). Likewise, variability between neap and spring tides is nominal with respective ranges of 31.9 to 33.9 PSU (n = 14; mean = 32.99 PSU) and 29.8 to 34.1 PSU (n = 12; mean = 32.5 PSU). These stable conditions persist between sampling sites. Intertidal values ranged between 33.3 and 34.1 PSU (n = 9; mean = 33.7 PSU), samples from the mouth of the creek system saw a range of 32.3 to 33.2 PSU (n = 9; mean = 32.7 PSU), while salinity at the end of the system saw the greatest variability ranging between 29.8 and 33.2 PSU. This suggests conditions are dominated by marine waters owing to the tidal influence within the creek system.

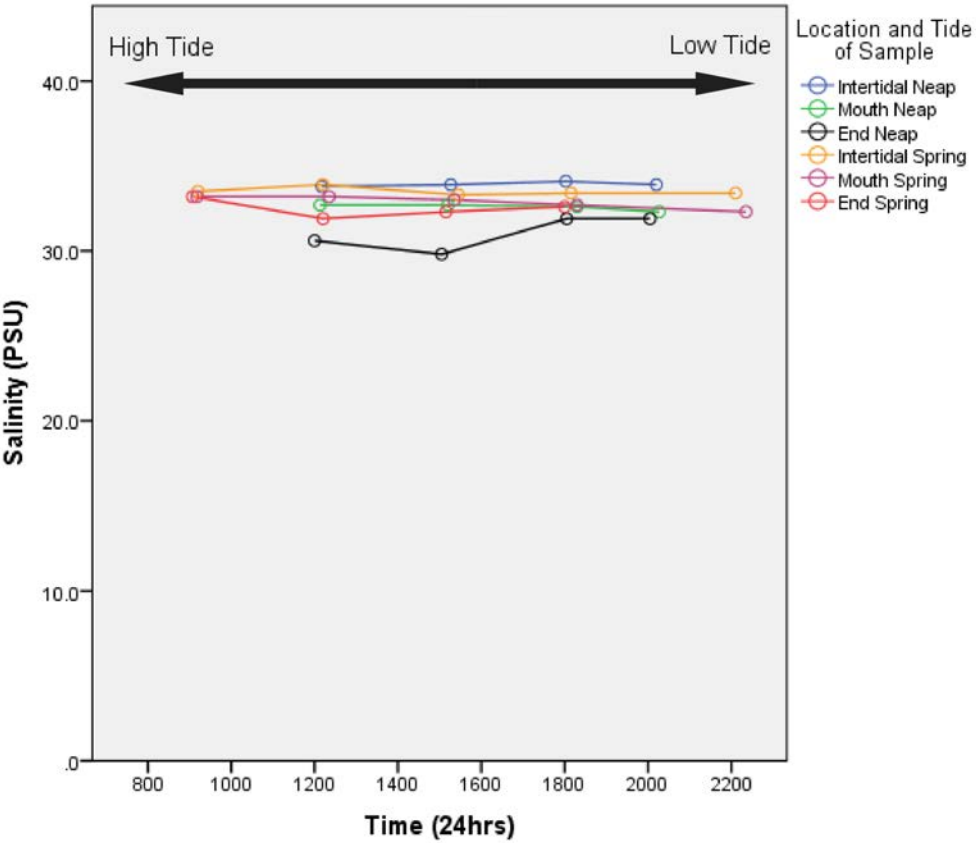

Figure 6.22 Salinity sample results from the 2014 dry season. Neap tide samples collected 20 July 2014, spring tide samples collected 13 July 2014.

Salinity values from Thundiy are indicative of conditions recorded at Mirdidingki, indicating homogenous salinity conditions around Bentinck Island (Table 6.7).

Table 6.7 Salinity readings from Thundiy track well with values from Mirdidingki.

Date	Time	Location	Salinity (PSU)
08/07/2014	1205	Thundiy Intertidal	33.5
09/07/2014	1120	Thundiy Intertidal	33.7
23/07/2014	0930	Thundiy Intertidal	35.5

$\delta^{18}O_{water}$

Water oxygen values from the 2014 dry season remain relatively stable, ranging from -1.9 to -0.4‰ with a mean of -1.2‰ (Figure 6.23). These values are on average 1.3‰ more negative than those from the 2013 dry season, indicating inter-annual variability. Comparing spring and neap tide sample sets reveals a similar pattern of stability with means of -1.2‰ (*n* = 14; range = -1.9‰ – -0.5‰) and -1.2‰ (*n* = 12; range = -1.7‰ – -0.4‰) respectively. Contrasting different sampling points shows minimal variation with intertidal values averaging -0.9‰ (*n* = 9; range = -1.3‰ – -0.9‰), mouth values returning a mean of -1.3‰ (*n* = 9; range = -1.9‰ – -0.8‰), and end of system samples averaging -1.3‰ (n = 9; range = -1.7‰ – -0.8‰). Thus, much like data from the 2013 dry season, all sample stations returned stable marine conditions.

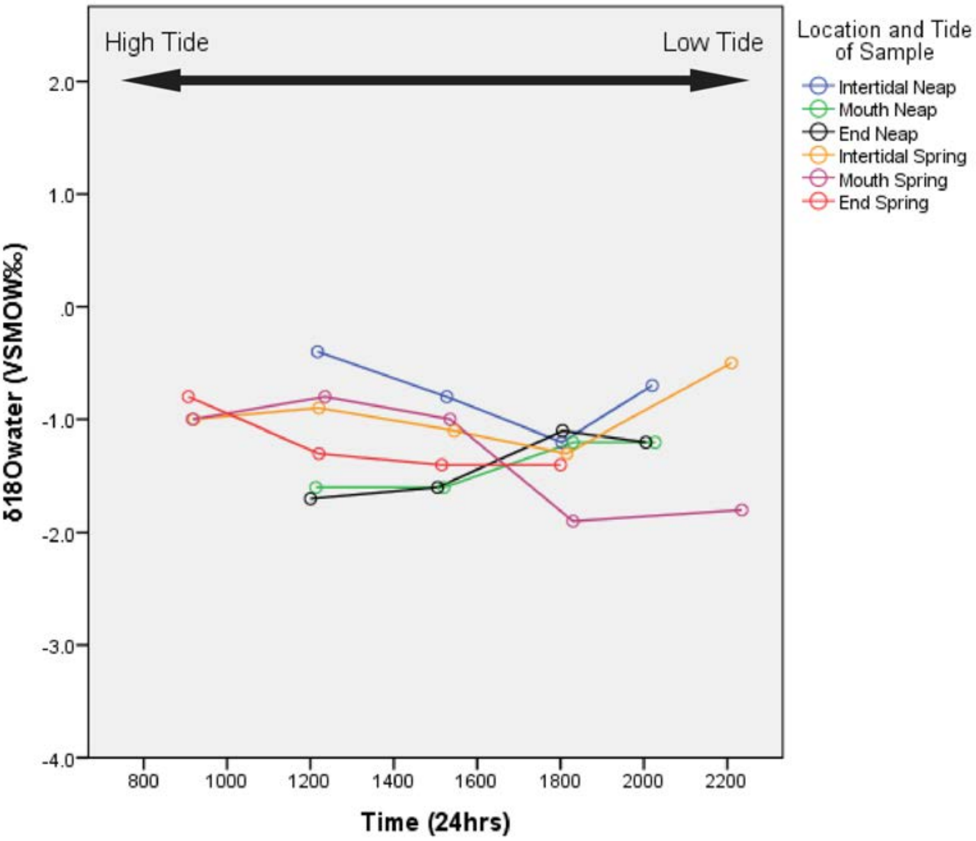

Figure 6.23 $\delta^{18}O_{water}$ sample results from the 2014 dry season. Neap tide samples collected 20 July 2014, spring tide samples collected 13 July 2014.

Water sampling undertaken in the intertidal zone adjacent to Thundiy reveals oxygen values consistent with the Mirdidingki intertidal zone, suggesting environmental conditions are relatively stable in the marine system surrounding Bentinck Island (Table 6.8). Thus, findings from the Mirdidingki area can be tentatively applied to similar locations around the island.

Table 6.8 Stable oxygen values from Thundiy are in line with those taken from Mirdidingki.

Date	Time	Location	$\delta^{18}O_{water}$ (‰)
08/07/2014	1205	Thundiy Intertidal	+0.3
09/07/2014	1120	Thundiy Intertidal	-1.1
23/07/2014	0930	Thundiy Intertidal	-0.7

$\delta^{13}C_{DIC}$

Unfortunately, issues arose with $\delta^{13}C_{DIC}$ samples from the 2014 dry season. A number of vials developed seal leaks over the course of the field season, allowing the escape of gas. In total 9 of the 26 samples were rendered unusable. The following data is taken from the remaining 17 samples (Figure 6.24). Significant variation was revealed with $\delta^{13}C_{DIC}$ ranging between -7.5‰

and +0.2‰ (*n* = 17; mean = -3.4‰). Although neap and spring tides returned similar ranges (*n* = 8; range = -7.5‰ – +0.2‰ and *n* = 9; range = -7.2‰ – -0.1‰ respectively), neap tide values were on average significantly more negative (mean = -4.1‰) than during the spring tide (mean = -2.8‰). Water samples taken from inside the creek system (mouth and end of system) returned significantly more negative values (mouth: *n* = 6, range = -6.5‰ – -0.1‰, mean = -4.2‰; end of system: *n* = 5, range = -7.5‰ – -2.1‰, mean = -6.2‰) than the intertidal (*n* = 6; range = -0.9‰ – +0.2‰; mean = -0.3‰). This suggests waters within the creek system have a significant terrestrial component, which does not appear to impact the adjacent marine environment. Moreover, during peak high tides incoming marine waters appear to partially suppress the terrestrial signal until mangrove systems are flooded. Neap tide values remain stable over the tidal cycles owing to minimal water movement.

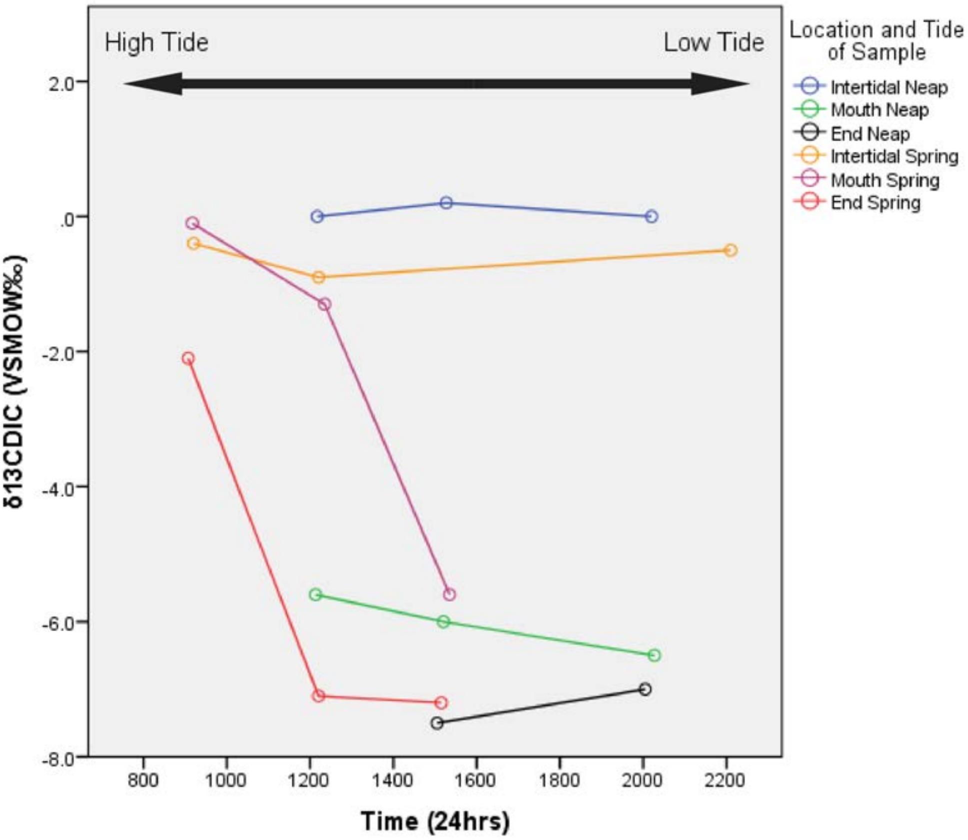

Figure 6.24 $\delta^{13}C_{DIC}$ sample results from the 2014 dry season. Neap tide samples collected 20 July 2014, spring tide samples collected 13 July 2014.

Sampling at Thundiy reveals $\delta^{13}C_{DIC}$ values largely consistent with the intertidal zone adjacent to Mirdidingki (Table 6.9). However, the final value taken on 23 July is significantly more negative. This can be principally attributed to changes in tidal heights. Preceding the 23 July sample was a tidal peak c.0.76m higher than that on 8 July (BOM 2014), allowing increased interaction with terrestrial carbon sources in the mangrove forest. This explanation is strengthened by the consistency of oxygen and salinity values.

Table 6.9 Water sampling from Thundiy demonstrates stable carbon values are indicative of marine conditions.

Date	Time	Location	$\delta^{13}C_{DIC}$ (‰)
08/07/2014	1205	Thundiy Intertidal	-0.2
09/07/2014	1120	Thundiy Intertidal	-0.4
23/07/2014	0930	Thundiy Intertidal	-2.0

6.4 Seasonal Characterisations

6.4.1 Dry Season

Dry season hydrology in the South Wellesley Islands is typified by relatively stable conditions dominated by marine influences (Table 6.10). The open marine environment displays only minor fluctuations in $\delta^{18}O_{water}$ and salinity over and between tidal cycles. Inter-annual variability is evident in $\delta^{18}O_{water}$ values between datasets collected in 2013 and 2014 with a mean shift of approximately 1.3‰. This is accompanied by a very minor salinity depression in 2014 (mean = 33.8 PSU) when compared to 2013 (mean = 34.5 PSU). Similar patterns are evident in estuarine environments, which returned mean $\delta^{18}O_{water}$ and salinity values indicative of marine conditions and inter-annual variability. While the source of decreased $\delta^{18}O_{water}$ and salinity values remains unclear, it is likely the result of broader environmental trends as localised 2013 – 2014 wet season conditions were less severe (less rainfall over a shorter period time) than that in 2012-2013. Mangrove habitats associated with *P. coaxans* exhibited a departure from other environments with significantly more negative $\delta^{18}O_{water}$ (-2.9‰) and lower salinity (20.1 PSU) values. This decoupling from broader hydrological trends raises questions regarding the usefulness of *P. coaxans* (as well as other mangrove shellfish species) to studies interested in conditions external to mangrove forests (see Chapter 7 for further discussion).

Table 6.10 Dry season $\delta^{18}O_{water}$ and salinity values indicate strong marine influences and stable conditions across environments with the exception of *P. coaxans* habitats.

$\delta^{18}O_{water}$ (‰)	2013		2014		Overall	
	Range	Mean	Range	Mean	Range	Mean
Marine	+0.1 – +0.9	+0.4	-1.3 – -0.4	-0.9	-1.3 – +0.9	-0.3
Estuarine	-0.5 – +0.5	+0.1	-1.9 – -0.8	-1.3	-1.9 – +0.5	-0.8
Mangroves						-2.9

Salinity (PSU)	2013		2014		Overall	
	Range	Mean	Range	Mean	Range	Mean
Marine	35.5 – 38.8	34.5	33.3 – 35.5	33.8	33.3 – 38.8	35.0
Estuarine	34.1 – 36.2	35.2	29.8 – 33.2	32.3	27.8 – 36.2	33.5
Mangroves						20.1

The exception to the broad hydrological stability of the dry season are $\delta^{13}C_{DIC}$ values (Table 6.11). While both marine and estuarine values remained relatively consistent between years (maximum annual shift of 1.1‰), significant variability occurs over individual tidal cycles. Values from *P. coaxans* habitats are significantly more negative than other environments (by up to 14.0‰), suggesting that mangrove systems are heavily influenced by terrestrial carbon. Inundation of these environments during peak high tides allows terrestrial carbon to be transferred into estuarine systems. As the tide recedes it carries waters enriched with terrestrial carbon into the open marine environment. Upon mixing with marine waters the terrestrial signal is slowly overwhelmed and eventually dissipates. Thus, pulses of more negative $\delta^{13}C_{DIC}$ values occur subsequent to high tides in marine environments surrounding estuaries and tidally fed mangrove stands (e.g. Mirdidingki Creek and Thundiy). The severity, timing, and periodicity of these pulses are likely linked to tidal amplitude with peak high tides causing the greatest influxes.

Table 6.11 Unlike other hydrological characteristics, $\delta^{13}C_{DIC}$ values are highly variable across all environments.

$\delta^{13}C_{DIC}$ (‰)	2013		2014		Overall	
	Range	Mean	Range	Mean	Range	Mean
Marine	-5.8 – +0.2	-1.5	-2.0 – +0.2	-0.5	-5.2 – +0.2	-1.0
Estuarine	-6.1 – +0.1	-4.4	-7.5 – -0.1	-5.1	-7.5 – +0.1	-4.7
Mangroves	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	-15.0

A time-lag of a number of hours between terrestrial carbon input into estuarine systems and its appearance in open marine environments suggests pulses are largely confined to medium/low tidal heights in intertidal and subtidal zones. It is currently unclear how quickly terrestrial carbon signals dissipate in the marine system, however it does appear that they remain strong until at least low tide. This pattern is less apparent in the 2014 dataset, potentially owing to the high rate of sample loss highlighted earlier. Moreover, similar fluctuations are absent from neap tide sampling, indicating a minimum tidal height is required to flush mangrove systems. Outside these periods of heightened terrestrial influence, estuarine systems display consistently more negative $\delta^{13}C_{DIC}$ compared to marine environments owing to ongoing contact with terrestrial habitats along their banks. Moreover, input of groundwater observed along Mirdidingki may serve to marginally increase terrestrial carbon content.

Only 5% of annual rainfall occurs during the dry season. What little precipitation does take place is largely confined to April or September/October, which encompass periods where climatic conditions rapidly shift between seasonal norms. Thus, these can be classed as transitionary months, which tend to share characteristics of both wet and dry seasons. Sea surface temperatures from Karumba highlight this pattern with April to May displaying a mean shift of 5.1°C (range = 3.8 – 7.0°C) and August to September showing an average increase of 3.3°C (range = 3.0 – 3.4°C). While April and September/October were initially considered part of the dry season, it is more appropriate to treat them as separate entities to remove any possibility of data skewing owing to their unique characteristics (Table 6.12). Further, this thinking is more congruous with local Aboriginal descriptions of annual climatic cycles, which also account for transitionary periods (see Chapter 3; Rosendahl 2012:60). As only instrumental data is available from these months, only temperature and rainfall are presented.

Table 6.12 Environmental characteristics of transitionary months in the South Wellesley Islands.

	April				September/October			
	Temperature (°C)		Rainfall (mm)		Temperature (°C)		Rainfall (mm)	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Subtidal	25.1 – 32.6	29.5			24.1 – 33.4	28.5		
Intertidal	24.0 – 33.5	29.0			21.1 – 37.8	28.9		
Estuarine	23.9 – 35.9	28.2			19.4 – 36.0	27.9		
Mangroves	24.2 – 38.1	28.1			17.9 – 56.8	28.7		
Karumba	24.7 – 31.4	28.4			25.8 – 31.8	28.2		
Overall			0 – 349.1	64.4			0 – 39.0	5.3

As transitionary periods (April and September/October) are now considered separate to the larger dry season dataset, associated results (temperature and rainfall) must be recalibrated to reflect this (Table 6.13). Temperatures across all environments remained consistent with averages displaying a maximum variability of 3.4°C. Environment-specific ranges show relatively high variability across all deployed sensors averaging 22.5°C, although this is inflated by the STN5H results. Results from Mirdidingki sensor stations closely track SST data from Karumba, although in some cases ranges differed significantly. As stated above, the intertidal temperature sensor (STN4) was subjected to periodic aerial exposure during some low tides, thus the dataset represents a combination of SST and atmospheric readings. While this could be construed as problematic, mollusc taxa inhabiting this environmental zone are subject to these same conditions (e.g. Broom 1985). The data collected by this sensor are therefore an accurate representation of the full range of temperatures experienced by intertidal taxa. Conversely, readings recovered from the *P. coaxans* habitat (STN5H) returned maximums up to 47.5°C, averaging 17.2°C higher than other environments. Environmental characteristics similar to those seen in supra-tidal rock pools, including shallow water depth, exposure to direct sunlight, dark sediments, and minimal flushing (Firth and Williams 2009; Hogg et al. 1998; Killingley 1981; Shackleton 1973), are the most likely causes of comparatively extreme temperatures found in landward mangrove habitats.

Table 6.13 Dry season sea surface temperature and rainfall results for the South Wellesley Islands and Karumba.

	Temperature (°C)		Overall Rainfall (mm)	
	Range	Mean	Range	Mean
Subtidal	13.3 – 30.1	23.2		
Intertidal	11.7 – 32.6	22.1		
Estuarine	12.0 – 28.4	19.8		
Mangroves	11.6 – 47.5	22.8		
Karumba	16.5 – 28.0	21.9		
Overall			0.0 – 41.3	2.5

Dry season hydrology in the South Wellesley Islands is largely dominated by stable marine signals reflected within the salinity and $\delta^{18}O_{water}$ values of most environments. This is principally maintained by limited input of meteoric/freshwater into estuarine and marine systems. The exception to this are mangrove systems that show significant deviations from broader environmental trends. Thus, it is necessary to consider that while shellfish living in landward mangrove habitats, such as *P. coaxans*, may accurately record ambient environmental conditions, these conditions may be unique to the local mangrove forest or individual pool of water. The isolated nature of pooled water may also lead to other non-climatic drivers, such as tidal cycles, overpowering seasonal signals. Moreover, the impact of physiological and ecological characteristics developed to survive the highly variable nature of landward mangrove environments may cause shell isotopes to enter disequilibrium with ambient conditions. The impact of these potential issues are discussed further in Chapter 7. Finally, $\delta^{13}C_{DIC}$ values are highly variable between environments and through time, although this is primarily linked with interactions between tidal forces and terrestrial carbon sources and therefore should not be viewed as a marker of seasonality. Comparatively low water temperatures are also a key characteristic of the dry season climate.

6.4.2 Wet Season

Wet season hydrological conditions in the South Wellesley Islands are influenced by a complex interplay of geographically broad and localised environmental trends. Mainland catchment systems expel up to 92,000GL of freshwater into the Gulf of Carpentaria during this period (Burford et al. 2009; Oliver and Thompson 2011), introducing a background freshwater signal to the marine environment in the region. This is accompanied by highly localised periods of monsoonal rainfall that flood low-lying areas of the South Wellesley Islands. Water that does not serve to recharge groundwater sources or evaporate is input into estuarine systems or directly into the open marine environment, temporarily strengthening the freshwater influence. However, as monsoonal precipitation is not constant, hydrological conditions fluctuate between baseline wet season values and those that are enhanced by additional freshwater influxes. To account for this wet season water isotope and salinity data have been divided into modes, *Tidal* and *Precipitation*. The *Tidal* mode denotes periods of time with minimal input from precipitation or flooding runoff and can be seen as a baseline for wet season conditions. Conversely, the *Precipitation* mode is entered during periods of heavy freshwater input from monsoonal rainfall and flooding runoff, leading to heightened environmental characteristics.

During the *Tidal* mode, marine $\delta^{18}O_{water}$ and salinity values are indicative of a stable mixture of fresh and marine waters with minimal fluctuations of 0.1‰ and 1.2 PSU respectively. Conversely, the *Precipitation* mode is typified by more negative values and a significant increase in variability (Table 6.14), reflecting the increased input of freshwater. Water sampling from estuarine environments reveals more negative values as well as far greater variability in both $\delta^{18}O_{water}$ and salinity than during the *Tidal* mode (Table 6.14). Mangrove systems do not see a departure from broader trends as in the dry season, instead both $\delta^{18}O_{water}$ and salinity values show similarities with averaged marine readings (Table 6.14). Consistency with marine conditions is incongruous with expected outcomes for wet season mangrove habitats, particularly in the case of salinity, as these waters should theoretically consist primarily of freshwater runoff and thus reflect estuarine, end system input ($\delta^{18}O_{water}$ = -6.1‰; salinity = 1.0 PSU), or clay pan ($\delta^{18}O_{water}$ = -6.4‰; salinity = 1.0 PSU) values. Instead, it appears marine waters are somehow influencing this environment. While it is difficult to pinpoint the origin of this influence, it is possible that these marine-like values may be caused by residual signals from tidal inundation during high tides.

Table 6.14 $\delta^{18}O_{water}$ and salinity values for key environments in Mirdidingki region divided into *Tidal* mode, *Precipitation* mode, and Average datasets.

$\delta^{18}O_{water}$ (‰)	Tidal Mode		Precipitation Mode		Average	
	Range	Mean	Range	Mean	Range	Mean
Marine	-3.2 – -3.1	-3.1	-5.5 – -3.5	-4.5	-5.5 – -3.1	-4.0
Estuarine	-5.7 – -3.9	-4.9	-5.9 – -5.2	-5.6	-5.9 – -3.9	-5.3
Mangroves						-4.1

Salinity (PSU)	Tidal Mode		Precipitation Mode		Average	
	Range	Mean	Range	Mean	Range	Mean
Marine	23.3 – 24.5	23.8	4.4 – 21.0	13.4	4.4 – 24.5	17.3
Estuarine	6.1 – 19.3	12.5	0.1 – 5.3	1.56	0.1 – 19.3	6.2
Mangroves						15.2

Overall wet season $\delta^{13}C_{DIC}$ values are significantly more negative than those typifying the dry season. For *Tidal* mode conditions this is likely tied to the broader hydrological changes associated with monsoonal runoff from continental catchments (Table 6.15). Marine values see high variability owing to a combination of high tide mangrove habitat inundation and input of terrestrial runoff from flooding. Estuarine values see a variation of up to 3.7‰, although fluctuations appear muted compared to the dry season likely owing to the higher quantity of background terrestrial carbon present throughout the region as well as near continuous input of flood runoff. Mean stable carbon values in both marine and estuarine environments during *Precipitation* mode conditions are marginally more negative when compared to *Tidal* mode results. Marine system variability is significantly higher, likely owing to increased terrestrial runoff. Much like $\delta^{18}O_{water}$ and salinity, $\delta^{13}C_{DIC}$ values collected from mangrove habitats did not display large deviations from broader conditions, adhering closely to estuarine environments. Although, they are significantly offset (7.1‰) from mean marine values. Such a close correlation between estuarine and mangrove carbon values is unsurprising as large quantities of water is directly input into Mirdidingki Creek from the mangrove habitat.

Table 6.15 Wet season $\delta^{13}C_{DIC}$ values reveal a strong terrestrial signal throughout all target environments.

	$\delta^{13}C_{DIC}$ (‰)					
	Tidal Mode		Precipitation Mode		Average	
	Range	Mean	Range	Mean	Range	Mean
Marine	-5.5 – -0.8	-3.2	-8.0 – -2.8	-4.9	-8.0 – -0.8	-4.4
Estuarine	-12.7 – -9.0	-10.9	-13.0 – -9.0	-11.3	-13.0 – -9.0	-11.2
Mangroves						-11.5

Mean seasonal data returned by a majority of sensors indicate temperatures are relatively homogenous between environments (Table 6.16). Using Karumba as a baseline, mean temperatures fluctuate by, at most, 1.3°C. Overall lows from the Mirdidingki sensors are similar, although are up to 6.5°C cooler than those from Karumba. Temperature variability is reduced across all environments when compared to dry season results with an average shift of 19.2°C (3.3°C lower than dry season variability). When ranges are compared it becomes apparent that variability is inconsistent among environments. In particular, mangrove habitats exhibit the highest variability of up to 32.2°C. Intertidal and estuarine temperatures also display significant variability of 17.6°C and 17.1°C, respectively. The subtidal zone exhibits the most consistent temperatures that fluctuate by a maximum of 9.8°C.

Monsoonal cycles active during the wet season lead to a significant increase in precipitation. A 14 year average of wet season conditions from the Sweers Island BOM station reveals a mean of 232.1mm of rainfall occurs monthly throughout the wet season, although this can reach as much a 1066.5mm per month (Table 6.16). This extremely high quantity of precipitation is the primary driver of seasonal hydrological and environmental change in the South Wellesley Islands and throughout much of Australia's tropical north.

Table 6.16 Wet season conditions are characterised by increased temperatures and periods of substantial precipitation tied to monsoonal cycles.

	Temperature (°C)		Overall Rainfall (mm)	
	Range	Mean	Range	Mean
Subtidal	24.5 – 34.3	30.3		
Intertidal	22.4 – 40.1	30.7		
Estuarine	23.5 – 40.6	31.2		
Mangroves	20.8 – 53.0	29.7		
Karumba	27.3 – 33.7	30.6		
Overall			0.0 – 1066.5	232.1

Wet season conditions within the South Wellesley Islands can be characterised as highly changeable, exhibiting elevated temperatures and tidal heights with hydrology dominated by freshwater signals originating from monsoonal precipitation. This is reflected within depressed $\delta^{18}O_{water}$ and salinity values seen throughout all environments. Further, increased input from flooding and terrestrial runoff causes a significant pan-environment depression in $\delta^{13}C_{DIC}$ values. All three of these negative trends enter a temporary *Precipitation* mode state during and subsequent to monsoonal downpours as freshwater input increases, before returning to a *Tidal* mode state as estuarine systems are flushed by tidal forces. The stark differences between these two hydrological modes typify the high variability of wet season conditions.

6.5 Predictions and Discussion

6.5.1 Modelled Predictions

Predicting chemical and physical responses of local shellfish populations to environmental oscillations outlined above can provide broad estimates of seasonal variability within shell carbonates. Assuming oxygen isotopic equilibrium, $\delta^{18}O_{shell}$ for tropical species reflects both temperature and the $\delta^{18}O$ value of the water (Figure 6.25) (Kennett and Voorhies 1995, 1996; Stephens et al. 2008). Thus, seasonal shifts in $\delta^{18}O$ of shell carbonate may reflect $\delta^{18}O_{water}$ observed around the South Wellesley Islands, particularly as the seasonal shift in temperature is more subdued. The impact of these factors on $\delta^{18}O_{shell}$ can be modelled using Equation 5.2 (see Chapter 5), the results of which ($\delta^{18}O_{shell\text{-}predicted}$) provide potential seasonal ranges and means.

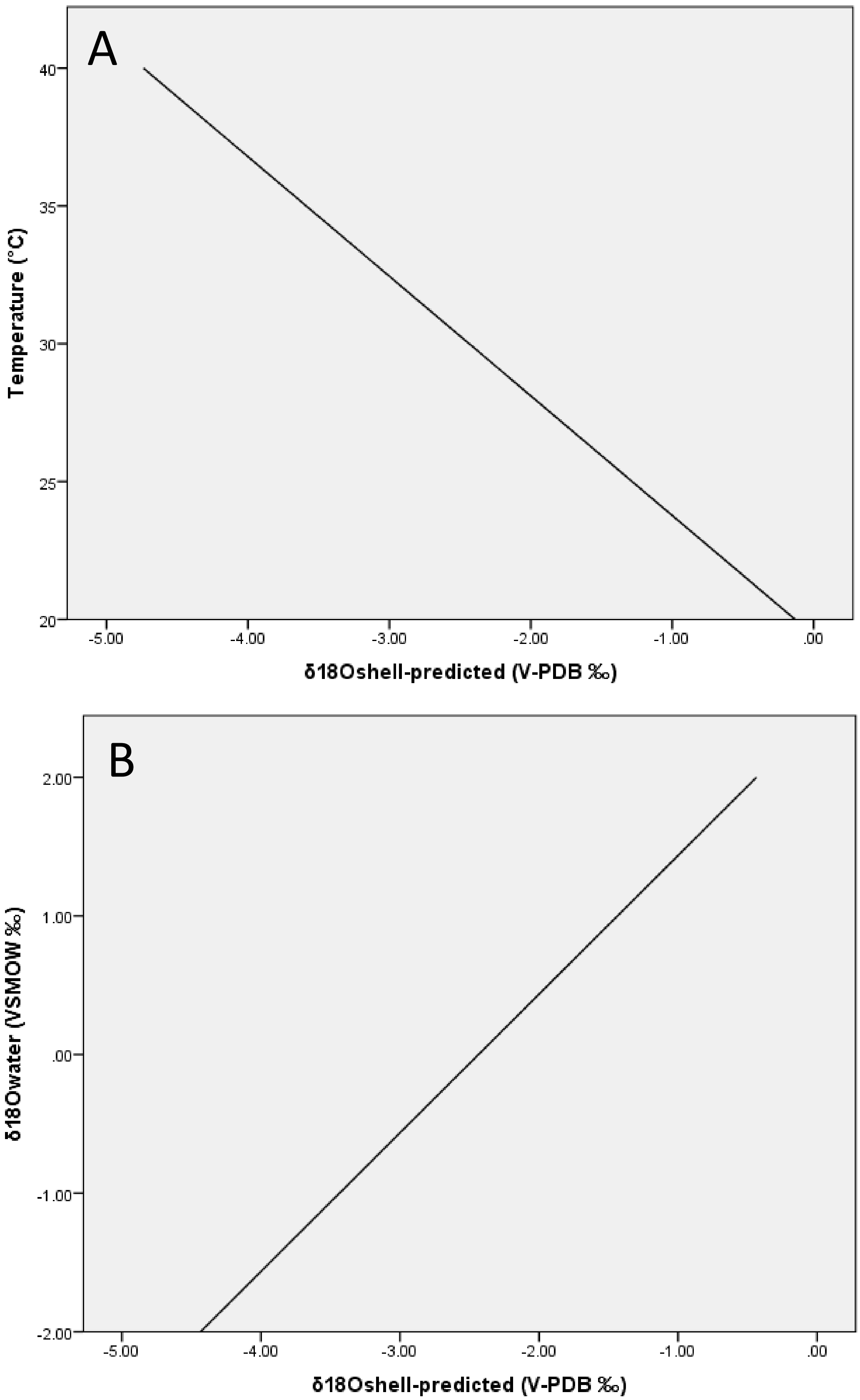

Figure 6.25 (A) Temperature shares an inverse relationship with $\delta^{18}O_{shell}$, every 4.34°C of temperature change equates to a 1‰ shift in $\delta^{18}O_{shell}$. (B) $\delta^{18}O_{water}$ has a positive 1:1 relationship with $\delta^{18}O_{shell}$.

As temperature is a key component of this equation, thought must be given to the highly variable nature of datasets from sensor stations. Some of the more extreme temperature maximums and minimums (particularly in intertidal and mangrove environments) have the potential to inflate $\delta^{18}O_{shell\text{-}predicted}$ seasonal ranges. Thus, in order to provide a more accurate representation of potential $\delta^{18}O_{shell}$ values, end quartiles and interquartile ranges (IQR) were calculated for each dataset. To account for the potentially aggressive nature of data removal using raw IQR, authors suggest multiplying IQR by 1.5 to generate upper and lower fences (Hodge and Austin 2004). Data outside of these fences are removed (Table 6.17).

Table 6.17 Interquartile ranges were used to provide a more accurate representation of temperature datasets for $\delta^{18}O_{shell}$ prediction.

	Environment			
No. of Data Points Removed	Subtidal	Intertidal	Estuarine	Mangroves
	41	21	0	199

Modelled average of dry season $\delta^{18}O_{shell\text{-}predicted}$ for subtidal, intertidal, and estuarine taxa remain relatively consistent (-1.2‰ – -0.9‰), suggesting these taxa will return comparative isotope values (Figure 6.26). Conversely, mangrove species are predicted to return average $\delta^{18}O_{shell}$ values up to 2.3‰ more negative than taxa from other environments owing to decoupled conditions in their growth environments. The implications of this for palaeoenvironmental research are discussed in Chapter 7. Ranges reveal the potential for a wide variety of values across all environments with an average amplitude of 6.1‰. As $\delta^{18}O_{water}$ values remain relatively stable throughout the dry season, variability in $\delta^{18}O_{shell\text{-}predicted}$ can be linked with temperature oscillations occurring at sub-daily scales. As current carbonate sampling techniques are incapable of working at these resolutions, a degree of time-averaging is introduced to each individual sample depending on species and ontogenetic age (see Chapter 2). Thus, extreme ranges will likely be lost to homogenisation with $\delta^{18}O_{shell}$ values more reflective of predicted means, although the possibility of high variably must be acknowledged.

Wet season $\delta^{18}O_{shell\text{-}predicted}$ values across all environments are significantly more negative than those calculated from dry season data (Figure 6.26). Mean values reveal high variably with an average fluctuation of 5.4‰. Likewise, individual ranges were relatively broad (4.4‰ – 6.5‰), although when compared with dry season results were marginally more consistent owing to a narrower temperature range. Comparisons between hydrological modes reveal a negative trend during *Precipitation* conditions across all environments owing to increased input of meteoric water. Yet, beyond this there are only minor differences between the two, which display overlapping ranges and minimal offsets between means, rendering model characterisation through $\delta^{18}O_{shell}$ impracticable. Changeability between *Tidal* and *Precipitation* modes should instead be viewed as a possible range for wet season values. Inter-environment variability is moderate with means remaining within 1.6‰ of one another. Species inhabiting subtidal environments are expected to return the most consistent results, although are subject to the a pronounced shift between *Tidal* and *Precipitation* modes as increasing amounts of freshwater are input into the marine system. Intertidal species are predicted to show significant variability owing to near constant mixing of marine and freshwater as well as highly changeable temperatures (range = -3.8‰ – -10.3‰). Similarly, estuarine values demonstrate the potential for increase variability (range = -4.8‰ – -10.8‰), yet experience only a minor negative shift during the *Precipitation* mode owing to consistent freshwater signals. Mangrove species returned the most consistent $\delta^{18}O_{shell\text{-}predicted}$ values (range = -4.4‰ – -8.9‰), likely owing to consistent flushing of the system by flood waters.

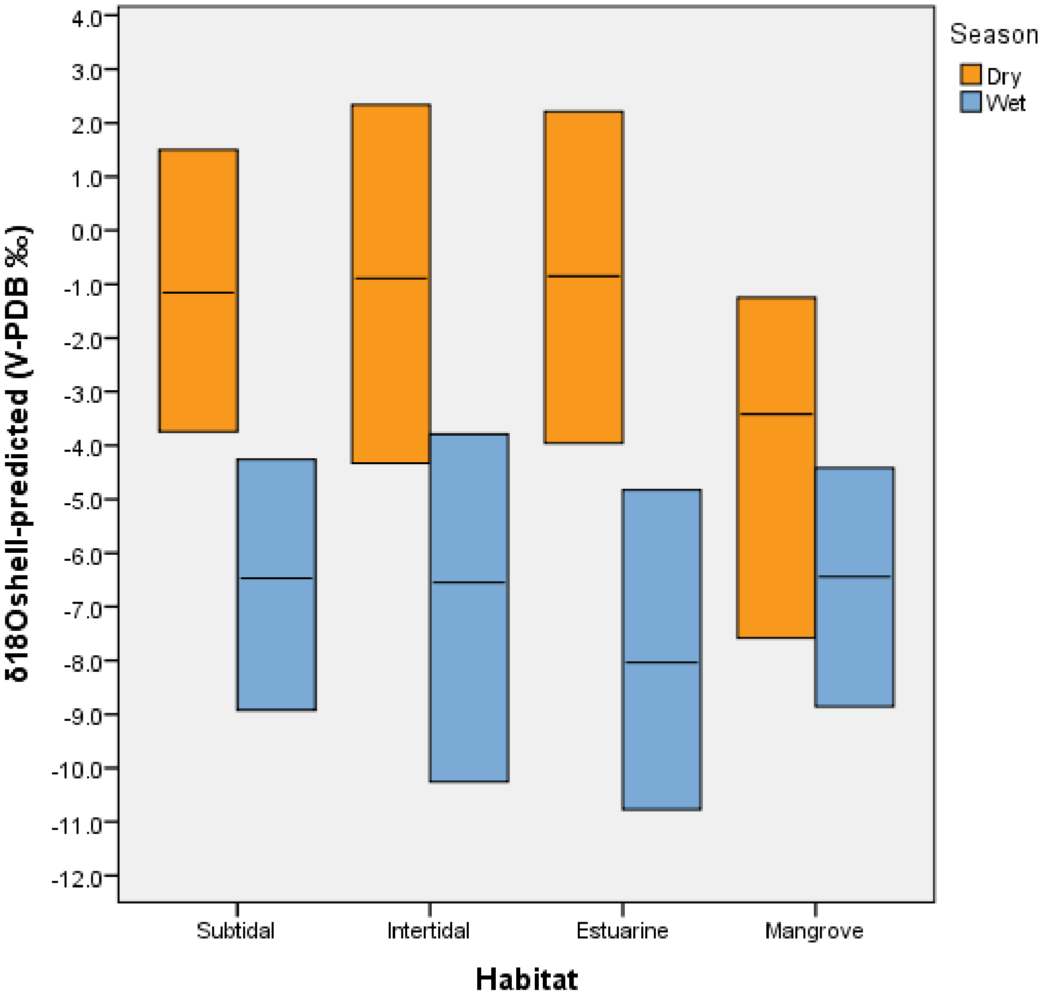

Figure 6.26 Seasonal ranges of $\delta^{18}O_{shell\text{-}predicted}$ were calculated using maximum, minimum, and mean temperature and $\delta^{18}O_{water}$ data.

Seasonal comparisons of $\delta^{18}O_{shell\text{-}predicted}$ values suggest difficulties could arise in accurately determining seasonality for intertidal and mangrove species under certain conditions owing to broad seasonal ranges in isotope compositions. Intertidal ranges see a slight overlap of 0.5‰, although seasonal means remain well defined. Seasonal ranges for mangrove species display the potential to overlap considerably (dry season: -1.3‰ – -7.6‰; wet season: -4.4‰ – -8.9‰). A majority of poorly defined values from both environments occur in conjunction with seasonal extremes (dry season: temperature highs and $\delta^{18}O_{water}$ minimums; wet season: temperature lows and $\delta^{18}O_{water}$ maximums). Seasonal means indicate that a majority of intertidal $\delta^{18}O_{shell}$ values should oscillate by approximately 5.6‰, while mean mangrove values are predicted to vary by only 2.8‰. The potential impact of these factors will be further discussed in coming chapters (see Chapter 7).

It is difficult to predict shell carbon values owing to uncertainties associated with species-specific physiological factors (see Schöne 2008; Tanaka et al. 1986). However, previous studies have found that $\delta^{13}C_{shell}$ can be used as a supplementary means of tracking shifts in salinity and water mixing as $\delta^{13}C$ values fluctuate depending on the admixture of marine and fluvial DIC (Gillikin et al. 2006; Keith et al. 1964; Kennett and Voorhies 1995). While mean seasonal $\delta^{13}C_{DIC}$ values from the South Wellesley Islands indicate significant variability between all environments, numerous ranges overlap (particularly marine values) making it difficult to determine seasonality from $\delta^{13}C_{shell}$ data. Instead, $\delta^{13}C_{shell}$ can assist in characterising environmental preferences of shellfish taxa, particularly when combined with $\delta^{18}O_{shell}$ values (see Petchey et al. 2013). Application and results of this technique will be discussed on a species-by-species basis in later chapters (see Chapter 7 – 9).

6.5.2 Seasonal Change and Variable Environmental Records

Although models can be used to predict the impact of temperature and water composition on shell geochemistry, additional biological and ecological factors can alter the completeness and accuracy of associated records. Environmental signals are only archived during periods of shell precipitation (see Hallmann et al. 2009; Mannino et al. 2003), thus records of ambient conditions are intrinsically linked with growth regimes. As outlined in Chapter 4, shellfish cease growth when ambient conditions pass beyond species-specific tolerances. By combining understandings of environmental and hydrological cycles in the South Wellesley Islands with the biology of target taxa (see Chapter 4) the timing and periodicity of sclerochronological environmental records can be estimated for local populations. Moreover, possible offsets and periods of missing data can be highlighted and accounted for.

Of particular import are salinity and temperature, which have been characterised as key environmental controls for shell growth (e.g. Craig et al. 1988; Jagadis and Rajagopal 2007a; Oon 1980). Likewise, periods of aerial exposure cause many bivalves to tightly close their valves and thus cease growth (Clemente 2007; Davenport and Wong 1986; Schöne 2008). Similar environmental factors may also effect the availability of taxa owing to broad climatic change during the mid-to-late Holocene (see Reeves et al. 2007, 2008, 2013; Shulmeister 1992, 1999; Shulmeister and Lees 1995). It must be noted that due to paucity in research into biological and ecological traits of some taxa, only partial optimal ranges could be generated (Table 6.18). Further, optimal ranges should be viewed as a guide for when shell precipitation rates are at their peak. Should environmental conditions move beyond these optimums growth does not cease immediately, instead there is leeway on either side where gradual slowdown occurs.

Table 6.18 Known optimal temperature and salinity conditions for target taxa as well as responses to aerial exposure (after Broom 1985; Clemente 2007; Davenport and Wong 1986; Kithsiri et al. 2004; Kurihara 2003; Nakamura and Shinotsuka 2007; Pathansali 1966; Thomas Stieglitz, pers. comm., 2015; Toral-Barza and Gomez 1986).

	Temperature (°C)	Salinity (PSU)	Exposure Response
Gafrarium pectinatum	Up to 34	Unknown	Close
Marcia hiantina	Up to 32	10 – 36	Subtidal (close)
Polymesoda coaxans	24 – 30	18 – 30	Close

Dry season salinity ranges for both marine (33.3 – 38.8 PSU) and estuarine (27.8 – 36.2 PSU) environments remain within or marginally above optimal conditions for all targeted intertidal and subtidal taxa. Water sampling from mangrove habitats indicates a salinity of 20.1 PSU, which is indicative of *P. coaxans* optimal range. However, this habitat likely experiences salinity fluctuations reflecting estuarine conditions (27.8 – 36.2 PSU) during periods of tidal inundation. While this places mangrove salinities above optimal *P. coaxans* conditions periodically, it is unlikely to trigger a growth stoppage.

Salinities across all environments are substantially depressed throughout the wet season, likely prompting extended or periodic growth cessations in a majority of target species. During *Tidal* conditions marine environments remain within the tolerances of all taxa, however lowered salinities caused by periods of monsoonal rainfall may expedite growth cessation. The exception to this is *M. hiantina*, which has been characterised as having a high tolerance for lowered salinities (Toral-Barza and Gomez 1986). Mean salinity values for estuarine environments suggest lengthy periods of time outside of growth optimums for all taxa. This is especially true of *Precipitation* conditions, which display a maximum of only 5.3 PSU, although the periodicity of these stoppages is difficult to estimate owing to the irregular nature of monsoonal events. Conditions in mangrove environments appear to remain just outside of *P. coaxans* optimums and thus are unlikely to cause an interruption in growth. However, periods of increased input from the clay pan system linked with monsoonal rainfall as well as tidal inundation by estuarine waters potentially cause sharp decreases in salinity and associated growth stoppages.

Mean dry season temperatures across all environments are within or marginally below known optima for the taxa under investigation. However, when temperature ranges are considered it is clear all environments have the potential to move beyond optimal conditions indicating temperature moderated growth cessation occurs periodically in all species during the dry season. Extremely high temperatures documented in mangrove habitats likely cause periodic growth stoppages. Likewise, low temperatures seen throughout all observed environments may cause similar growth cessations. The length of these stoppages is likely short as temperature variations coincide with daily cycles. Assuming this is true, the loss of data derived from low temperatures may cause dry season $\delta^{18}O_{shell}$ values to be slightly more negative than those predicted in Section 6.5.1. Similarly, growth stoppages in mangrove species likely truncate environmental records timed with extreme temperature highs.

Increased temperatures during the wet season place a majority of means and ranges in or marginally above shellfish optima with the exception of mangrove environments where, much like the dry season, extreme temperatures likely truncate growth regimes in conjunction with sub-daily or tidal cycles. Similar patterns were observed during transitionary months (April and September/October). Thus, temperature-derived growth stoppages are limited during transitionary months and the wet season.

For mollusc species inhabiting tidally influenced environments, i.e. intertidal, estuarine, and mangrove, periods of aerial exposure linked with tidal cycling may trigger short-term growth stoppages. However, this is highly dependent on preferences for shoreline positioning with infaunal and high-shore species being subjected to longer periods of exposure than taxa inhabiting the low-shore or interface between intertidal and subtidal zones. Applying this to target taxa, *P. coaxans* are subjected to the longest periods of aerial exposure, *G. pectinatum* undergo short (although frequent, almost daily) exposure, while *M. hiantina* are likely only exposed during exceptionally low tides if at all. Additionally, seasonal changes in tidal height may impact exposure periodicity with increased tidal heights during the wet season decreasing the frequency and periodicity of exposure-mediated growth cessation. The potential impact of changing tidal heights will be discussed on a species-by-species basis in the coming chapters (see Chapters 7 – 9).

Environmental controls may also have an impact on the availability of some shellfish taxa. While *M. hiantina* is evident throughout much of the archaeological record (Rosendahl et al. 2014a; Ulm et al. 2010), live specimens of these species are uncommon in the South Wellesley Islands today (Morrison 2003; personal observation, 2013, 2014, 2016). Numerous authors have linked the late Holocene disappearance of the sandy-mud bivalve *Tegillarca granosa* along Australia's north coast to changing environmental conditions (e.g. Beaton 1985; Bourke 2003; Faulkner 2013; Hiscock and Faulkner 2006). Moss et al. (2015) describe changing coastal environments on Bentinck Island during the mid-to-late Holocene, thus similar changes may have led to the constriction of local *M. hiantina* populations. However, further local palaeoenvironmental data is required to better constrain interpretations.

Changing environmental and climatic conditions potentially impact how modern analogues map to archaeological specimens. Heightened Holocene temperatures (see Shulmeister 1992, 1999; Shulmeister and Lees 1995) and changing hydrological inputs (see Moss et al. 2015) have the potential to offset seasonal stable isotope signals within constituent molluscan populations. Climatic changes associated with the Medieval Climatic Optimum and Little Ice Age may also cause variability in seasonal conditions and archives within contemporary shell carbonates (Moss et al. 2011; Williams et al. 2010). Moreover, additional temperature increases during the wet season may place conditions beyond the tolerances of a majority of target taxa causing more regular or longer-term growth cessations and a further truncation of palaeoenvironmental records. It is therefore imperative that modern analogues are employed only to guide interpretation, rather than directly characterise archaeological results.

6.6 Summary

This chapter presented results of continuous instrumental monitoring, end-member water sampling, and third-party measurements of temperature, tidal heights, and precipitation. Seasonal hydrological and climatic cycles associated with a variety of key environments were characterised. Stark differences between wet and dry seasons were observed, primarily owing to extended periods of monsoonal rainfall occurring from November to March. Inter-environment variability was also demonstrated with mangrove habitats displaying significant decoupling from environmental trends present in estuarine and marine zones. Geochemical representations of seasonal cycles were predicted for constituent shellfish populations using a modelling equation, indicating seasonal shifts in environment and hydrology will be reflected within stable isotopes derived from molluscan shell. This was augmented by discussion of the limitations placed upon the environmental records archived within molluscan shell by species-specific environmental tolerance and responses. While it was concluded that some truncation of environmental records is likely, this should not impact seasonal determinations. Further, issues associated with mapping modern analogues onto archaeological material were explored.

Chapter 7 Analysis of Modern Live-Collected *Polymesoda coaxans*

7.1 Introduction

Relationships between molluscan shell carbonates and the conditions in which they precipitated are well documented, with the most readily employed connections found amongst shell isotopes and ambient environments. However, the usefulness of associated records cannot be automatically assumed owing to species-specific variability in physiology, ecology, and habitat characteristics (e.g. Petchey et al. 2012, 2013). Meaningfully incorporating molluscan shell isotopes into archaeological interpretative frameworks therefore requires interactions between target shellfish taxa and environmental conditions to be characterised and tested. While all species targeted in this research will undergo evaluation (see Chapters 8 and 9), this chapter is concerned with the mangrove bivalve *Polymesoda coaxans*. While *P. coaxans* is common throughout modern and archaeological contexts across the northern Australiasian region, there are few data available to evaluate the usefulness of isotopic records derived from its shell. Moreover, numerous biological and physiological attributes, exhibited by adult *P. coaxans* to survive the harsh conditions of their preferred landward mangrove habitats, have the potential to markedly complicate the interpretation of associated isotope data. This chapter explores these potential issues and their effects on associated palaeoenvironmental and radiocarbon data.

7.2 Potential Hurdles and Previous Applications

Suspension-feeding bivalves have long been preferentially chosen for isotopic analyses as they subsist on suspended phytoplankton and form shell structures from dissolved inorganic carbon (DIC) drawn directly from ambient seawater (Tanaka et al. 1986). The geochemistry of associated shell structures therefore reflects contemporary marine environments, facilitating accurate palaeoenvironmental and radiocarbon determinations. Conversely, deposit-feeding shellfish are frequently found to be problematic as the detritus they ingest can contain carbon from both marine and terrestrial sources (Anderson et al. 2001; Dye 1994).This can introduce ^{14}C of variable age, altering ^{14}C concentrations and significantly offsetting radiocarbon dates in an unpredictable manner (Hogg et al. 1998). Moreover, relationships between molluscan shell constructed from variably sourced carbon and ambient environmental conditions are difficult to characterise and interpret. *P. coaxans* can alternate between suspension and deposit-feeding modes (Clemente 2007; Morton 1976), potentially causing intra-specimen shell isotope values to vary depending on the source of carbon uptake (see Hogg et al. 1998 for an example of anomalous carbon values owing to regular shifts in feeding modes).

The effects of species-specific molluscan physiology and ecology was examined by Petchey et al. (2013) as part of a study into the efficacy of radiocarbon dating bivalves, including *P. coaxans*, common throughout archaeological deposits at Caution Bay, Papua New Guinea. Findings suggest the tolerance of *P. coaxans* to brackish waters (also see Clemente 2007 for laboratory experiments demonstrating the same) provides a pathway for terrestrial ^{14}C to be incorporated into shell carbonates. The presence of strong terrestrial influences is confirmed by consistently highly negative $\delta^{13}C_{shell}$ values (Petchey et al. 2013). Moreover, relationships between ΔR, $\delta^{18}O_{shell}$, and $\delta^{13}C_{shell}$ values are indicative of carbonate built from respired CO_2, which likely originates from *P. coaxans* ability aerially respire (Clemente 2007; Morton 1976). Carbonates precipitated during aerial respiration tend to reflect diet rather than ambient conditions, causing associated $\delta^{13}C_{shell}$ values to enter a state of environmental disequilibrium (McConnaughey 1989; McConnaughey and Gillikin 2008). These factors led the authors to recommend that *P. coaxans* shell not be used in the development of radiocarbon chronologies.

Stable isotope records may be prone to similar effects, with physiological and ecological characteristics impacting $\delta^{18}O_{shell}$ values. As landward mangrove habitats are often inundated only during peak high tides (Figure 7.1) (Clemente 2007; Clemente and Ingole 2011; Gimin et al. 2004), isolation from larger estuarine or marine systems can cause local conditions to diverge from wider environmental trends (see Chapter 6). Moreover, processes of evaporation, infiltration, and terrestrial runoff cause surface water in mangrove habitats to pond into disconnected pools (personal observation, June 2013, July 2014), allowing unique conditions owing to variable depth, exposure to direct sunlight (and hence ambient temperature) from inconsistent canopy cover, and interactions with carbon and water sources to develop. Similar processes have been observed in supra-tidal rock pools, with associated taxa deemed unsuitable for isotopic analyses owing to inconsistencies between specimens from different habitats (see Firth and Williams 2009; Hogg et al. 1998; Killingley 1981; Shackleton 1973). Thus, environmental conditions reflected by $\delta^{18}O_{shell}$ (and $\delta^{13}C_{shell}$) values from *P. coaxans* shell are potentially narrow representations specific to mangrove habitats or isolated pools rather than wider external trends.

Figure 7.1 A Landward mangrove habitat on Bentinck Island that is infrequently inundated by tidal waters. It is common for *P. coaxans* populations in this environment to undergo long periods of exposure.

Chemical representations of the ambient environment are only recorded during shell carbonate precipitation, meaning any conditions coinciding with periods of growth cessation are not represented (Goodwin et al. 2003; Schöne 2008). *P. coaxans* shell growth is largely dictated by environmental tolerances (Clemente 2007; Clemente and Ingole 2009; Morton 1976, 1988), with stark changes in temperature, salinity, or periods of aerial exposure potentially resulting in irregularly timed stoppages (see Chapter 6). Thus, associated environmental archives likely represent sporadic instances of optimal growth conditions rather than continuous records. While this issue is relatively common among shellfish taxa (e.g. Goodwin et al. 2003), the high frequency with which environmental change can occur within landward mangrove habitats suggests that associated growth stoppages may cause substantial record truncation.

While physiological, biological, and ecological attributes suggest isotopic data derived from *P. coaxans* shell are highly complex and difficult to accurately parse, researchers have previously argued that this species represents an effective palaeoenvironmental proxy (see Hinton 2012; Stephens et al. 2008). 'Saw-tooth' patterning in ontogenetic isotope profiles of modern live-collected *P. coaxans* specimens (Figure 7.2) is cited as a product of seasonal fluctuations during growth (Hinton 2012; Stephens et al. 2008). This assumes alternating isotopic peaks and troughs are linked with seasonally timed climatic changes, with pairs of features representing complete annual cycles (e.g. Burchell et al. 2013b; Goewert and Surge 2008; Hallmann et al. 2009). However, studies of *P. coaxans* are hindered by small assemblage sizes, limited understandings of local hydrological cycles, and minimal explanations of isotope-environment calibrations, casting doubt upon associated findings. The authors concede these limitations may have impacted their results, suggesting more robust environmental monitoring regimes and larger modern collections are required (Hinton 2012; Stephens et al. 2008).

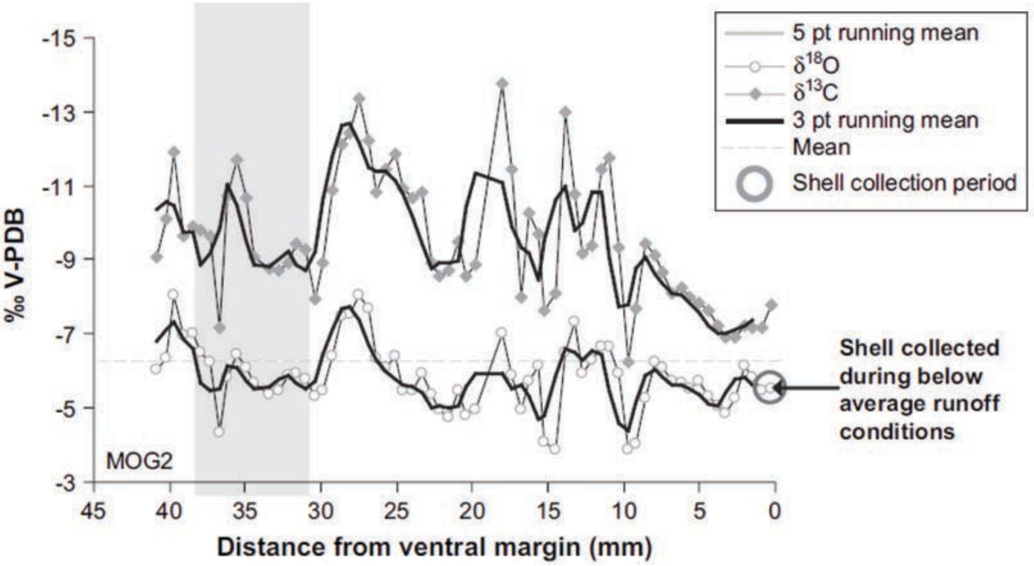

Figure 7.2 Example of 'saw-tooth' patterning (oscillations) from an isotopic profile of a live-collected *P. coaxans* specimen. Fluctuations are argued to coincide with seasonal environmental change (adapted from Stephens et al. 2008:2693).

While the issues highlighted above may dissuade many researchers from studying *P. coaxans*, its importance to past economic systems, particularly in northern Australia and Southeast Asia, demands expanded research. Petchey et al. (2013) highlighted difficulties surrounding the use of this species for radiocarbon dating, yet the efficacy of stable isotopes requires further investigation. As suggested by Hinton (2012) and Stephens et al. (2008) this can be achieved by rigorous analysis of modern assemblages coupled with detailed characterisations of local environmental conditions and cycles. The following discussion combines environmental observations presented in Chapter 6 with stable isotope analysis of live-collected modern *P. coaxans* shell to better understand this species applicability to archaeological interpretation.

7.3 Live-Collected Specimens

Modern *P. coaxans* were sourced from the extensive mangrove forest fringing Mirdidingki Creek (Figure 7.3). Specimens were live-collected over two dry seasons (2012 and 2014), one dry-wet transition period (September 2015), and one wet season (2014). During collection it was observed that local *P. coaxans* populations appeared sparse in comparison to densities reported for other regions (see Ingole et al. 2002), particularly during the wet season when no individuals were present in some previously inhabited locations. Low population numbers may be caused by a combination of ongoing exploitation by contemporary Kaiadilt foragers and mortality or temporary relocation of specimens associated with harsh wet season conditions, however systematic biological and ecological surveys would be required to characterise distribution patterns.

Figure 7.3 The mangroves fringing Mirdidingki Creek are home to abundant *P. coaxans* populations (Photograph: Daniel Rosendahl, 2014).

Using the selection criteria outlined in Chapter 5, 19 specimens were selected for isotopic analyses. This included 12 from the dry season (2012, *n*=6; 2014, *n*=6), three from the dry-wet transition (2015), and four from the wet season (2014) (see Appendix A for details). Carbonate was collected from the right valve of all specimens using targeted ventral margin collection. The left valves of two specimens (1/2 and 5/7) were selected for additional high-resolution micro-milling. Isotope ratio mass spectrometry was employed to generate $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values from all carbonate samples.

7.4 Results

7.4.1 Targeted Ventral Margin Sampling

Ventral margin $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values of seasonal *P. coaxans* catch cohorts reveal a number of season-specific differences and similarities. Results from dry season catch cohorts returned a broad range of $\delta^{18}O_{shell}$ values (range = -8.9‰ – -3.5‰; mean = -5.9‰) indicative of highly variable hydrological conditions (Figure 7.4). However, when the 2012 and 2014 cohorts are viewed individually it becomes apparent much of this variability originates from specimens collected in 2012. $\delta^{18}O_{shell}$ values from the 2012 catch range between -8.9‰ and -3.5‰ (mean = -6.9‰; 1σ = ±2.2‰), while the 2014 cohort displays significantly less variability (range = -6.1‰ – -3.7‰; 1σ = ±0.9‰) and a more positive mean (-4.9‰). Despite this, $\delta^{13}C_{shell}$ values are highly negative and tightly grouped across both cohorts (range = -10.7‰ – -8.3‰; mean = -9.5‰; 1σ = ±0.7‰), mirroring the findings of Petchey et al. (2013) and suggesting a similar tolerance to brackish conditions and input from terrestrial carbon sources.

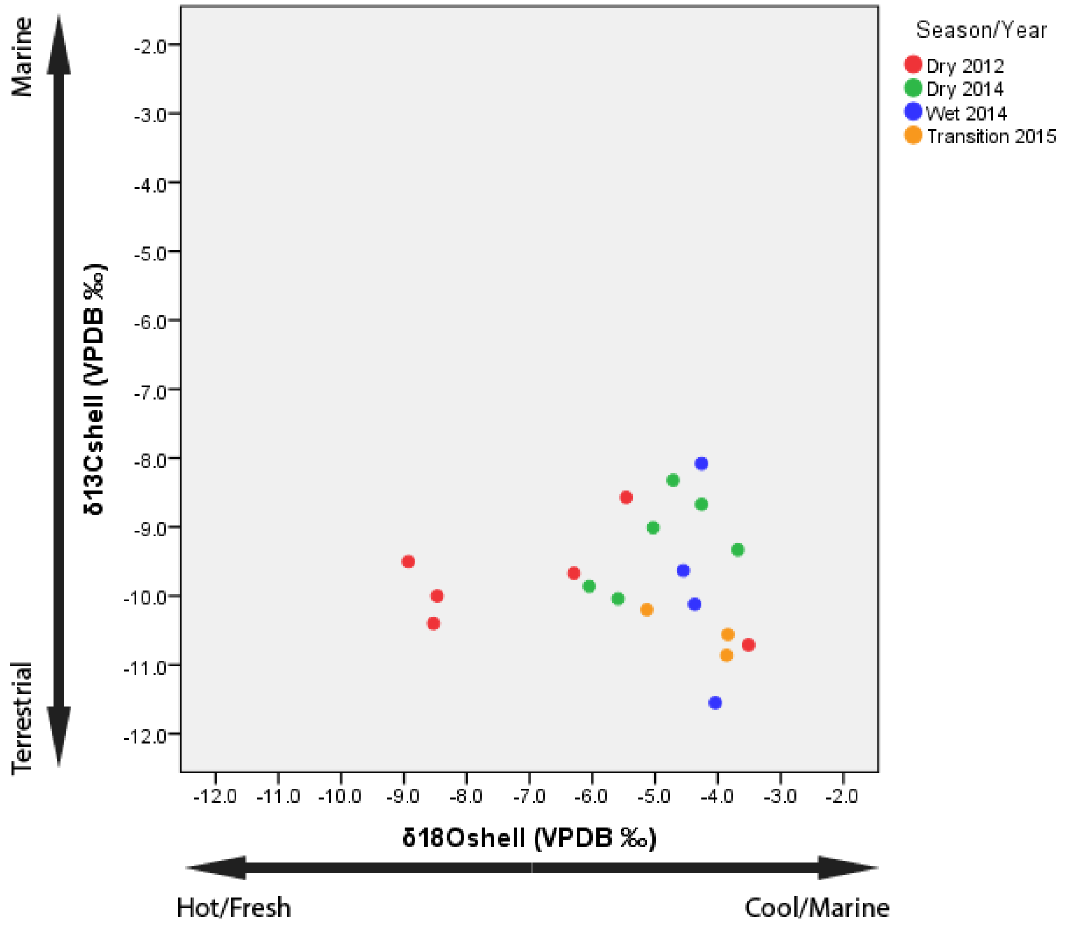

Figure 7.4 Stable oxygen and carbon isotope values from the edge margins of unique catch cohorts of *P. coaxans* indicate the presence of habitat-specific variability as well as the influences of terrestrial carbon sources.

Edge margin $\delta^{18}O_{shell}$ values from the 2014 wet season catch cohort were tightly grouped (range = -4.6‰ – -4.0‰; mean = -4.3‰; 1σ = ±0.2‰) (Figure 7.4). The homogeneity of these signals is potentially linked with near continuous inundation of local mangrove environments by monsoonal floodwaters (personal observation, March 2014). Associated $\delta^{18}O_{water}$ values remained relatively consistent (see Chapter 6), removing a primary pathway for variability. Likewise, sensor data indicates local water temperature fluctuations are lessened during the wet season (see Chapter 6), further contributing to more consistent $\delta^{18}O_{shell}$ values. Moderately spaced $\delta^{13}C_{shell}$ data are evident ranging from -11.6‰ to -8.1‰ (mean = -9.9‰; 1σ = ±1.4‰) (Figure 7.4). Continued highly negative $\delta^{13}C_{shell}$ signals indicate *P. coaxans* remain heavily influenced by terrestrial carbon sources during wet season conditions.

Specimens collected during the 2015 dry-wet transitionary period (September/October) returned results resembling wet season values (Figure 7.4). $\delta^{18}O_{shell}$ values are relatively tightly grouped (range = -5.1‰ – -3.8‰; 1σ = ±0.7‰) with a mean of -4.3‰. Likewise, $\delta^{13}C_{shell}$ values remain highly negative, ranging between -10.9‰ and -10.2‰ (mean = -10.5‰; 1σ = ±0.3‰).

Results from water sampling and modelling of $\delta^{18}O_{shell\text{-}predicted}$ values presented in Chapter 6 suggested that seasonal delineations in *P. coaxans* $\delta^{18}O_{shell}$ would be minimal. This is confirmed in the above findings with considerable overlap between wet season, dry season, and dry-wet transition values. What variability does exist appears to be linked with intra-cohort differences or inconsistencies between dry season catches. The implications of these findings for reconstructing past environments and determining seasonality are discussed in Sections 7.5.2 and 7.7, respectively.

7.4.2 Micro-Milled Specimens

7.4.2.1 Specimen 1/2

Specimen 1/2 was collected during the 2014 wet season from the mangrove forest fringing Mulla Island (5 March 2014). Valve length (86.1mm) indicates this individual was sexually mature and in its second year of growth (Dolorosa and Dangan-Galon 2014). Biological studies have established that at 80mm the rate of *P. coaxans* shell precipitation slows from 3.3 to 5mm per month to c.2.5mm per month (Clemente 2007; Dolorosa and Dangan-Galon 2014), suggesting growth in Specimen 1/2 slowed within the last 2 to 3 months prior to collection. Carbonate sampling transects were spaced between 125 and 532µm in accordance with growth features, covering a total distance of 11160µm along the section (Figure 7.5). Growth rates suggest sampling encompassed approximately 3.4 to 4 months of growth. Therefore, given the collection date, the sampled portion is estimated to represent carbonated precipitated exclusively during wet season conditions. Each sample transect produced 26 to 88µg (mean = 60.3µg) of carbonate powder. Two sets of two samples were combined to reach the minimum weight requirements (1/2_11.1 and 1/2_11.2; 1/2_19.1 and 1/2_19.2), while a further two samples were discarded owing to material loss during sampling (1/2_22) and an error during analysis (1/2_15).

Figure 7.5 Milled portion of *P. coaxans* specimen 1/2.

Ontogenetic analysis of Specimen 1/2 reveals $\delta^{18}O_{shell}$ values (Figure 7.6) ranging between -8.2‰ and -3.0‰ (mean = -4.5‰; 1σ = ±1.1‰). While regular fluctuations are apparent, they are largely constrained between c.-3.0‰ and c.-6.0‰. Only two samples (20 and 21) returned values outside of this range (-7.7‰ and -8.2‰, respectively). Thus, $\delta^{18}O_{shell}$ values suggest the analysed portion of Specimen 1/2 was primarily precipitated in brackish water conditions and moderately high temperatures. $\delta^{13}C_{shell}$ values display less variability with a range encompassing -10.6‰ to -7.6‰ (mean = -9.1‰; 1σ = ±0.6‰) (Figure 7.6). Consistently negative $\delta^{13}C_{shell}$ values suggest this specimen was exposed to strong terrestrial influences.

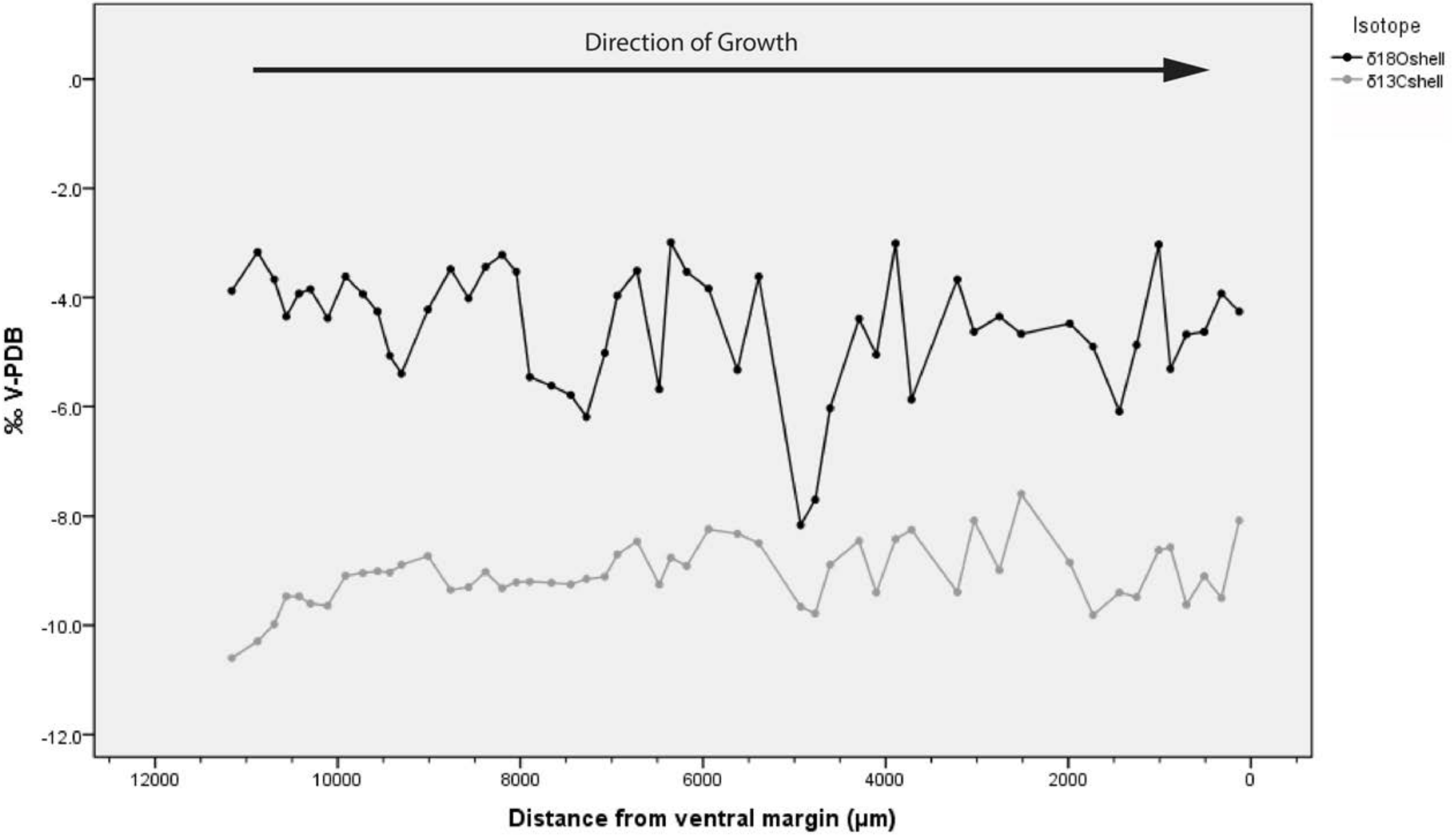

Figure 7.6 The isotope profile of *P. coaxans* specimen 1/2 extends across 11.16mm of the 86.1mm shell. While $\delta^{18}O_{shell}$ fluctuations are evident, they do not appear to correlate with seasonal climatic shifts.

7.***4.2***.2 ***Specimen 5/7***

Live-collected during the 2014 dry season (20 July 2014), Specimen 5/7 originates from the dense mangrove forest fringing Mulla Island (Figure 7.7). Valve length (80.02mm) indicates this specimen was sexually mature and in its second year of growth at collection (Dolorosa and Dangan-Galon 2014). Known growth rates suggest Specimen 5/7 was growing 3.3 to 5mm per month prior to collection (see Clemente 2007; Dolorosa and Dangan-Galon 2014). Micro-mill transects were spaced between 75 and 306µm (mean = 188µm), producing carbonate samples ranging from 14 to 84µg (mean = 59.3µg). A total distance of 11236µm was sampled along the section, equating to c.2.7 months of growth (see Clemente 2007; Dolorosa and Dangan-Galon 2014). Given its collection date, the sampled portion is estimated to represent early to mid-dry season conditions. While no samples were discarded, two pairs were combined to adhere to minimum weight requirements (5/7_9.1 and 5/7_9.2; 5/7_17.1 and 5/7_17.2).

Figure 7.7 Milled portion of *P. coaxans* specimen 5/7.

Stable isotope values derived from Specimen 5/7 reveal high variability in $\delta^{18}O_{shell}$ (mean = -4.4‰; range = -8.8‰ – -1.6‰; 1σ = ±2.0‰). Regular sinusoidal fluctuations are apparent at consistent intervals throughout the profile (Figure 7.8), however the cause of these fluctuations remains unclear (discussed further in Section 7.5.2). $\delta^{13}C_{shell}$ values display substantially less variability (mean = -10.1‰; range = -12.1‰ – -7.4‰; 1σ = ±1.0‰) (Figure 7.8). Moreover, $\delta^{13}C_{shell}$ values remain highly negative, suggesting terrestrial carbon was incorporated during shell precipitation.

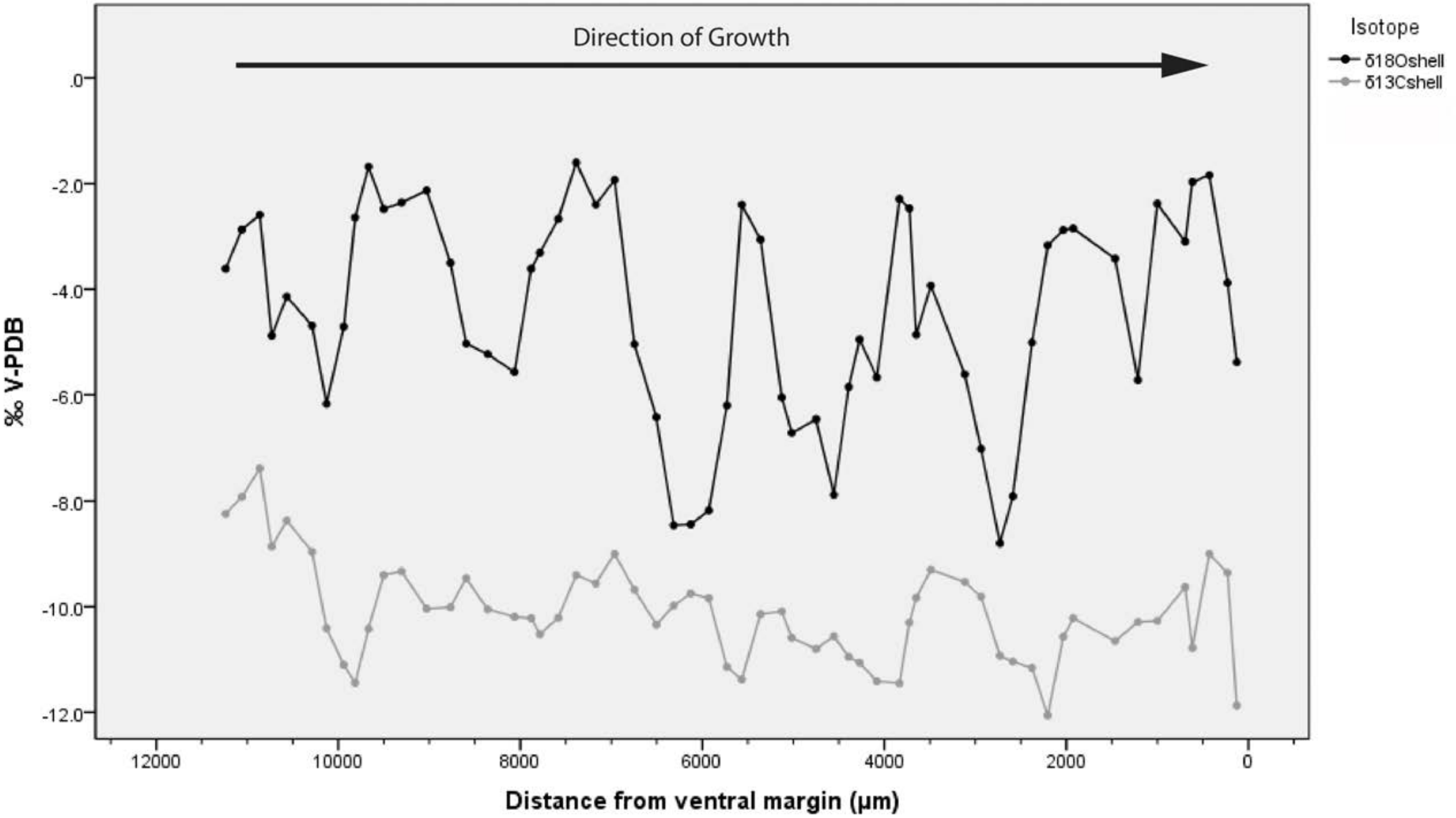

Figure 7.8 The isotope profile of *P. coaxans* specimen 5/7 extends across 11.24mm of the 80.02mm shell. While $\delta^{18}O_{shell}$ fluctuations are evident, they are too numerous to represent seasonal variation.

7.5 Complex Mangrove Environments

7.5.1 Tidal Inundations and Environmental Records

Results of water sampling and instrumental observation in and around Mirdidingki Creek highlighted the potential impact of infrequent tidal flushing on landward mangrove habitats, suggesting that these forces play a key role in the decoupling of mangrove environments from broader external trends (see Chapter 6). Observations of these same environments undertaken in September 2015 reveal a significantly lower rate of inundation than initially expected, with tides of 3.64m (maximum height during observation) failing to inundate *P. coaxans* habitats. Using this observed maximum tidal height as an estimate of the minimum height required for inundation, it is possible to establish the regularity of tidal flushing.

Tidal data from Sweers Island indicates that of the 383 tidal highs in 2014, only 147 rose to heights above 3.64m (BOM 2014). Therefore, mangrove habitats are isolated from external hydrological trends for a minimum of 62% of the year (Figure 7.9), suggesting a majority of environmental data recorded within *P. coaxans* shell are representative of highly localised conditions. Delimiting this data by seasons suggests a relatively even spread of inundations throughout the year with 39% (*n* = 58) occurring during the dry season and 46% (*n* = 67) in the wet season. The remaining 15% (*n* = 22) of inundations are divided equally between dry-wet and wet-dry transitions. These same tidal patterns may cause the formation of highly sporadic environmental records, owing to growth cessations coinciding with frequent periods of aerial exposure. However, it must be noted processes subsequent to inundation are largely unknown. Water likely remains trapped in mangrove systems after initial inundation, facilitating growth and the archiving of ambient conditions. Therefore, environmental records may be more comprehensive than tidal data suggest.

Shoreline positioning of mangrove habitats and location of individuals within those habitats is an important variable impacting record completeness. *P. coaxans* inhabiting environments bordering intertidal zones have the potential to display more comprehensive records than those from landward estuarine areas owing to varying frequencies of inundation. Moreover, *P. coaxans* are mobile between niches over their lifecycle, with juveniles preferring low-tide areas and adults found almost exclusively in high-tide habitats (Clemente and Ingole 2011). Adults may also relocate during wet season conditions, as suggested by the absence of populations observed in the dry season (see Section 7.3), although further research is required to confirm this. As it is extremely difficult to accurately determine precise foraging sites of archaeological material, meaningfully accounting for the above factors is implausible. Thus, mixed assemblages gathered from mangrove stands with variable shoreline positioning may introduce latent inconsistencies into data, making the accuracy of associated interpretations difficult to establish.

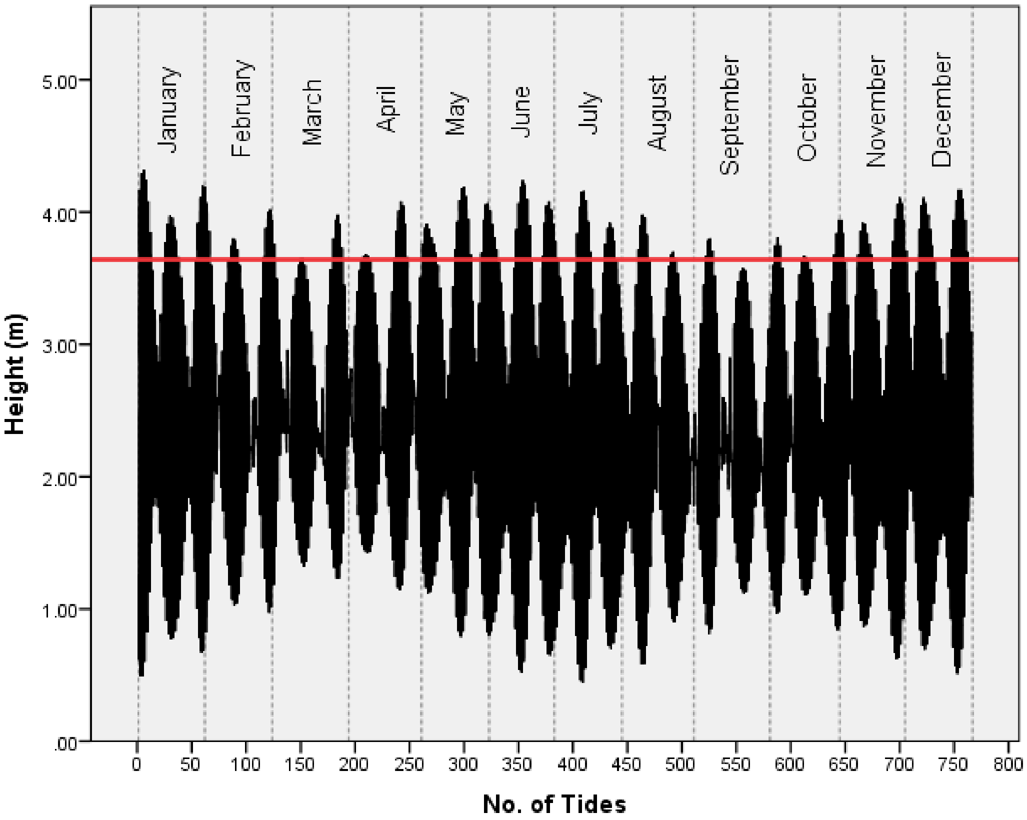

Figure 7.9 Tidal heights for 2014 recorded at Sweers Island (BOM 2014). Dotted grey lines delimit months. Red line indicates estimated minimum tidal height (3.64m) required to inundate Mirdidingki mangrove environments.

7.5.2 Intra-Habitat Variability

The irregular pattern of tidal flushing suggests that landward mangrove forest hydrology is extremely complex and variable. Between inundations water pools in isolated depressions (Figure 7.10), forming habitats with unique sets of highly localised geochemical conditions. As molluscan shell isotope values reflect conditions during carbonate precipitation, environmental archives found within the shells of *P. coaxans* inhabiting different pools may vary significantly. Therefore, assessing palaeoenvironmental data recovered from *P. coaxans* requires intra-habitat variability to be explored.

Results from targeted edge margin analysis of the two dry season cohorts (2012 and 2014) provide a salient case study to better understand variability within landward mangrove forests. The similarly timed collection of these catch cohorts means they were exposed to comparable overarching environmental conditions (BOM 2016), however each cohort was gathered from a different geographic context. The 2012 catch was sourced from Mosquito Story, while 2014 dry season specimens were gathered c.150m to the east near Mulla Island (Figure 7.11). As outlined in Section 7.4.1, key differences exist in the $\delta^{18}O_{shell}$ values of the two cohorts, with individuals collected in 2012 exhibiting a significantly broader set of values and more negative mean than those gathered in 2014. A statistical comparison confirms the presence of inter-cohort differences, finding no significant relationship between the $\delta^{18}O_{shell}$ datasets ($F(10) = 7.015$, $p = .024$).

Given similarities in broader environmental conditions, inconsistencies evident between the two dry season cohorts likely stem from intra-habitat variability. Internal discontinuity may again be linked with the frequency and periodicity of tidal inundation. The Mosquito Story collection site is located further landward than the Mulla Island site, exposing it to less frequent tidal flushing. This likely facilitates a pronounced environmental divergence at Mosquito Story, and other similarly landward habitats, from more frequently flushed areas. Thus, environmental records found within *P. coaxans* shell carbonates are likely narrow representations of highly localised conditions dependent on their collection site, making reconstructions of broader climatic conditions difficult.

Figure 7.10 An isolated pool of water formed in the depression surrounding mangrove roots at Mirdidingki, Bentinck Island (Photograph: Daniel Rosendahl, 2013).

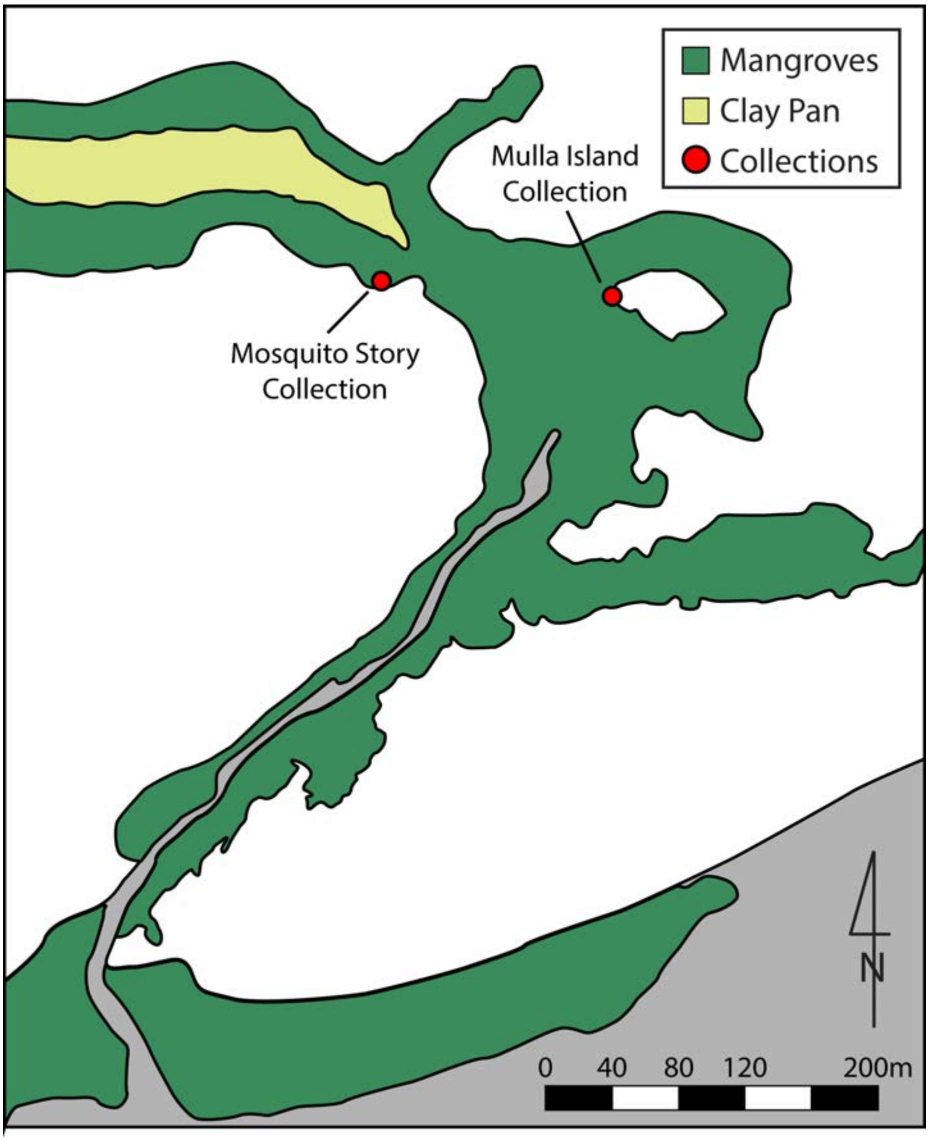

Figure 7.11 The 2012 catch cohort was collected at Mosquito Story, approximately 150m west of the 2014 cohort from around Mulla Island.

7.6 Ontogenetic Patterns

7.6.1 'Saw-Tooth' Patterning

Regular sinusoidal oscillations in $\delta^{18}O_{shell}$ profiles are commonly considered indicators of seasonal change in temperate shellfish taxa (e.g. Aguirre et al. 1998; Andrus and Crowe 2000; Hallmann et al. 2013; Jones and Quitmyer 1996; Quitmyer et al. 1997). It has been argued that similar patterns observed within *P. coaxans* shell are also indicative of seasonal climatic cycles (Hinton 2012; Stephens et al. 2008). However, principle drivers of stable oxygen isotope fractionation can differ between temperate and tropical species. Many temperate environments exhibit only minor seasonal oscillations in $\delta^{18}O_{water}$, leaving water temperature as the primary source of change for $\delta^{18}O_{shell}$ values (Andrus 2011; Burchell et al. 2013a). Conversely, hydrological conditions in the tropics are significantly more variable, with both water temperature and $\delta^{18}O_{water}$ having a greater influence on $\delta^{18}O_{shell}$ values (Eerkens et al. 2013; Kennett and Voorhies 1995, 1996). Thus, past assumptions regarding links between seasonal cycles and shell isotope values may not be applicable to tropical taxa such as *P. coaxans*.

While the isotopic profiles of specimens 1/2 and 5/7 display regular isotopic fluctuations similar to those highlighted in previous studies (particularly Specimen 5/7), complexities associated with tropical mangrove habitats and *P. coaxans* physiology make connections between shell stable isotopes and environment difficult to characterise. In particular, it is unclear whether isotopic oscillations are representative of seasonally timed climatic change or other more irregularly timed factors. Assumptions surrounding 'saw-tooth' patterning, where pairs of isotopic peaks and troughs represent annual cycles (see Section 7.2), suggest profiles of milled specimens should encompass 4 to 8 years (Figure 7.12). This is incongruous with the c.2.7 to 4 month time period calculated from size/age relationships and growth rates (see Section 7.4.2). Moreover, the average lifespan of *P. coaxans* is approximately 3 to 4 years (Clemente 2007; Dolorosa and Dangan-Galon 2014), making it unlikely that isotopic profiles are representative of the long periods of time suggested by saw-toothed oscillations. These findings suggest a lack of direct connections between stable isotope peak/trough pairings in *P. coaxans* shell and seasonal climatic cycles. However, findings also pose the question: *if isotopic oscillations are not linked with seasonal environmental change, what is causing the shifts evident through ontogeny?*

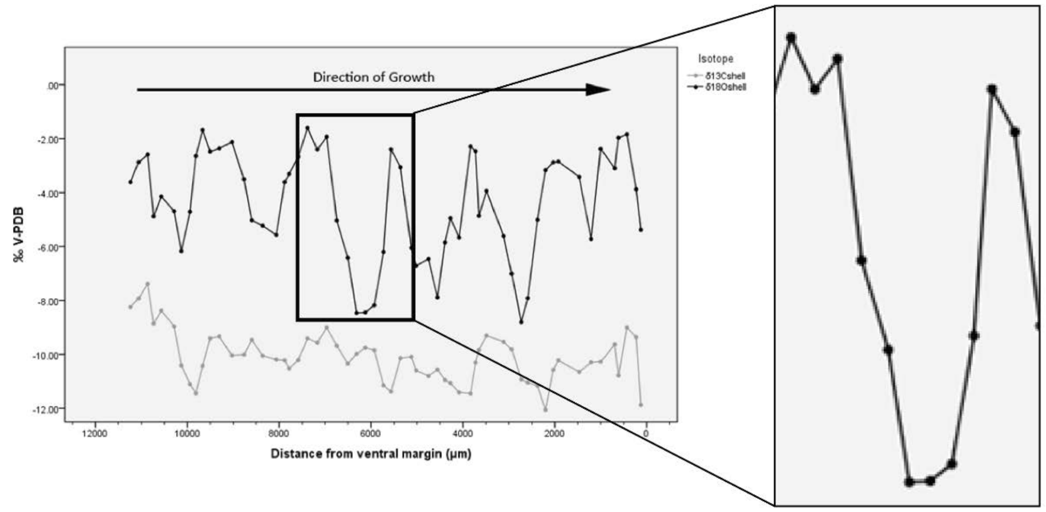

Figure 7.12 An isotopic peak/trough pairing from the isotopic profile of specimen 5/7. For *P. coaxans* assuming a correlation between these pairs and seasonal cycles is problematic owing to highly changeable ecological and physiological factors.

Changes in environmental stability coinciding with seasonal climatic change may assist in explaining ontogenetic fluctuations present in the isotopic profiles of *P. coaxans* shell. Dry season conditions expose *P. coaxans* to highly variable environments owing to irregular tidal inundations and the formation of isolated habitats (see Section 7.5), linking fluctuations with tidal cycles. Between inundations evaporation preferentially removes ^{16}O isotopes causing $\delta^{18}O_{water}$ (and thus $\delta^{18}O_{shell}$) to trend more positively. Moreover, evaporation, infiltration, and run-off gradually diminish the size/depth of pools allowing rapid temperature changes in associated waters (see Chapter 6). This continues until pools are re-inundated by tidal waters, essentially 'resetting' conditions to reflect those found in Mirdidingki Creek before tidal waters recede and the process repeats. Conversely, the combination of tidal action, heavy rainfall, and extensive flooding that typify the wet season leads to sustained inundation, facilitating more consistent conditions (personal observation, February/March 2014; Chapter 6). While some fluctuations may coincide with tidal inundations, run-off and rainfall rapidly flush mangrove systems with fresh meteoric waters causing changes to remain relatively brief. Changing seasonal variabilities are congruous with patterns in isotopic profiles with specimen 1/2 (wet season) exhibiting relatively constrained $\delta^{18}O_{shell}$ values, while specimen 5/7 (dry season) displays a significantly broader range. While it is difficult to directly link isotopic patterns found in *P. coaxans* shell to a single environmental characteristic owing to the complexity of landward mangrove environments, data suggests that tidal inundations are a key driver behind these oscillations.

7.6.2 Relationships between Growth Features and Stable Isotope Values

Relationships between isotopic values and growth feature types (lines and increments) are frequently employed as markers of specimen age, growth regimes, and seasonality as well as providing context for palaeoenvironmental reconstructions (e.g. Andrus and Crowe 2000; Jones and Quitmyer 1996; Kirby et al. 1998). These applications operate under the assumption that growth feature types form predictably in response to specific conditions; for example Andrus and Crowe (2000) demonstrate low temperatures (and thus more positive $\delta^{18}O_{shell}$ values) are the principle cause of growth line formation in the oyster *Crassostrea virginica*. However, complexities associated with tropical environments, landward mangrove habitats, and physiology call this assumption into question for *P. coaxans* (see Hinton 2012).

Scatter plots of $\delta^{18}O_{shell}/\delta^{13}C_{shell}$ values exhibit poor correlation between isotopes and growth structures (Figure 7.13; see also Hinton 2012). Light (normal growth) and dark (slow growth) sections see significant $\delta^{18}O_{shell}$ value overlap with ranges spanning -8.5‰ to -1.7‰ and -8.8‰ to -1.6‰ respectively. Further, an ANOVA test reveals significant similarities between feature types ($F(2) = .285$, $p = .773$). Comparable overlaps are present for $\delta^{13}C_{shell}$ values with ranges of

-12.1‰ to -7.4‰ for increments and -11.5‰ to -8.5‰ for lines, with an ANOVA test again finding significant similarities (*F*(2) = .141, *p* = .868).

While changes in temperature and water constitution likely drive some growth feature formation in *P. coaxans* shell (see Chapter 6), the lack of discernible relationships between isotopes and the features they are associated with suggests that ancillary environmental and ecological mechanisms play a similar role. The most likely explanation being responses to frequent periods of aerial exposure causing irregularly timed growth stoppages (see Section 7.4.1). This would explain why $\delta^{18}O_{shell}$ values of dark sections (slow growth) are so variable, as environmental conditions during growth stoppages are not necessarily consistent. Moreover, variable $\delta^{18}O_{shell}$ values from lightly coloured bands (normal growth) are indicative of the fluctuating environmental conditions that typify landward mangrove habitats. These factors make it extremely difficult to macroscopically or chemically differentiate growth features linked with seasonal change from those caused by other factors, rendering much of their interpretive utility unreliable.

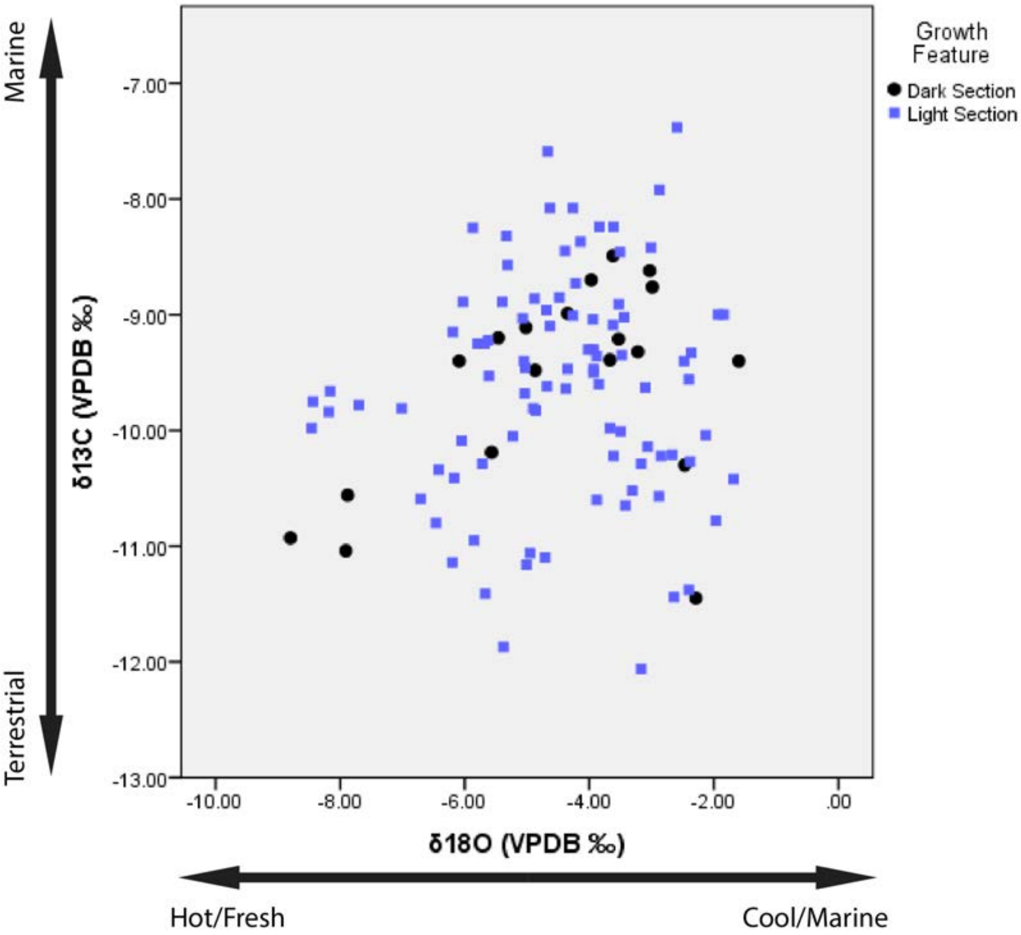

Figure 7.13 Results from micro-milled *P. coaxans* display little correlation between internal growth features and isotopic values, contrary to some temperate species.

7.7 Palaeoenvironments and Seasonality

Shell stable isotopes must provide unambiguous and easily interpretable representations of past conditions for molluscan taxa to be useful in characterising seasonality and palaeoenvironments. Alternatively, researchers must be able to identify and correct aberrations via consistent offsets. In the case of *P. coaxans*, fundamental physiological and ecological factors significantly complicate these processes. This research posits a majority of difficulties associated with interpreting geochemical data from *P. coaxans* shell are linked with three key factors – differently scaled environmental variability; sporadic completeness of environmental records; and ambiguity of seasonal determinations.

7.7.1 Differently Scaled Environmental Variability

As suggested throughout this chapter, the complexity and variability of conditions typifying *P. coaxans* habitats play an integral role in determining the efficacy of this species as a palaeoenvironmental proxy. Particular attention has been given to the isolated nature of mangrove habitats and how this manifests within environmental records. Evidence presented in Chapter 6 demonstrates mangrove environments become seasonally decoupled from broader external trends, narrowing the applicability of associated data. Further, analysis of seasonal catch cohorts revealed a further layer of complexity with evidence of intra-habitat variability within mangrove forests (see Section 7.5.2).

These internal and external discontinuities are principally driven by patterns of inundation, which alter mangrove hydrology through processes of interaction and isolation. This is particularly salient during the dry season when hydrological flushing (tidal or otherwise) of mangrove systems is rare (see Section 7.5.1). Conditions may also differ depending on shoreline positioning owing to variable timing and periodicity of tidal inundations, making the application of localised understandings to geographically distinct habitats difficult. When considered in unison, these findings indicate that environmental variability linked with landward mangrove habitats manifests on a variety of scales, severely complicating relationships between *P. coaxans* and ambient conditions, narrowing the applicability of associated environmental data, and introducing uncertainties into interpretation.

7.7.2 Sporadic Environmental Records

The complexity of environments inhabited by *P. coaxans* forces effective interpretation of associated environmental data to rely upon the completeness and accuracy of geochemical records. However, attributes intrinsic to mangrove habitats are not conducive to continuous record formation owing to sporadic interruptions to shell precipitation (Clark 1974; Schöne 2008; Chapter 6). Shell growth cessation is frequently linked with species-specific environmental tolerances, such as changes in water temperature and salinity (e.g. Burchell et al. 2013b; Hallmann et al. 2009; Jones 1980). While it is clear these factors impact *P. coaxans* shell growth (Clemente 2007; Morton 1988; Chapter 6), the timing and periodicity of aerial exposure is equally significant given this taxa's landward positioning (see Section 7.6.2). Moreover, the relative importance of these attributes shift throughout annual cycles. Dry season growth is largely controlled by aerial exposure owing to the irregularity of tidal flushing (see Section 7.5.1) with water temperature and salinity impacting growth during periods of inundation – particularly in isolated pools (e.g. Firth and Williams 2009). Meanwhile, more consistent inundation during the wet season significantly decreases the periodicity of aerial exposure, leaving fluctuations in temperature and salinity as principle growth controls. The availability of food and reproductive cycles may also impact growth regimes (see Clemente 2007; Clemente and Ingole 2009), however measuring these is beyond the scope of this research.

The key concern with environmental records derived from *P. coaxans* is not that they may be incomplete or inaccurate, other authors have employed numerous techniques to overcome similar issues (e.g. Goodwin et al. 2003), the problem instead lays in the irregularity of the timing, periodicity, and cause of stoppages. Effective interpretation of associated stable isotopes becomes problematic as it is unclear when, for how long, and for what reason *P. coaxans* shell cease recording ambient environmental conditions. Without this context, links between environment and shell stable isotopes are tenuous and extremely difficult to accurately characterise.

7.7.3 Ambiguous Seasonal Determinations

Employing molluscan shell carbonates to characterise seasonality requires $\delta^{18}O_{shell}$ values to exhibit predictable seasonally timed variability. However, ecological and physiological characteristics associated with *P. coaxans* add significant complexity to this otherwise simple mechanism. In Chapter 6 seasonal ranges and means of $\delta^{18}O_{shell\text{-}predicted}$ were modelled for mangrove habitats, revealing a broad seasonal overlap (3.2‰) that encompasses a majority of predicted wet season values. While these models should only be used as a guide, it was posited that similarities between predicted wet and dry season values would prove problematic (especially for seasonal determinations). This is confirmed through comparisons of modern specimens live-collected during both wet and dry seasons.

Edge margin $\delta^{18}O_{shell}$ values reveal only minor differences between wet and dry season specimens, with numerous values falling within the predicted overlap (Figure 7.14). The findings of an ANOVA confirms the presence of significant relationships (*F*(2) = 1.146, *p* = .356) between wet season, dry season, and dry-wet transition catch cohorts (note: the 2012 dry season cohort was excluded from this calculation as it was collected from a different geographic location). Moreover, while some values do fall in definitive wet or dry season predicted ranges, many do not accurately represent their known season of collection. Comparatively positive values derived from wet season specimens are more indicative of cool marine dry season conditions, while a majority of values from dry season specimens are either significantly more negative than expected or overlap with their wet season counterparts.

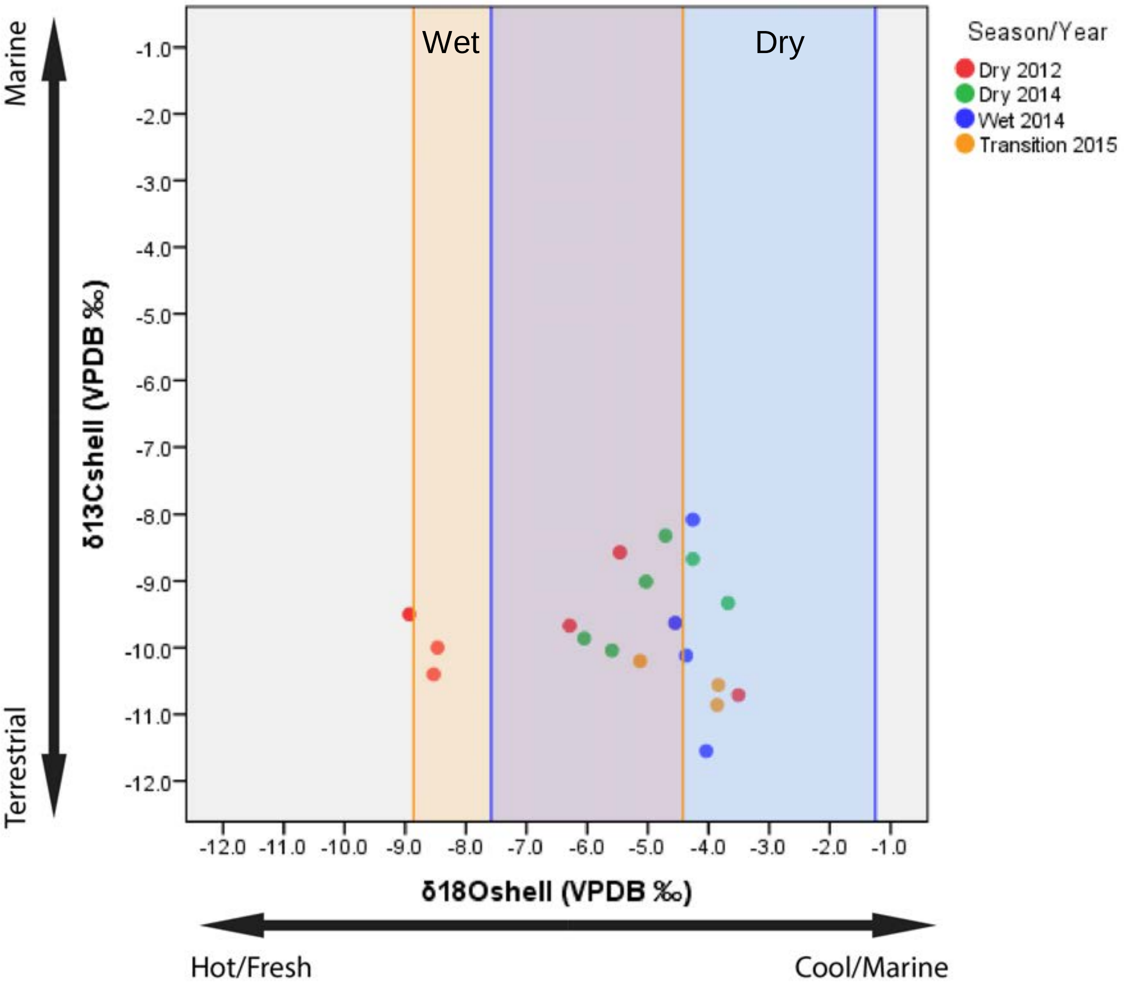

Figure 7.14 A substantial amount of edge margin values could not be unequivocally linked with specific seasons or were difficult to differentiate (blue = predicted dry season range; orange = predicted wet season range; purple = overlap in predicted seasonal ranges).

Plotting stable isotope values derived from ontogenetic profiles against predicted ranges reveals a similar lack of seasonal definition (Figure 7.15), with a large portion of $\delta^{18}O_{shell}$ values from both specimens falling within the predicted seasonal overlap.

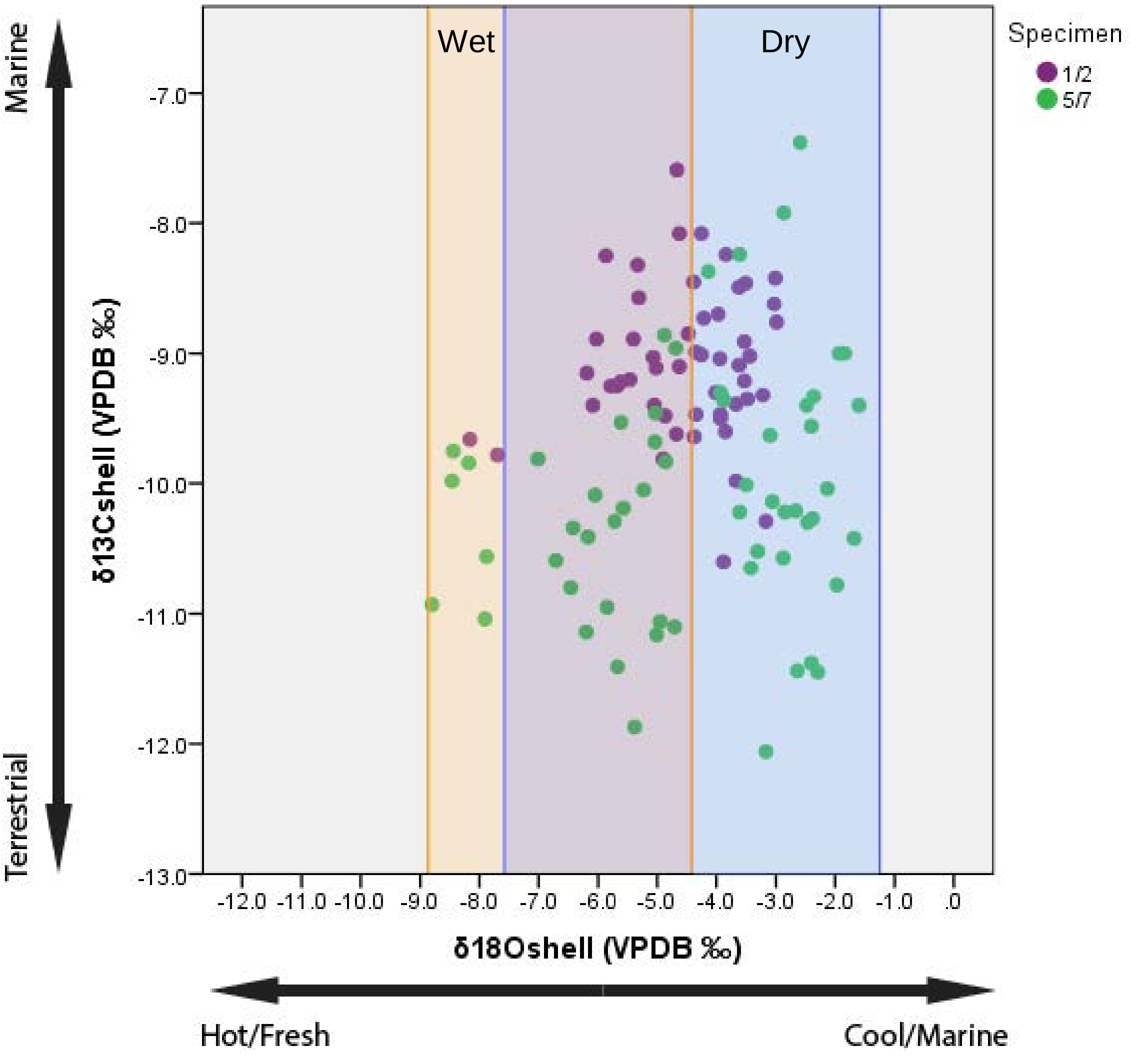

Figure 7.15 Stable oxygen values derived from ontogenetic profiles of *P. coaxans* valves indicate a high quantity of data falls within predicted seasonal the overlap (blue = predicted dry season range; orange = predicted wet season range; purple = overlap in predicted seasonal ranges), making it extremely difficult to accurately determine timing of carbonate precipitation.

Multiple factors serve to explain the seasonally ambiguous results recovered from *P. coaxans* specimens. In particular, the application of predictive modelling to landward mangrove environments appears problematic owing to the complexity of environmental conditions. As temperature is a key component in calculating $\delta^{18}O_{\text{shell-predicted}}$ values, highly variable water temperatures may adversely impact modelled values. Despite having significantly different lows and means, both wet and dry seasons display similar temperature maximums (40.1°C and 40.0°C, respectively) resulting in an inflated negative termination for the dry season predicted range (Figure 7.16). While an interquartile range was utilised for these calculations (see Chapter 6), raw data also indicate strong similarities between wet and dry season temperature maximums (53.0°C and 47.5°C, respectively). The highly negative dry season termination causes all but the most negative predicted wet season values to fall within a seasonal overlap, making seasonal determination extremely difficult (Figure 7.16).

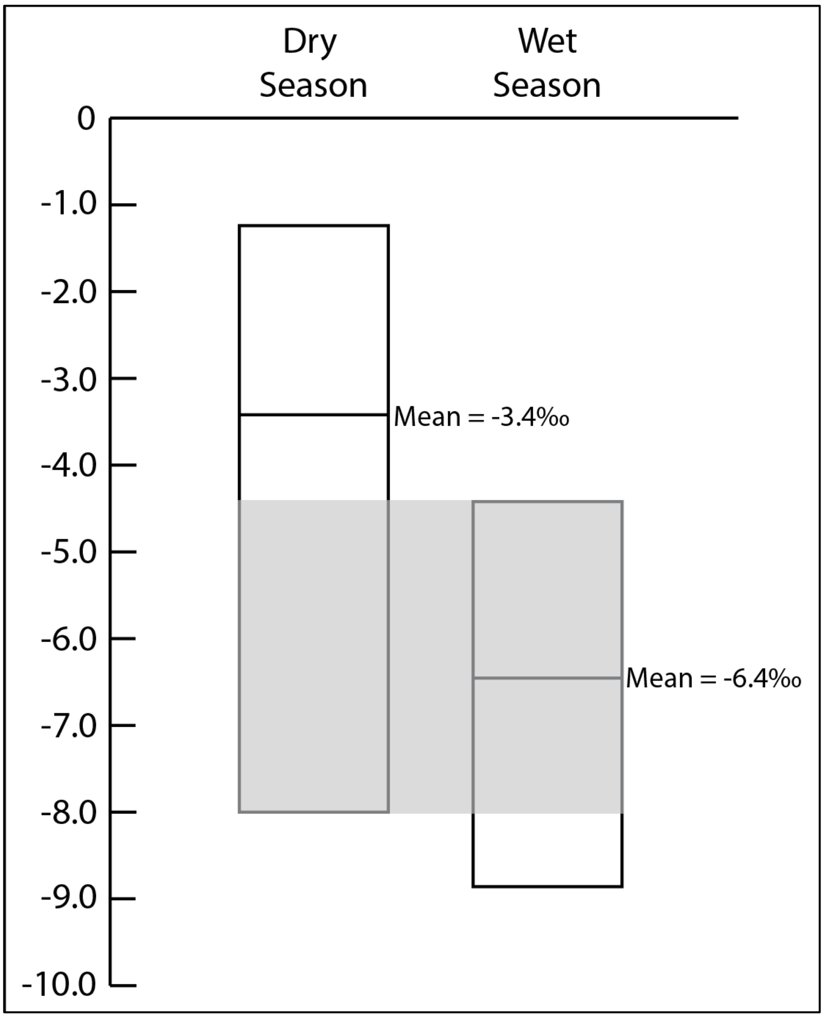

Figure 7.16 Modelled seasonal ranges for $\delta^{18}O_{\text{shell-predicted}}$ in mangrove species return a wide overlap (grey shaded area), making accurate seasonal determinations difficult.

Highly localised environmental conditions may also be key in explaining the presence of ambiguous seasonal results. Environmental data employed here are based upon monitoring at a single site within an extensive mangrove forest. This may prove problematic given the intra-habitat variability demonstrated by edge margin values (see Section 7.5.2). Therefore, this model is unlikely to be directly applicable to other mangrove habitats in the South Wellesley Islands, or elsewhere.

Despite the issues discussed above, findings should not be taken to imply modelled data are incorrect. Rather, they demonstrate conditions typifying landward mangrove environments are inherently difficult to characterise and, in this context, relying solely on stable oxygen isotopes is an inadequate means of reaching accurate seasonal determinations. Future research into using *P. coaxans* as a proxy for seasonality should employ consistent observation of numerous sites within landward mangrove forests over a full annual cycle, including water sampling and specimen live-collection. This would greatly improve knowledge of how landward mangrove conditions differ both internally and externally as well as assisting to characterise how localised environmental conditions manifest within *P. coaxans* shell geochemistry. Further, observing *P. coaxans* specimens in a controlled aquarium environment would allow relationships between known hydrological conditions, growth regimes, and shell carbonates to be accurately characterised.

7.7.4 Recommendation

In isolation, concerns associated with *P. coaxans* are not insurmountable, complex hydrological or physiological factors may be approached using corrective measures while environmental decoupling may simply limit potential applications. However, when taken holistically interactions between the myriad environmental, physiological, and ecological complications make disentangling causes and effects highly problematic. While it has been suggested localised offsets may assist in ameliorating *P. coaxans* from at least some limitations (Petchey et al. 2013), the potential for intra-habitat variability forces corrections to be highly specific. Moreover, determining precise geographic provenience of archaeological shell is extremely difficult leading to questionable connections between offsets and material assemblages. Current findings indicate environmental records found within *P. coaxans* shell are sporadic, geographically and temporally limited, and have the potential to be variably offset by basic physiological and ecological processes. It is therefore recommended *P. coaxans* not be used as a source of palaeoenvironmental or seasonality data.

7.8 Radiocarbon Dating

Generating accurate radiocarbon determinations from molluscan shell requires researchers to control for various environmental and physiological factors. For a majority of filter-feeding bivalve species this process is relatively simple as localised ΔR calibrations can be employed to offset the mixing of differently aged marine carbon reservoirs (Ulm 2006b). However, for species inhabiting estuarine or landward environments the pathways and impacts of carbon mixing are significantly more complex. Hydrological systems typifying these areas see interactions between terrestrial and marine reservoirs that introduce carbon of undeterminable age, inconsistently offsetting ^{14}C shell values and making corrections difficult (Ulm 2002). Moreover, species-specific biological and ecological attributes can further impact the source and uptake of carbon. This research suggests a combination of factors intrinsic to mangrove environments and *P. coaxans* physiology negatively impact the accuracy and validity of associated radiocarbon dates.

Consistently negative $\delta^{13}C_{shell}$ values (mean = -9.7‰) are evidenced throughout the entire modern *P. coaxans* assemblage, irrespective of timing or location of collection. This suggests the consistent presence of strong terrestrial carbon influences. Previous research posits *P. coaxans* tolerance to brackish waters facilitates terrestrial ^{14}C input into shells (Petchey et al. 2013). Salinity and $\delta^{18}O_{water}$ values suggest brackish conditions typify *P. coaxans* habitats in the South Wellesley Islands (see Chapter 6), acting as a vector for the incorporation of terrestrial carbon into shell carbonates. However, variability within these environments must also be considered, with irregular mixing of marine, estuarine, meteoric, and mangrove waters leading to erratic hydrological conditions. It should therefore not be assumed that associated waters are consistently brackish, suggesting additional factors contribute to the negative $\delta^{13}C_{shell}$ values typifying *P. coaxans* shell geochemistry.

The impacts of physiological mechanisms employed by *P. coaxans*, including adaptive feeding and respiration strategies, are difficult to directly characterise owing to their irregular nature and similarities in how they manifest. However, results of stable isotope analyses offer hints as to their influence on *P. coaxans* shell geochemistry. Shell $\delta^{13}C$ results reflect feeding behaviours as species that frequently ingest detrital and sedimentary matter exhibit negative $\delta^{13}C_{shell}$ values (Anderson et al. 2001; Dye 1994; Meyers and Teranes 2001). Biological studies have indicated *P. coaxans* are capable to shifting between filter- and detrital-feeding behaviours depending on the abundance of food and periodicity of aerial exposure (Morton 1985). Consistently negative $\delta^{13}C_{shell}$ values typifying the *P. coaxans* shell carbonates analysed here are likely a product of this process. The inclusion of detrital matter in the diet of *P. coaxans* provides an additional pathway for terrestrial carbon to enter shell geochemistry. Moreover, associated signals may be bolstered by *P. coaxans* ability to aerially respire, causing shell isotope values to be reflective of diet rather than environmental conditions (McConnaughey et al. 1997).

A combination of environment, physiology, and ecology make it difficult to argue that *P. coaxans* provide accurate radiocarbon determinations. Consequently, this research agrees with the findings of Petchey et al. (2013), recommending *P. coaxans* not be used to develop radiocarbon chronologies. However, in doing so it is important to discuss the broader repercussions of this for archaeological research, particularly in the context of those studies that have previously dated *P. coaxans* shell. Approximately 30 radiocarbon chronologies (41 unique determinations) from sites situated along Australia's north coast have incorporated *P. coaxans* shell (e.g. Brockwell 2006a; Brockwell and Ackerman 2007; Brockwell et al. 2009; Hinton 2012; Rosendahl 2012; Sim and Wallis 2008). Reviewing $\delta^{13}C_{shell}$ values associated with these dates (note only 27 of the 41 dates report $\delta^{13}C_{shell}$) reveals negative values (mean = -6.3‰; range = -10.8‰ – -1.4‰)

indicative of mixing between marine and terrestrial carbon sources, much like those observed in the South Wellesley Islands. Although a majority of the impacted chronologies do not rely solely on dates derived from *P. coaxans* (with the exception of select mono-specific sites from Brockwell 2006a; Hinton 2012; Rosendahl 2012; Sim and Wallis 2008), the issues surrounding this species impact the validity of associated interpretation. Thus, it is recommended that dates linked with *P. coaxans* are approached with extreme caution and, if possible, tested against more reliable shellfish species from similar temporal contexts.

7.9 Summary

Analysis of modern live-collected *P. coaxans* has revealed interpretation of isotope records archived within the carbonates of this species shell are highly complex. A combination of factors render *P. coaxans* shell an unsuitable source of palaeoenvironmental and seasonality data owing to sporadic and inconsistent environmental records, tenuous connections with seasonal shifts in ambient conditions, high variability among mangrove habitats and broader external trends, and the presence of changeable internal patterning. Likewise, radiocarbon determinations derived from *P. coaxans* shell are erratically offset by a variety of physiological and ecological influences. Stable isotope results mirror those presented in previous studies, suggesting tolerances to brackish conditions and the landward positioning of *P. coaxans* populations facilitates interactions with terrestrial carbon. Moreover, more difficult to test survival mechanisms such as irregularly timed detrital feeding and aerial respiration further complicate shell carbon signals. When considered in combination these factors indicate *P. coaxans* is a source of highly complex and potentially problematic palaeoenvironmental and radiocarbon data, therefore no further analysis of this species will be pursued in the characterisation of Kaiadilt occupation patterns in the South Wellesley Islands.

Chapter 8 Analysis of Modern Live-Collected *Gafrarium pectinatum*

8.1 Introduction

The intertidal bivalve *Gafrarium pectinatum* is common throughout much of the archaeological record in the South Wellesley Islands. Although not present in the quantity of other species (see Chapter 9), the frequent inclusion of this taxa highlights its importance to past Kaiadilt populations (see Peck 2016). Thus, isotopic records found within *G. pectinatum* shell may provide insight into Kaiadilt behavioural patterns. While the shoreline positioning and filter-feeding behaviour exhibited by this taxa suggest associated isotopic records are suitable environmental proxies, species-specific physiological and ecological factors must be examined to assess its applicability to this research. Results from geochemical assay of modern live-collected *G. pectinatum* specimens are combined with hydrological and environmental data presented in Chapter 6 to characterise relationships between shell isotope data and ambient conditions. Findings are used to assess the efficacy of utilising *G. pectinatum* shell in interpreting seasonality and reaching radiocarbon determinations.

8.2 Potential Hurdles and Previous Applications

G. pectinatum features prominently throughout literature concerning mid-to-late Holocene Aboriginal use of Australia's tropical north coast. This species was commonly exploited as part of traditional subsistence practices, ensuring its frequent inclusion within a variety of shelly archaeological features including middens, surface scatters, and mounds (e.g. Beaton 1985; Brockwell et al. 2009, 2011; Faulkner 2013; Sim and Wallis 2008). Such ubiquity has led to *G. pectinatum* being utilised within numerous studies, particularly as part of radiocarbon chronologies (see Ulm and Reid 2000; Williams et al. 2014). The efficacy of this practice was recently explored by Petchey et al. (2013) who expressed confidence in radiocarbon determinations derived from this species, provided local marine reservoir offsets (Δ*R*) are employed. The only concerns centred on the potential for terrestrial carbon and hardwater sources to impact ^{14}C values as isotopic analyses of *G. pectinatum* indicated a preference for high intertidal estuarine environments (Petchey et al. 2013). Despite this, applying localised Δ*R* values largely mitigates these issues.

Ecological and physiological factors not considered as part of previous studies may further impact the usefulness of isotopic records archived within *G. pectinatum* shell carbonates. Of particular concern is the frequent presence of this mollusc in intertidal rock pools (personal observation, July 2013, March 2014, July 2014). Hydrological conditions found within rock pools frequently differ from those in open marine environments owing to processes of evaporation, temperature differences, variable water inputs, and depth (Firth and Williams 2009; Hogg et al. 1998). Moreover, tidal flushing facilitates movement of individuals between rock pool and intertidal environments, forming records of mixed origin. As it is difficult to determine the geographic provenance of archaeological specimens, particularly those that move between environments, exposure to rock pool conditions may complicate associated environmental data. These factors have prompted some authors to argue molluscan taxa that inhabit rock pool systems should not be used as palaeoenvironmental proxies (Killingley 1981; Shackleton 1973).

Low-power microscopic analysis of *G. pectinatum* shell thick sections revealed that growth features are exceptionally difficult to accurately differentiate (see Chapter 4). While some ambiguous growth structures are present, a majority of lines and increments are functionally indistinguishable. This has the potential to substantially reduce the accuracy and validity of carbonate collection as sampling cannot be consistently aligned with growth structures. Thus, the impact of time-averaging on associated isotopic values remains unknown and relationships between carbonate isotopes and growth rates cannot be characterised.

8.3 Live-Collected Specimens

Live *G. pectinatum* specimens were collected over four field seasons from intertidal flats and rock pools at Raft Point, Bentinck Island, and Ngathald, Sweers Island, as well as intertidal flats along the northeast coast of Fowler Island (Figure 8.1). Using the selection criteria outlined in Chapter 5, a total of 34 specimens were chosen for isotopic analysis (see Appendix B for more details). This included four specimens from the dry season (2014), 15 from the dry-wet transition (2015), and 15 from the wet season (2014 *n* = 8; 2016 *n* = 7). Ventral margin carbonate was extracted from the right valve of each specimen. High-resolution carbonate sampling was undertaken on the left valve of one dry season (18) and one wet season specimen (2/10) using a computer assisted micro-mill. Isotope ratio mass spectrometry was employed to reach $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values from all carbonate samples.

Figure 8.1 *G. pectinatum* are typically found associated with intertidal flats and rocky platforms across the South Wellesley Islands (Photograph: Sean Ulm, 2015).

8.4 Results

8.4.1 Targeted Ventral Margin Sampling

Stable isotope values derived from ventral margin carbonates of *G. pectinatum* specimens revealed an unexpected consistency between seasons that was incongruous with observed differences in environmental conditions (Figure 8.2; Chapter 6). Overall $\delta^{18}O_{shell}$ values ranged between -3.6‰ and -0.3‰ with a mean of -2.4‰. However, a majority of the more positive values are attributable to specimens collected from rock pools during the dry-wet transition (2015), potentially owning to environmental differences between isolated rock pools and the open marine system (discussed further in Section 8.5). When these specimens are excluded, the homogeneity of $\delta^{18}O_{shell}$ values increases with a range of -3.6‰ to -2.0‰ (mean = -2.7‰). $\delta^{13}C_{shell}$ values display a similar level of consistency with a range of -4.1‰ to -0.4‰ (mean = -1.7‰). Removal of rock pool specimens causes a minor change, with the overall range (-4.1‰ – -0.6‰) and mean (-1.6‰) remaining highly similar.

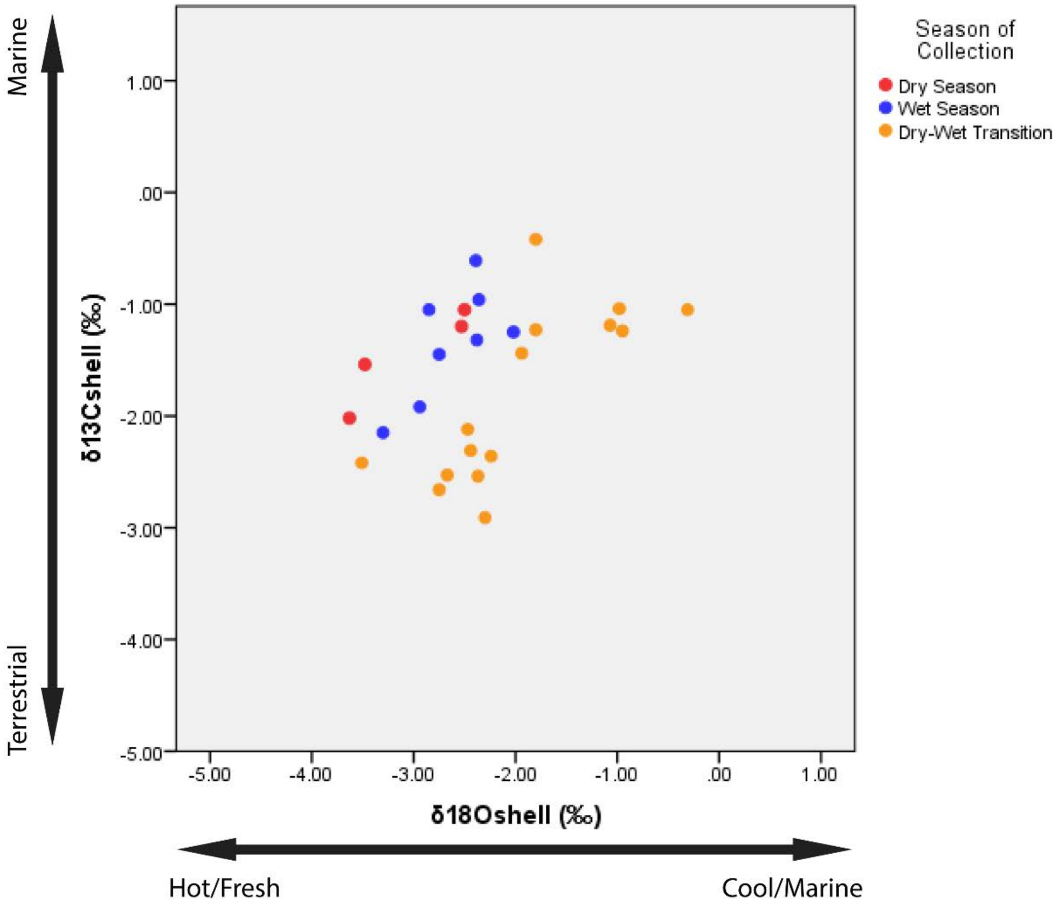

Figure 8.2 Analysis of edge margin carbonates reveal little variability between stable isotopes from *G. pectinatum* specimens collected at different stages of the annual cycle. Note that a majority of the Dry-Wet Transition specimens were collected from rock pool systems while the Dry and Wet Season catch cohorts originated from open marine waters.

Comparisons between seasonal catch cohorts reveal little variation in specimens gathered during wet, dry, and transitionary conditions. Dry season specimens expressed $\delta^{18}O_{shell}$ values ranging between -3.6‰ to -2.5‰ (mean = -3.0‰) and $\delta^{13}C_{shell}$ values of -2.0‰ to -1.1‰ (mean = -1.5‰). Wet season specimens returned similar values with a $\delta^{18}O_{shell}$ mean of -2.6‰ (range = -3.3‰ – -2.0‰) and $\delta^{13}C_{shell}$ averaging -1.7‰ (range = -4.1‰ – -0.6‰). Similar variability is evident in the dry-wet transition cohort ($\delta^{18}O_{shell}$: range = -3.5‰ – -0.3‰, mean = -2.0‰; $\delta^{13}C_{shell}$: range = -2.9‰ – -0.4‰, mean = -1.8‰). Thus, neither stable oxygen nor carbon isotopes display the stark seasonally timed shifts expected between catch cohorts. The implications of this finding are discussed in Sections 8.5 and 8.7.

The relative lack of seasonal variability demonstrated by *G. pectinatum* edge margins would suggest consistent environmental conditions, however as outlined in Chapter 6 intertidal water temperature, $\delta^{18}O_{water}$, and salinity differ significantly between seasons. Other factors may therefore be overwhelming seasonal signals, which may prove problematic for researchers wishing to utilise *G. pectinatum* as a palaeoenvironmental proxy or marker for seasonality (see

Section 8.7). Despite this, consistently positive $\delta^{13}C_{shell}$ across all specimens indicate this taxa is rarely influenced by terrestrial carbon sources, constructing its shell carbonates from ambient marine DIC, suggesting its efficacy for radiocarbon dating (see Section 8.8).

8.4.2 Micro-Milled Specimens

8.4.2.1 Specimen 2/10

Specimen 2/10 was collected from the intertidal rock platform near Raft Point during the 2014 wet season. Valve length at collection (37.1mm) indicates this specimen was sexually mature and in its third year of growth (Baron 1992; Jagadis and Rajagopal 2007a, 2007b; Kurihara 2003). At this age growth rates average c.5.9mm per year (Jagadis and Rajagopal 2007a; Kurihara 2003). Individual growth features were exceptionally difficult to discern throughout the entire section (Figure 8.3). Sampling transects were digitised at a mean resolution of c.164µm (range = 88 to 267µm) over 9517µm across the section. Each transect produced between 4 and 84µg (mean = 41.75µg) of carbonate powder. Age and growth rates suggest the analysed portion of shell extends over at least one annual cycle (Jagadis and Rajagopal 2007a; Kurihara 2003).

Figure 8.3 Specimen 2/10 after micro-mill assessed carbonate extraction. Growth features were extremely difficult to distinguish throughout the entirety of the section.

A majority of small powder samples originate from the area adjacent to the ventral margin where the upper shell layer is very thin. In order to reach the minimum weight required for isotopic analysis, numerous samples were combined (2/10_1 to 2/10_5; 2/10_6 to 2/10_8;

2/10_9 and 2/10_10; 2/10_15 and 2/10_16; 2/10_18.1 and 2/10_18.2; 2/10_20.1 and 2/10_20.2; 2/10_29.1 and 2/10_29.2; 2/10_33.1 and 2/10_33.2; 2/10_33.3 and 2/10_34; 2/10_39.2, 2/10_39.3, and 2/10_40). Two samples (2/10_46 and 2/10_50) were discarded due to material loss, while one value set (2/10_29.2) was removed owing to an error during analysis. Given the degree of sample homogenisation required for this specimen caution must be exercised when interpreting the associated profile, as five of the first 11 isotopic values (extending from the ventral margin to c.2500µm) are averages of multiple carbonate samples. The potential impact of this on interpretation is further discussed in Sections 8.6 and 8.7.

The isotopic profile of Specimen 2/10 reveals high variability in $\delta^{18}O_{shell}$ values (Figure 8.4), which range between -4.4‰ and -0.2‰ (mean = -2.5‰; 1σ = ±0.8‰). Fluctuations between highs and lows are largely sinusoidal in nature. However, variability is not consistent throughout, with the c.2500µm adjacent to the ventral margin displaying less defined fluctuations (range = -3.2‰ – -2.0‰) than the remaining profile (range = -4.4‰ – -0.2‰). This pattern is likely linked with the homogenisation of 13 individual samples into five amalgamated values within this section, although remaining single values (2/10_11, 2/10_12, 2/10_13, 2/10_14, 2/10_17, 2/10_19) demonstrate similarly minor variations (range = -3.2‰ – -2.6‰; mean = -2.9‰).

Stable carbon isotope values ($\delta^{13}C_{shell}$) display relatively minor variability throughout the profile (Figure 8.4) with a range of -1.4‰ to +0.8‰ (mean = -0.2‰; 1σ = ±0.6‰). Comparisons between the heavily homogenised ventral portion of the profile (mean = +0.2‰; range = -0.5‰ – +0.8‰) and the remaining section (mean = -0.4‰; range = -1.4‰ – +0.5‰) reveal minor differences. Comparisons of $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ profiles using linear regression analysis indicates a weak relationship (r^2 = .086), indicating oxygen and carbon records are largely independent from one another. Overall, $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values suggest this specimen inhabited an environment exhibiting fluctuating water temperatures and $\delta^{18}O_{water}$ content as well as being consistently in contact with a marine carbon reservoir.

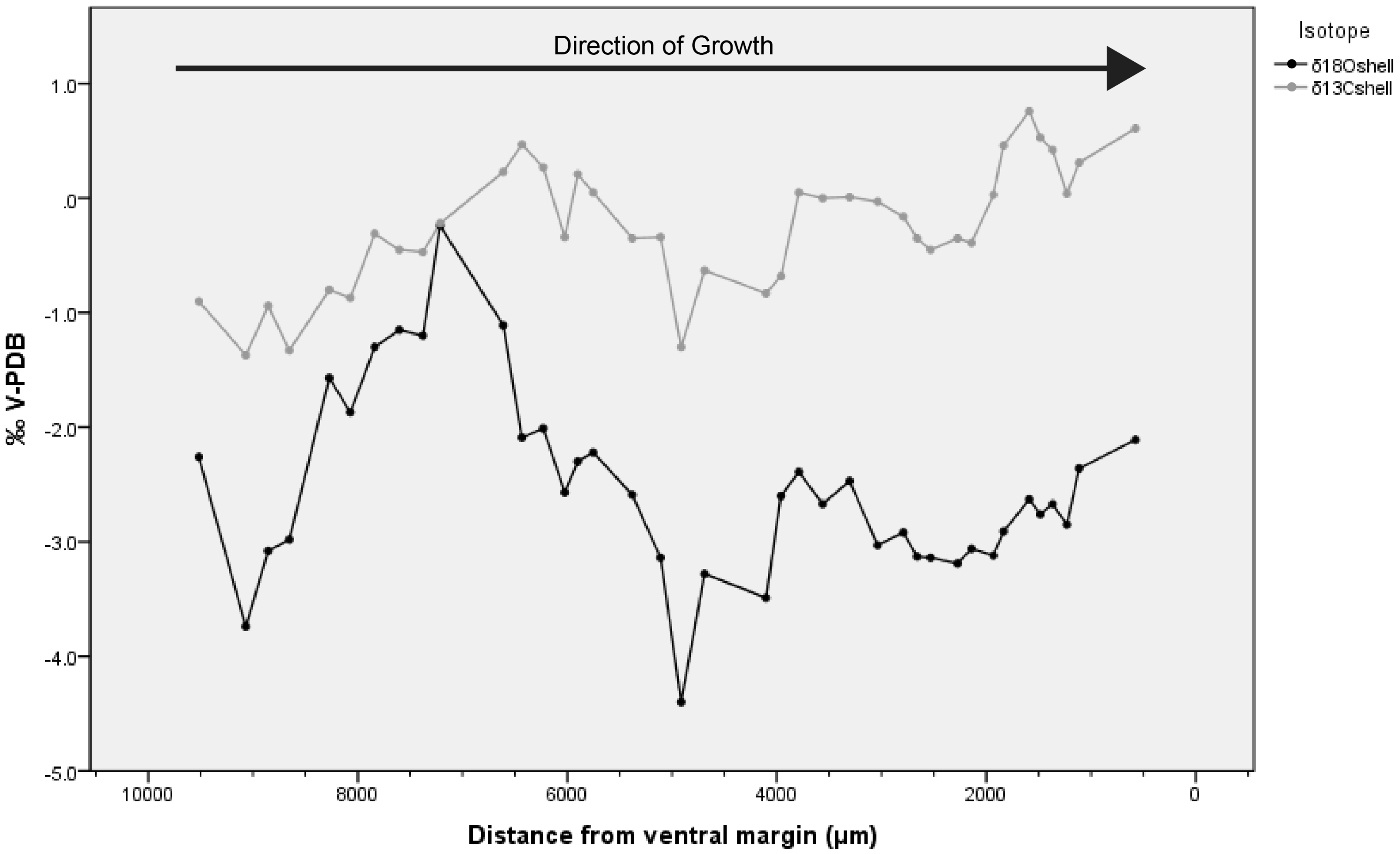

Figure 8.4 The isotopic profile of specimen 2/10 extends across 9.5mm of the 37.1mm shell. Approximately half of the values derived from the c.2.5mm of shell closest to the ventral margin are heavily averaged owing to minimum weight requirements for isotopic analysis.

8.4.2.2 Specimen 18

Specimen 18 was collected during the 2014 dry season from the intertidal rock platform near Raft Point. With a length of 35.9mm, this specimen is estimated to be in its third year of growth, sexually mature, and to have been growing at a rate of c.7.5mm per year at collection (Jagadis and Rajagopal 2007a; Kurihara 2003). Individual growth features were again poorly delineated throughout the section (Figure 8.5). Sampling transects were digitised at an average resolution of c.210µm (range = 87 to 381µm), extending over 9633µm (Figure 8.6). Comparing this to growth rates and age suggests the sampled section of Specimen 18 extends across at least one annual cycle (Jagadis and Rajagopal 2007a; Kurihara 2003).

Figure 8.5 Specimen 18 after micro-milling had been undertaken. Note that growth features were again near impossible to accurately distinguish under a reflected light microscope.

Carbonate sample weights ranged between 18 and 113µg (mean = 67.17µg). A majority of smaller samples originated from the ventral margin area where the upper shell layer is thin. Low weights required the amalgamation of some samples to reach minimum requirements for stable isotope analysis (18/1 and 18/2; 18/3 and 18/4; 18/5 and 18/6; 18/7 and 18/8; 18/9 and 18/10; 18/11 and 18/12; 18/16 and 18/16.1; 18/22 and 18/23). Beyond this no samples were discarded. Like Specimen 2/10, caution must be exercised when interpreting this profile as the initial 6 values are amalgamations of two samples each introducing a degree of time-averaging.

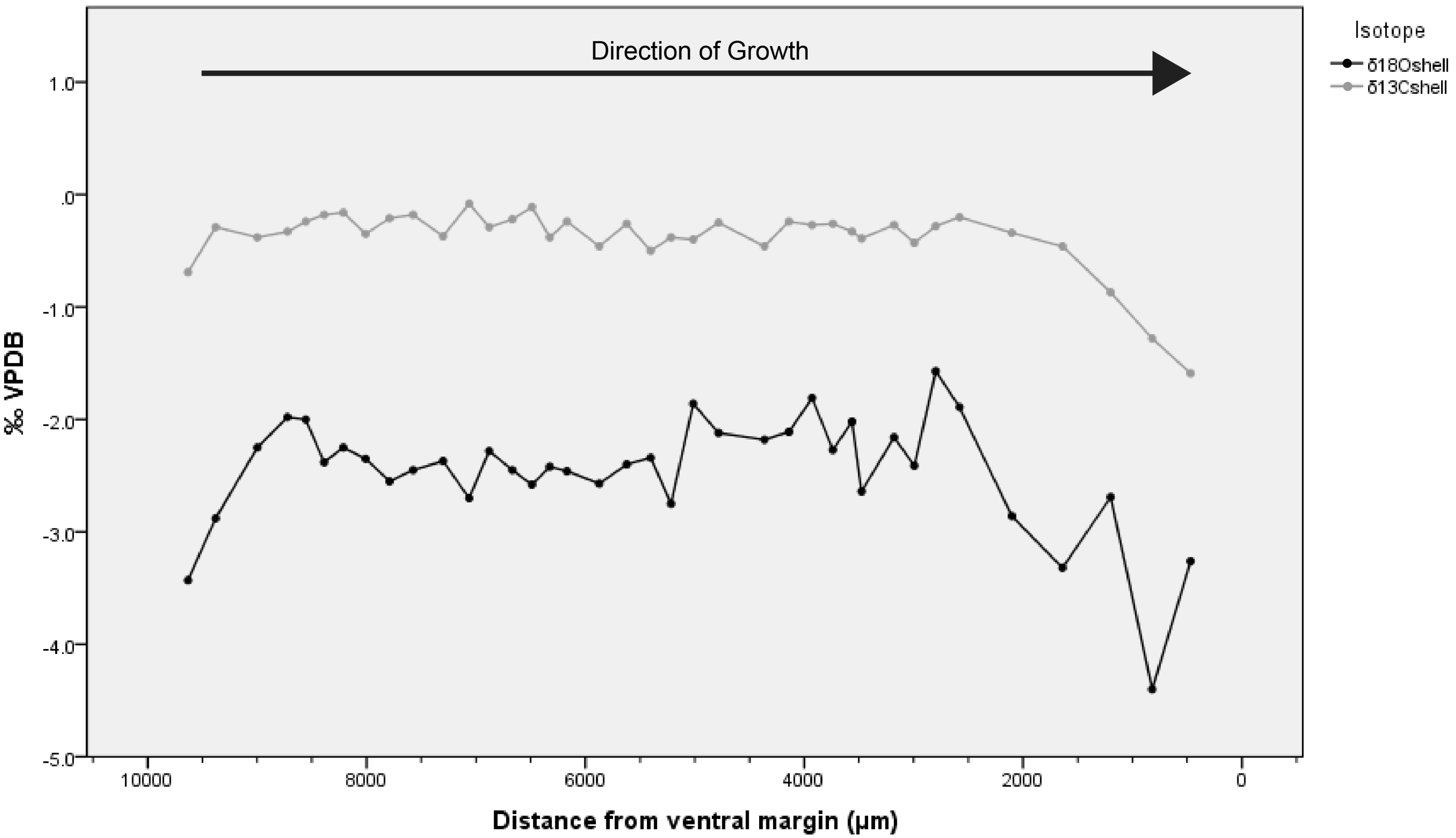

Figure 8.6 The isotopic profile of Specimen 18 extends across 9.6mm of the 35.9mm shell. Eight samples were combined to reach minimum weight requirements for isotopic analysis, potentially causing some smoothing across the profile.

When considered in its entirety, the isotopic profile of Specimen 18 suggests moderate variability with $\delta^{18}O_{shell}$ values ranging from -4.4‰ to -1.6‰ (mean = -2.5‰; 1σ = ±0.5‰). However, much like Specimen 2/10, isotopic fluctuations do not remain consistent throughout the profile. The first seven data points (up to c.2800μm) exhibit values encompassing the entire range. Subsequent variability lessens substantially (range = -2.8‰ – -1.8‰) until the final two values (18/44 and 18/45), which trend increasingly negative (-2.9‰ and -3.4‰, respectively). While it is possible this pattern is linked with the homogenisation of carbonate samples from the first c.2600μm (from the ventral margin) of the section, time-averaging is more likely to smooth results rather than increasing the magnitude of variability (e.g. Eerkens et al. 2013; Goodwin et al. 2004b).

The $\delta^{13}C_{shell}$ profile for Specimen 18 displays only minor variability through ontogeny (Figure 8.6), ranging between -1.4‰ and +0.8‰ (mean = -0.2‰; 1σ = ±0.3‰). When $\delta^{13}C_{shell}$ is compared to corresponding $\delta^{18}O_{shell}$ values via linear regression a moderately strong relationship is revealed (r^2 = .413), suggesting links between oxygen and carbon isotope patterning. Overall, $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values suggest relatively stable marine conditions with occasional fluctuations in water temperatures and $\delta^{18}O_{water}$ content and minimal interaction with terrestrial carbon reservoirs.

8.5 Complex Intertidal Environments

G. pectinatum inhabit a variety of intertidal contexts, including rocky platforms, rock pools, and sandy-mud flats, that are routinely flushed by waters from the open marine system as part of tidal cycling. This process leads to temporarily homogenous conditions across all three environments. However, processes associated with shallow rock pool systems (Figure 8.7), formed across rocky platforms as tidal waters recede, can allow environmental conditions to diverge from broader trends (see Firth and Williams 2009; Hogg et al. 1998). Evaporation, pool depth and volume, temperature, and differential contact with water and carbon sources can cause $\delta^{18}O_{water}$, $\delta^{13}C_{DIC}$, and salinity values of individual pools to vary, with $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ of associated shellfish reflecting these dissimilarities (e.g. Firth and Williams 2009; Hogg et al. 1998; Killingley 1981; Shackleton 1973). Thus, geochemical records derived from the shells of contemporaneously gathered molluscs have the potential to reflect differing conditions, impacting the usefulness of *G. pectinatum* as a proxy for seasonality and broader environmental trends.

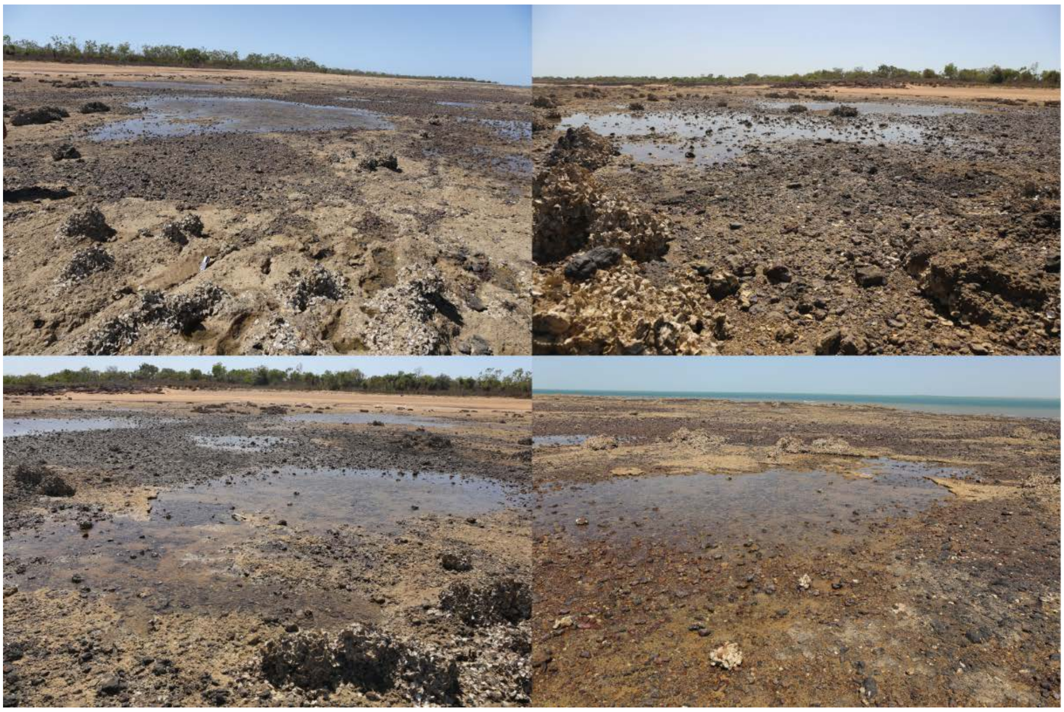

Figure 8.7 Shallow rock pools displaying differing environmental characteristics are formed and isolated across intertidal rocky platforms as tidal waters recede (Photographs: Sean Ulm, 2015).

Variability associated with rock pool systems is demonstrated by water samples and *G. pectinatum* specimens collected from the rocky platform and open marine system at Ngathald, Sweers Island (Figure 8.7). Sampling was undertaken during a neap tide in the 2015 dry-wet transition (September) when tidal movement was at a minimum. As a result, targeted rock pools had not undergone tidal flushing for a number of days, giving environmental processes the opportunity to form unique conditions. While $\delta^{18}O_{water}$ and salinity values for the open marine samples were indicative of marine conditions, rock pools returned heighted values likely owing to evaporation preferentially removing ^{16}O isotopes while increasing salinity in remaining water (Table 8.1). Similarly, $\delta^{13}C_{DIC}$ values were suggestive of exclusively marine carbon reservoirs at all sample collection points. Comparisons between rock pools revealed variability in $\delta^{18}O_{water}$ values, displaying an overall amplitude of 1.6‰. Minor variability was evident in $\delta^{13}C_{DIC}$ and salinity (Table 8.1), suggesting minimal input from external water and carbon sources. Larger inconsistencies were evident between pools and open marine waters, with differences of 1.4‰ to 3.0‰ in $\delta^{18}O_{water}$, 0.6‰ to 1.2‰ in $\delta^{13}C_{DIC}$, and 4.6 to 7.9 PSU for salinity. Therefore, while some variability is evident when individual rock pool environments are compared, the most substantial differences occur between pools and the open marine system.

Isotopic analyses of shell carbonates reveal that overall $\delta^{18}O_{shell}$ values range between -3.5‰ and -0.3‰, with cohort-specific means of -2.9‰ to -1.6‰ (Figure 8.8). Assessing values on a cohort-by-cohort basis finds some differences in $\delta^{18}O_{shell}$, with pool systems returning higher variability (mean amplitude = 1.8‰) than the open marine environment (amplitude = 0.7‰). Similar patterns are evident in $\delta^{13}C_{shell}$ where a majority of values fall within a -2.9‰ to -1.0‰ range. The exception to this is a specimen from Pool 1, which returned a value of -0.4‰. The amplitude of values from rock pool specimens (amplitude = 1.8‰) is again higher than those from the open marine system (amplitude = 0.9‰).

Table 8.1 Water sampling from rock pools and the open marine zone around Ngathald reveal hydrological inconsistencies between closely related environmental contexts.

Sample Context	$\delta^{18}O_{water}$ (VSMOW ‰)	$\delta^{13}C_{DIC}$ (VSMOW ‰)	Salinity (PSU)
Rock pool 1	+2.9	+0.8	43.0
Rock pool 2	+3.5	+1.4	44.0
Rock pool 3	+3.5	+1.2	43.2
Rock pool 4	+4.5	+1.2	46.3
Open Marine System	+1.5	+0.2	38.4

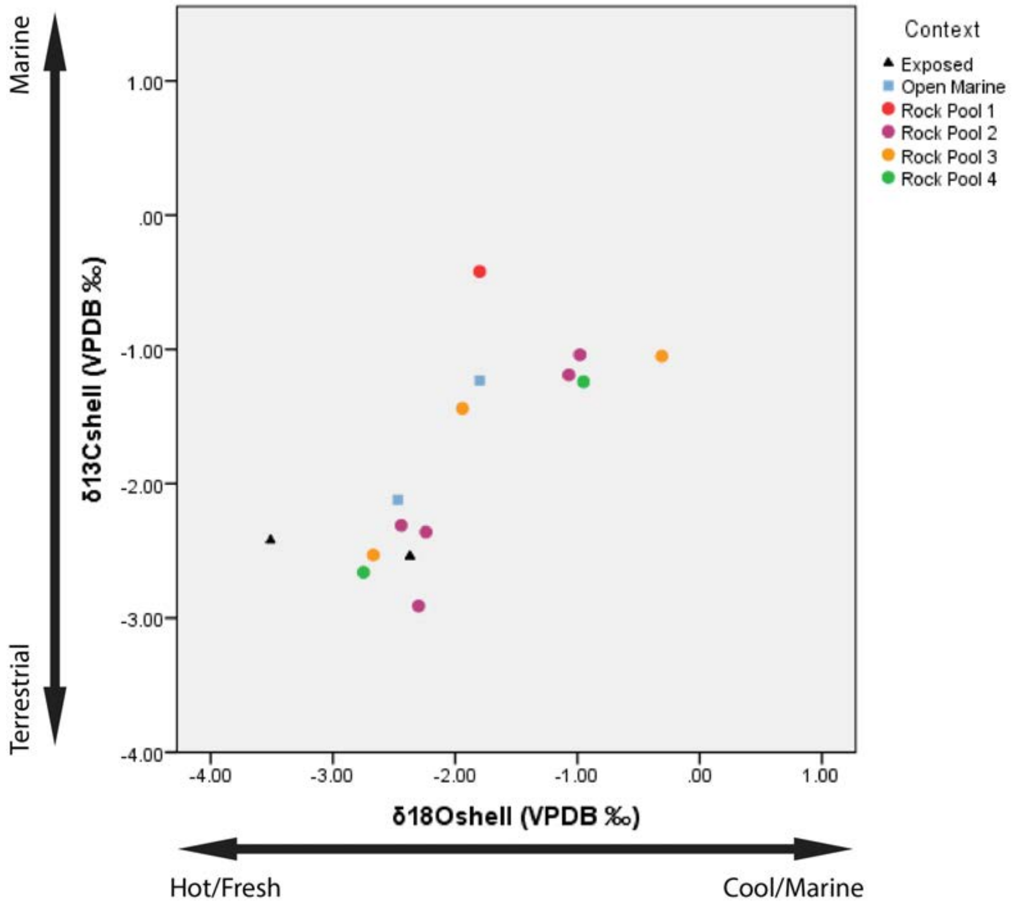

Figure 8.8 Edge margin shell stable isotopes reveal only minor variability between rock pool and open marine system specimens.

Highly positive $\delta^{18}O_{water}$ values exhibited across all collection sites suggest edge margin $\delta^{18}O_{shell}$ values have the potential to return equally positive results. However, associated $\delta^{18}O_{shell}$ values were up to 7.3‰ more negative than ambient $\delta^{18}O_{water}$, indicating other environmental or physiological factors play a key role in determining shell oxygen content. However, the relative importance of such factors appear to differ between environmental contexts. At the time of collection open marine systems were hydrologically stable owing to minimal rainfall during the preceding months (BOM 2016), leaving shifts in water temperature or shellfish moving between habitat zones as primary sources of associated $\delta^{18}O_{shell}$ change.

Relationships between hydrological conditions and shell isotopes in rock pool systems are significantly more complex given the presence of variable $\delta^{18}O_{water}$ content, linked with evaporation and tidal inundation, as well as frequent changes in water temperature. As outlined above the preferential removal of light oxygen isotopes by evaporation leads to increasingly positive $\delta^{18}O_{water}$ values. However, differences in pool size, frequency and intensity of exposure to direct sunlight and wind, water depth, surface area, shoreline position, and temperature can alter evaporation rates, causing $\delta^{18}O_{water}$ values to differ between pools (e.g. Table 8.1). Rock pool environments are also prone to rapid changes in temperature depending on the time of day, ambient conditions, depth, volume, and exposure to direct sunlight (Altermatt et al. 2009). Further, ambient conditions can heat surrounding rocks allowing elevated water temperatures to be maintained for extended periods of time, particularly during the wet season (personal observation, February 2016).

These processes allow diverging hydrological conditions to continue to develop until rock pools are flushed by high tides, causing environments to once again homogenise and reflect the broader marine system. This cycle then repeats with the recession of tidal waters. Thus, the periodicity and frequency of inconsistent environmental conditions in intertidal rock pools are highly dependent on tidal cycles, much like landward mangrove habitats (see Chapter 7). *G. pectinatum* inhabiting rock pools are therefore subjected to highly variable temperatures and $\delta^{18}O_{water}$ values between periodic tidal inundations, causing increasingly broad fluctuations in $\delta^{18}O_{shell}$ values when compared to specimens from the open marine environment.

8.6 Ontogenetic Patterns

8.6.1 Variable Patterns and Environmental Factors

Ontogenetic isotope profiles produced for *G. pectinatum* display changeable trends both within and between specimens, potentially obfuscating factors critical to accurate interpretation. For Specimen 2/10, when the individual's estimated age, time represented by the profile, and isotopic patterning are considered together, ontogenetic oscillations appear to resemble seasonal environmental shifts (see Section 8.4.2.1). However, inconsistent patterning (particularly in the most recent c.2.5mm of growth) makes confirming links between changes in environmental conditions and isotopic oscillations difficult. Specimen 18 presents a further set of interpretative challenges, displaying a largely 'flat' profile with little variation that could be attributed to changing environmental or physiological conditions.

As discussed in Section 8.5 the intertidal environments inhabited by *G. pectinatum* can display complex hydrological characteristics, including fluctuations in temperature, $\delta^{18}O_{water}$, and salinity, manifesting within *G. pectinatum* shell geochemistry as environment-specific $\delta^{18}O_{shell}$ values. These same attributes may assist in explaining isotopic patterning displayed by ontogenetic profiles. Given the preferred high-shore positioning of *G. pectinatum*, the timing of shell precipitation is closely linked to periods of aerial exposure coinciding with tidal cycles. However, tidal inundations occur at regular intervals, minimising the length and frequency of associated growth stoppages. While this taxa exhibits a moderate tolerance to variable temperatures (Kurihara 2003), heightened temperatures associated with rocky platform environments have the potential to cause periodic interruptions to growth regimes. The regularity and length of associated cessations may be increased during wet season conditions owing to higher ambient temperatures (see Chapter 6). Finally, while little research has characterised *G. pectinatum* responses to salinity, attributes of other species explored in this research suggest that growth will slow or cease above c.36 PSU (see Chapters 4 and 6). The heightened salinities (up to 46.3 PSU) displayed by rock pools are therefore likely to negatively impact growth. This again may differ seasonally with influxes of freshwater from rainfall and terrestrial run-off leading to decreased salinities during wet season conditions, however the degree to which these processes alter rock pool hydrology is currently unclear.

Movement between environments may also alter growth regimes, with the variability that typifies rock pool systems irregularly interrupting the archiving of associated environmental conditions. While both profiled specimens were collected from an open marine context it cannot be assumed that they inhabited this environment continuously. As *G. pectinatum* prefers to remain on the surface of intertidal substrates (Kurihara 2003), tidal fluctuations can easily facilitate its movement between open marine and rock pool systems. Thus, associated isotopic profiles are likely representative of both habitats, making accurate interpretation difficult without detailed life-histories.

While the effects of these influences likely manifest within the isotopic profiles of Specimens 2/10 and 18, they are difficult to directly demonstrate owing to uncertainties stemming from methodological issues (see Section 8.6.2 for a detailed discussion). Approaching solutions to the difficulties posed by environmental factors requires further research focused on characterising and comparing conditions in *G. pectinatum* habitats with associated shell geochemistry. This research recommends a combination of continuous sensor monitoring, specimen growth tracking, and regular collection of water samples and live *G. pectinatum* for isotopic analysis take place simultaneously across all environmental zones inhabited by *G. pectinatum*. These measures would provide increasingly detailed understandings of environmental and hydrological cycles, how conditions are recorded within shell geochemistry, and the impact of inter-habitat variability. Moreover, better characterisations of *G. pectinatum* growth regimes would facilitate more accurate temporal calibration of isotopic profiles. Increasing the length of ontogenetic sampling to encompass a larger portion of each individual's lifespan may also offer greater insight into the nature of isotopic oscillations.

8.6.2 Methodological Hurdles

Changeability evident within and between ontogenetic profiles may be linked with a number of methodological complications that presented themselves over the course of this research. The most potentially harmful to interpretation are those caused by sample homogenisation. As outlined in Section 8.4.2, numerous milling transects, particularly those adjacent to the ventral margin, produced carbonate samples that did not meet minimum weight requirements for analysis. This presented a dilemma as discarding these small samples would leave large gaps in the profile, impacting the validity of associated interpretations. In an attempt to address this adjacent samples were combined, however this increased time-averaging and smoothed isotopic fluctuations associated with seasonal shifts. The impact of this can be seen in Specimen 2/10's isotopic profile, where the 2.5mm section adjacent to the ventral margin underwent significant sample homogenisation (see Section 8.4.2.1). This appears to have normalised evidence of short-term environmental fluctuations, like that seen in the remaining profile. While Specimen 18 was also likely effected, it is difficult to characterise the degree to which time-averaging impacted the profile owing to its overall 'flat' appearance. However, as less samples were homogenised and isotopic values from mixed samples closely resemble their unmixed counterparts, it can be concluded that the effects of sample mixing were largely overridden by other influences.

The impact of time-averaging may be amplified by the lack of easily discernible growth features in *G. pectinatum* shell (see Chapter 4). Internal growth structures provide a visual guide for carbonate collection, allowing isotopic values to be contextualised not only within the growth history of the shell but also against broader temporal perspectives (e.g. Burchell et al. 2013b;

Hallmann et al. 2009). Without this framework limiting the impact of time-averaging becomes increasingly difficult as associations between carbonate samples and discrete time periods cannot be ensured. Moreover, relationships between growth features and shell geochemistry cannot be characterised meaningfully. As patterns of growth within molluscan shell are not uniform between species or through ontogeny (Figure 8.9), observations from other species or portions of shell cannot be employed to assist interpretation. While associated impacts are difficult to directly demonstrate, it is safe to assume that the isotopic profiles of both specimens are affected. In particular, the flattened profile displayed by Specimen 18 may be an artefact of latent time-averaging, however alternative explanations must also be considered.

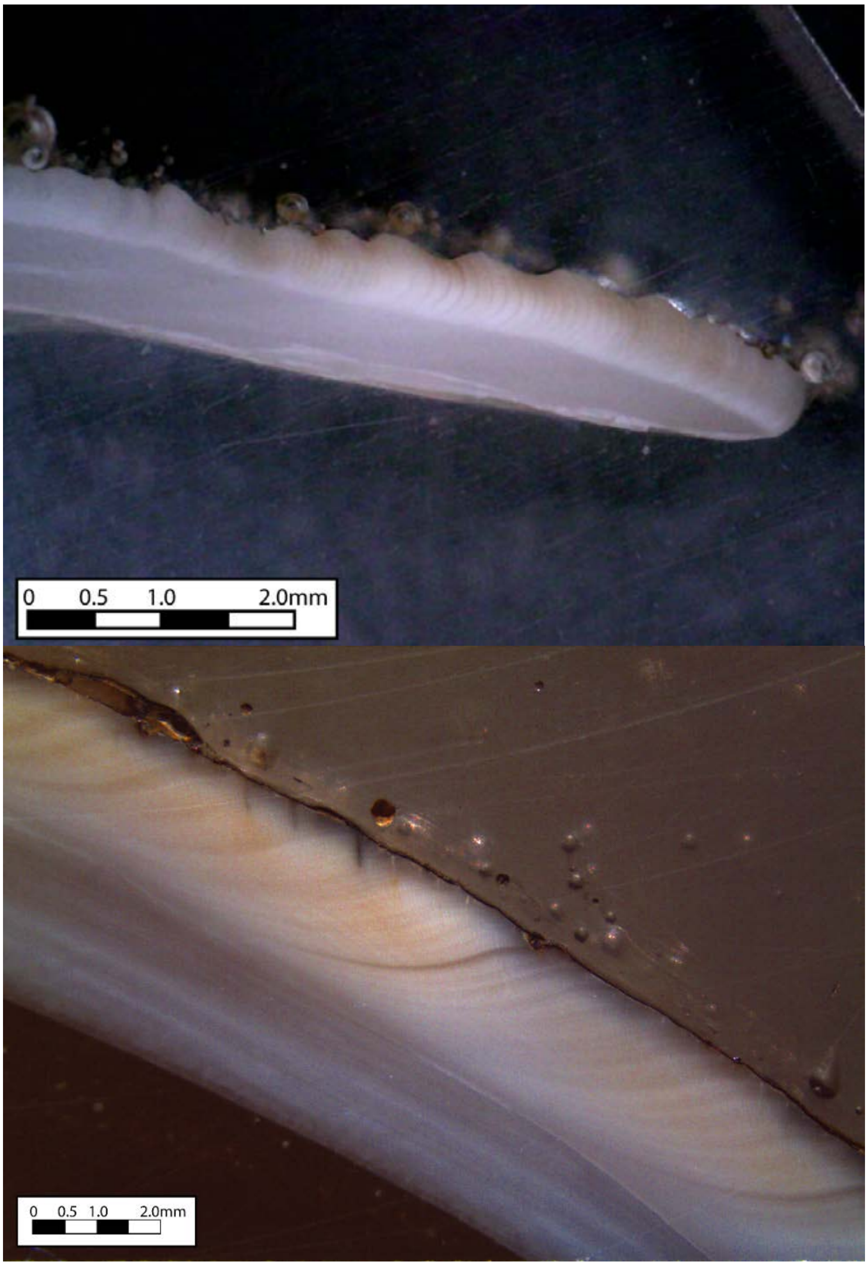

Figure 8.9 Top: Growth features of an adult *M. hiantina* collected as part of this research. Bottom: Growth features of a mature *P. coaxans* live-collected from the South Wellesley Islands.

Solutions to these problems can be approached via the application of alternative carbonate extraction methods. While micro-milling has facilitated the generation of numerous high-resolution isotopic profiles (e.g. Burchell et al. 2013c; Hallmann et al. 2013; Wurster et al. 1999), its reliance on growth feature visibility makes the application of this procedure to *G. pectinatum* problematic. Instead employing techniques that provide increasingly high-resolution profiles from *in situ* specimens using extremely small amounts of carbonate (e.g. sensitive high resolution ion microprobe (SHRIMP) (Long et al. 2014), secondary ion mass spectrometry (SIMS) (Hanson et al. 2010; Vihtakari et al. 2016; Weidel et al. 2007), or laser ablation (Spötl and Mattey 2006; Stephens et al. 2008)) may alleviate many associated concerns. However, while these techniques remove issues associated with limited carbonate sample sizes, the context provided by growth features remains invaluable to interpretation. Researchers are therefore encouraged to characterise growth features through other means, e.g. staining (see Schöne et al. 2005b). Moreover, many advanced analytical techniques (particularly SHRIMP and SIMS) require highly specialised equipment and training, potentially limiting their availability.

8.7 Palaeoenvironments and Seasonality

When assessed purely upon ecological and biological merits, *G. pectinatum* display many characteristics that paint this taxa as a source of palaeoenvironmental data useful for seasonality determinations. However, interactions between ambient conditions and shell geochemistry introduce a layer of complexity to the interpretation of isotopic records. A majority of these difficulties fall into similar categories as those proposed for *P. coaxans* (see Chapter 7), including environmental variability occurring at a variety of scales, inconsistent recording of environmental conditions, and a lack of definition in seasonal determinations.

8.7.1 Environmental Variability on Differing Scales

As demonstrated throughout this chapter, environments inhabited by *G. pectinatum* are highly complex with variability evident at numerous scales. The broadest differences occur between the open marine system and rock pool environments, with fundamental dissimilarities in hydrology. However, variability is also evident at increasingly localised resolutions, with numerous processes forming environmental conditions unique to individual pools (see Section 8.5). Further complicating this is the notion that the frequency and periodicity of environmental conditions are driven by tidal forces, with cycles of inundation and exposure playing an integral role in dictating the formation of habitat variability. Finally, as *G. pectinatum* are highly mobile between rock pool and open marine environments, it is difficult to pinpoint the origin of environmental records without detailed life-histories directly linked with individual specimens.

These sources of variability are particularly problematic for the interpretation of archaeological material. Assemblages frequently contain individuals gathered from a variety of environments and, as archaeological specimens were collected significant periods of time prior to analysis, detailed life-histories are unavailable. Thus, differently scaled patterns of environmental variability may skew interpretations of palaeoenvironmental conditions and seasonality, introducing latent inaccuracies into broader understandings.

8.7.2 Inconsistent Environmental Records

A number of environmental factors impact the consistency of growth regimes, and thus geochemical records, found in *G. pectinatum* shell. Changes in salinity, temperature, and aerial exposure dictate the timing and periodicity of environmental recording (see Section 8.6.2). Thus, individuals inhabiting highly changeable rock pool systems may undergo irregular growth stoppages. Sporadically archived records are therefore likely skewed towards optimal growth conditions rather than representing the full range experienced by individuals, adversely impacting the validity of associated interpretation. Much like *P. coaxans* (see Chapter 7), the prevailing concern is not that environmental records are inaccurate, rather the potential irregularity of timing, periodicity, and origin makes interpretation overly complex and imprecise. This becomes increasingly problematic for *G. pectinatum* owing to its lack of internal growth features, which removes another layer of context for isotopic values. Moreover, the high mobility of *G. pectinatum* makes it extremely difficult to attribute environmental records to conditions within a specific context.

8.7.3 A Lack of Definition in Seasonal Determinations

Likely the largest hurdle towards utilising *G. pectinatum* to accurately characterise seasonality and palaeoenvironmental conditions are inconsistencies between changes in environmental conditions and those observed in shell geochemistry. The most salient demonstration of this is the poor delineation between edge margin isotope values of specimens collected from different seasonal contexts, despite environmental observations demonstrating stark differences (Table 8.2).

Table 8.2 Seasonal hydrological variability in the intertidal zone (see Chapter 6 for details).

	$\delta^{18}O_{water}$ (‰)	$\delta^{13}C_{DIC}$ (‰)	Salinity (PSU)	Temperature (°C)
Dry Season	-0.3	-1.0	35	22.1
Wet Season	-4.0	-4.4	17.3	30.7

To better characterise similarities between seasonal catch cohorts one-way ANOVA tests were applied to edge margin values. It must be noted that values derived from specimens collected from rock pools were not included in these calculations to limit unnecessary habitat-specific variability. Results reveal significant similarities between seasons in both $\delta^{18}O_{shell}$ ($F(2) = 2.479$, $p = .129$) and $\delta^{13}C_{shell}$ ($F(2) = .377$, $p = .694$) datasets. When edge margin values are placed within predicted ranges for intertidal species, all specimens fall within modelled dry season values regardless of their known season of collection (Figure 8.10).

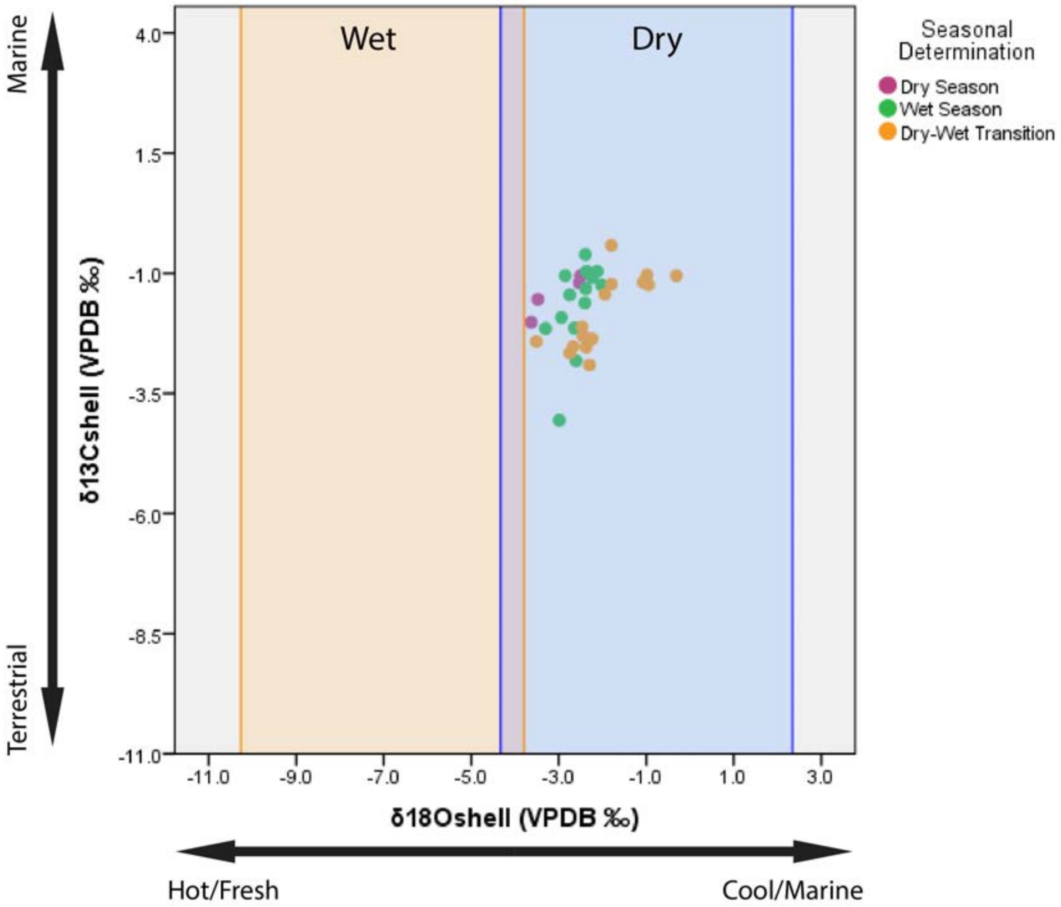

Figure 8.10 Predicted seasonal ranges suggest that all specimens were gathered from dry season conditions, regardless of actual season of collection. Note: specimens collected from rock pool systems are not included within this figure in order to remove unnecessary habitat-specific variability and complexity.

Similarly, plotting values derived from ontogenetic profiles against the same predicted ranges reveals a lack of seasonal delineation, with the vast majority of $\delta^{18}O_{shell}$ values from both specimens reflecting dry season conditions (Figure 8.11). Only two data points fall outside the predicted dry season range, in the upper wet season.

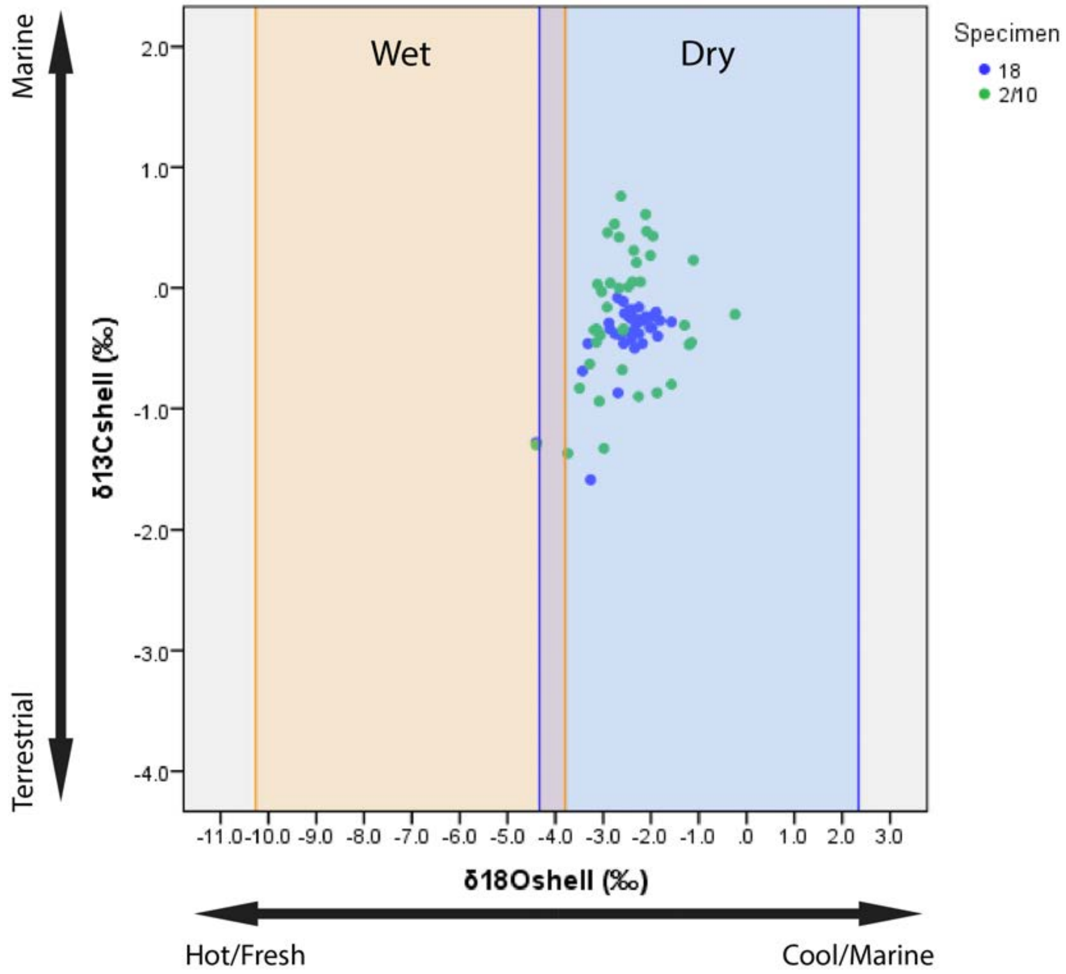

Figure 8.11 $\delta^{18}O_{shell}$ values from both micro-milled *G. pectinatum* specimens are closely linked with cool marine conditions throughout much of their isotopic profiles, with only two determinations suggesting wet season conditions. This is particularly surprising for Specimen 2/10, whose isotopic oscillations initially appeared to resemble seasonal cycles.

A number of factors may assist in explaining the lack of seasonal delineation between specimens. While there exists an overlap in the modelled seasonal ranges, it is constrained to less than 1‰ with no determinations falling in its confines. Thus, it appears that this overlap does not add to the ambiguity of seasonality determinations. Unlike *P. coaxans* and mangrove environments (see Chapter 7), the intertidal model remains largely unaffected by environmental similarities with broad seasonal differences in temperature and $\delta^{18}O_{water}$ values (see Chapter 6). Instead, conditions used to produce predicted seasonal ranges for intertidal environments are similar to those associated with the subtidal model, which is appears to be highly accurate (see Chapter 9). It is therefore unlikely that modelled ranges are inaccurate, with other factors leading to the ambiguity of seasonal determinations.

Issues associated with carbonate collection methodology are the most likely source of ambiguous seasonal results for isotopic profiles with the introduction of latent time-averaging via sample homogenisation (see Section 8.6.2). Explanations associated with edge margin values are likely significantly more complex and at this time remain largely unclear, however a number of possibilities can be suggested. As discussed in Section 8.6.2 and again in Section 8.7.2, understandings of the effects environmental conditions have on *G. pectinatum* shell precipitation rates are currently limited. Thus, it is unclear whether *G. pectinatum* record environmental conditions consistently throughout annual cycles. Seasonally timed climate change may therefore lead to the truncation of growth, particularly during the wet season when salinity and water temperatures are at their most extreme. This may also serve to explain the paucity of isotopic values indicative of wet season conditions in shell profiles. However, directly demonstrating this requires extensive tracking of both environmental conditions and contemporaneous growth rates, which rests beyond the scope of this research. There may also exist some factor, physiological or otherwise, impacting isotopic records that has not been considered here. It must therefore be suggested that records derived from *G. pectinatum* may not be in isotopic equilibrium with the ambient environment, although further research is required to demonstrate and better qualify this notion.

8.7.4 Recommendation

While it was originally posited that environmental records found within *G. pectinatum* shell would likely provide an easily interpretable proxy for seasonality and palaeoenvironmental data, it has become clear that this taxa is significantly more complex than anticipated. Relationships between ambient environmental conditions and *G. pectinatum* shell stable isotopes remain unclear, despite targeted analysis of both. In particular, complexities surrounding intra-habitat variability in rock pool systems, a paucity of internal growth features, and the inability to geochemically distinguish between specimens collected during different seasons make interpretation extremely difficult. It is hoped that further analysis will be able to approach solutions to these issues, allowing this archaeologically prevalent species to be utilised in the future. Thus, while there remains the possibility that *G. pectinatum* could be proven useful, significant gaps in current knowledge bases make it necessary to recommend that this taxa not be used as a source of palaeoenvironmental and seasonality data until further research is undertaken.

8.8 Radiocarbon Dating

Stable isotope values presented as part of this research largely mirror the findings of Petchey et al. (2013), with $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values indicating live-collected *G. pectinatum* inhabited marine environments and were rarely exposed to terrestrial carbon sources. Moreover, physiological and ecological factors that impact ^{14}C values in other species (see Chapter 7) do not effect *G. pectinatum* as this taxa is a consistent filter-feeder that does not aerially respire. One concern that was not addressed by Petchey et al. (2013) is the possibility that *G. pectinatum* were being gathered from intertidal or high-shore rock pools. As isolated rock pool hydrology can differ considerably from that of the open water (see Hogg et al. 1998; Section 8.5), differential interactions with carbon sources may exist. Moreover, regular tidal flushing of rock pool systems may facilitate the movement of *G. pectinatum* specimens between environments, causing shell carbonates to reflect both rock pool and marine systems. In order to accurately demonstrate the presence and impact of these factors, detailed life histories of the specimens in question are required. Unfortunately, these simply do not exist for archaeological material. Despite the potential issues posed by rock pool habitats, when results from this and past studies (Petchey et al. 2013) are considered in unison it appears *G. pectinatum* provides accurate radiocarbon determinations, with local Δ*R* corrections ameliorating dates from a majority of environmental offsets.

8.9 Summary

While *G. pectinatum* was initially thought of as a species with high potential for use as a source of palaeoenvironmental and seasonality data owing to fundamental physiological and ecological factors, complications surrounding relationships shared by environments and associated shell isotope values suggest this is not the case. Complexities associated with the rock pool systems frequently inhabited by this taxa introduce a series of factors that lead to inconsistent recording of environmental conditions, ambiguous connections with seasonal climatic change, and difficulties in interpreting isotopic patterning. Moreover, the absence of physical growth features in *G. pectinatum* shell makes connections between growth patterning and isotopic values difficult to reach. This also introduced uncertainties into the accuracy of carbonate extraction and impacts of time-averaging on ontogenetic isotope profiles. Despite these complex issues, biological and ecological understandings of *G. pectinatum* remain nascent with future research holding the potential to approach solutions. Thus, while *G. pectinatum* will not be utilised further in this research, it continues to hold potential as a palaeoenvironmental proxy and should be reassessed at a later date.

Chapter 9 Analysis of Modern Live-Collected *Marcia hiantina*

9.1 Introduction

The low-shore/subtidal bivalve *Marcia hiantina* dominates shelly archaeological deposits across the South Wellesley Islands, making this mollusc highly significant in exploring Kaiadilt occupation patterns. It is therefore imperative that links between associated shell isotope data and changing environmental conditions are explored and characterised. Much like *G. pectinatum*, the shoreline positioning and filter-feeding behaviour of *M. hiantina* underpins its potential usefulness. However, species-specific physiological and ecological factors must be explored to accurately evaluate its utility. This chapter combines local environmental and hydrological data with isotopic analyses of carbonates from modern live-collected *M. hiantina* specimens to characterise mollusc-environment relationships. These findings are then used to discuss the efficacy of geochemical data derived from *M. hiantina* shell in the context of the archaeological component of this research.

9.2 Potential Hurdles and Previous Applications

M. hiantina is associated with Aboriginal subsistence economies along Australia's coastline, particularly in the tropical north where it is a prominent component of numerous midden features, surface scatters, and mounds (e.g. Faulkner 2013; Morrison 2003, 2013; Peck 2016; Rosendahl et al. 2014a; Sim and Wallis 2008; Ulm et al. 2010). The widespread inclusion of *M. hiantina* in various archaeological contexts has meant this taxa has been key in interpreting past Aboriginal behaviours, particularly as a species used to develop radiocarbon chronologies (see Chapter 4; Ulm and Reid 2000; Williams et al. 2014). Despite its prominence within the literature, little research has explored the potential of isotopic data derived from *M. hiantina* beyond radiocarbon dating. When this is coupled with the paucity of general biology and ecology understandings of *M. hiantina* discussed in Chapter 4, it becomes clear that assessing the efficacy of this species may be more difficult than other more rigorously studied taxa. However, combining detailed characterisations of localised environmental cycles with isotopic analysis of modern live-collected specimens provides a solid foundation for interpretation of isotope values in archaeological specimens.

Unlike other molluscan species discussed in previous chapters (see Chapters 7 and 8), *M. hiantina* appears to possess few ecological or biological attributes that could cause major ambiguities in the interpretation of isotopic values derived from the species. Its preferred shoreline position, at or just beyond the interface of intertidal and subtidal zones, guards *M.*

hiantina against long periods of aerial exposure and a majority of terrestrial carbon inputs. Moreover, this taxa's preference for comparatively deeper marine waters provides increased environmental stability, potentially muting patterns associated with daily shifts in salinity and temperature common in high-intertidal and estuarine systems (e.g. Burchell et al. 2014; Culleton et al. 2009; Petchey et al. 2013). These same factors suggest that *M. hiantina* may engage in more consistent feeding and growth regimes, which are only interrupted by substantial environmental changes. Thus, this species is unlikely to employ aerial respiration or deposit feeding, instead maintaining constant filter-feeding behaviours. Environmental shifts that do impact *M. hiantina* populations are more likely to be tied to seasonal climatic changes, such as the monsoonal cycles, given their wide-reaching effects. Moreover, the high likelihood of *M. hiantina* shell maintaining relatively stable growth suggests environmental archives may prove more complete than other species (see Chapters 7 and 8).

While the characteristics outlined above suggest *M. hiantina* shell has the potential to act as a useful source of palaeoenvironmental and geochronological information, testing this may prove challenging owing to a variety of methodological and mechanical constraints. Chief among these is the small assemblage of modern individuals available for analysis (detailed in Section 9.3). Kaiadilt informants (Netta Loogatha, Amy Loogatha, Ethel Thomas, and Duncan Kelly) provided information as to the best locations to source modern specimens, however only extremely sparse populations were found. Despite the paucity of live individuals, freshly deceased specimens were frequently observed during collection surveys, making it unclear whether *M. hiantina* only appeared rare and researchers were searching in incorrect areas/conditions or numbers had indeed diminished. It should be noted that no discussion of a possible depopulation of *M. hiantina,* similar to that of *Tegillarca granosa* (e.g. Faulkner 2013:147; Morrison 2003), appears within biological, ecological, or archaeological literature, although other authors have observed short-term decreases in *M. hiantina* populations on the mainland coast (Meehan 1977, 1982:162-165). Whatever the reason, a limited number of live *M. hiantina* specimens were obtained, making it difficult to assess potential variability between specimens.

The 2014/2015 and 2015/2016 wet seasons saw extremely limited rainfall across the South Wellesley region, with Sweers Island reporting its lowest rainfall in recent years (BOM 2016; Texas Battle, resident of Sweers Island, pers. comm., 2016). This caused diminished flooding across Bentinck Island (personal observation, February 2016), substantially reducing run-off into estuarine and marine systems. Lessened input of freshwater from rainfall and run-off caused hydrological conditions to remain more consistent over the annual cycle than previous years, including 2013-2014 when a majority of environmental monitoring took place. Thus, these conditions likely impacted the applicability of isotopic results (particularly $\delta^{18}O_{shell}$) derived from the carbonates of associated specimens as ambient hydrological conditions are uncharacteristic of the wet season. The effects and limitations of this are explored further in Section 9.5.

Carbonate collection may be challenging for *M. hiantina* as individual shell layers are exceptionally thin (Figure 9.1), providing an extremely limited cross-section for carbonate sampling. Micro-mill transects are therefore likely to be highly truncated in length, limiting their capacity to produce carbonate powder samples that meet minimum weight requirements. Alternative carbonate collection methods are employed to assist in alleviating these issues, particularly in the generation of ontogenetic stable isotope profiles (see Section 9.4.2).

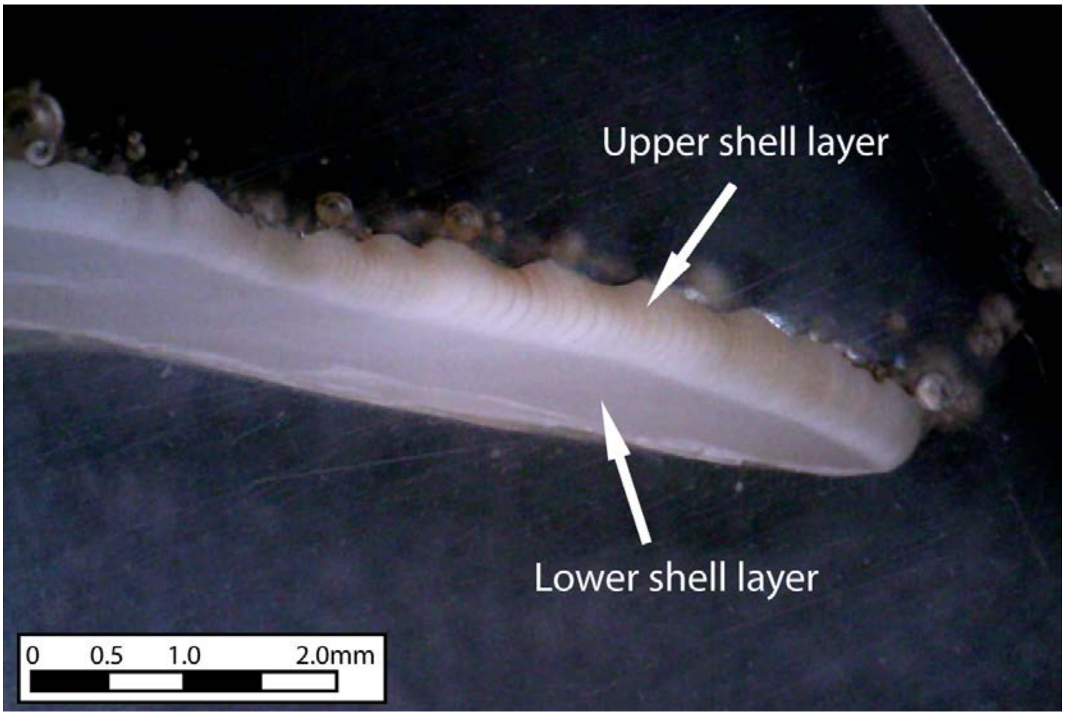

Figure 9.1 *M. hiantina* display extremely thin shell layers, severely limiting the length of micro-mill transects.

9.3 Live-Collected Specimens

Live specimens were collected from three sites, Mirdidingki (near STN6), Raft Point, and the northern tip of Fowler Island, during the 2014 dry season (*n* = 4) and 2016 wet season (*n* = 4) (see Appendix C for full details). In order to maximise data from this relatively limited modern assemblage, all live-collected specimens underwent carbonate extraction and stable isotope analysis. Carbonate was collected from the right valve of all specimens using targeted ventral margin collection.

The left valves of two specimens (1/4 and 31/1) were selected for additional analysis. Initially both specimens were to be micro-milled, however it was found that the layers comprising *M.*

hiantina shell are too thin to reliably obtain adequately weighted carbonate samples. Reaching minimum analysable weights required the amalgamation of an average of 3.75 samples, equating to an average sample resolution of 511µm compared to c.194µm for *P. coaxans* and c.253µm for *G. tumidum*. Thus, associated results were exposed to significant time-averaging and smoothing of isotopic profiles. To assist in alleviating these issues, micro-drill spot sampling was substituted for micro-milling (see Chapter 5 for procedures). While not as precise as micro-milling, spot sampling reliably produced carbonate samples of appropriate weight (see Sections 9.4.1.1 and 9.4.1.2). However, it should be noted that these circumstances are highly specific to this assemblage of *M. hiantina* and therefore this solution should not be applied to other material without mechanical testing. All carbonate samples underwent mass spectrometry to derive $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values. Results of these analyses are presented and discussed below.

9.4 Results

9.4.1 Targeted Ventral Margin Sampling

Ventral margin carbonates extracted from eight live-collected *M. hiantina* specimens display results indicative of minor seasonal variability (Figure 9.2). Overall $\delta^{18}O_{shell}$ values ranged from -3.7‰ to -0.5‰ with a mean of -1.9‰. Similar to other marine-focused species, $\delta^{13}C_{shell}$ values were relatively positive with a mean of -2.3‰ (range = -5.5‰ – -1.4‰). Specimens collected during the dry season returned tightly grouped $\delta^{18}O_{shell}$ values between -2.0‰ and -0.5‰ (mean = -1.2‰). Likewise, dry season $\delta^{13}C_{shell}$ values display minimal variation (mean = -1.8‰; range = -2.1‰ – -1.4‰). $\delta^{18}O_{shell}$ values derived from wet season specimens display an overall more negative mean (-2.6‰) and range (-3.7‰ – -1.9‰), suggesting seasonally timed hydrological shifts are recorded by *M. hiantina* shell. A similar negative shift is evident in wet season $\delta^{13}C_{shell}$ values (mean = -2.8‰; range = -5.5‰ – -1.44‰), although values remain typical of carbonates constructed from marine DIC.

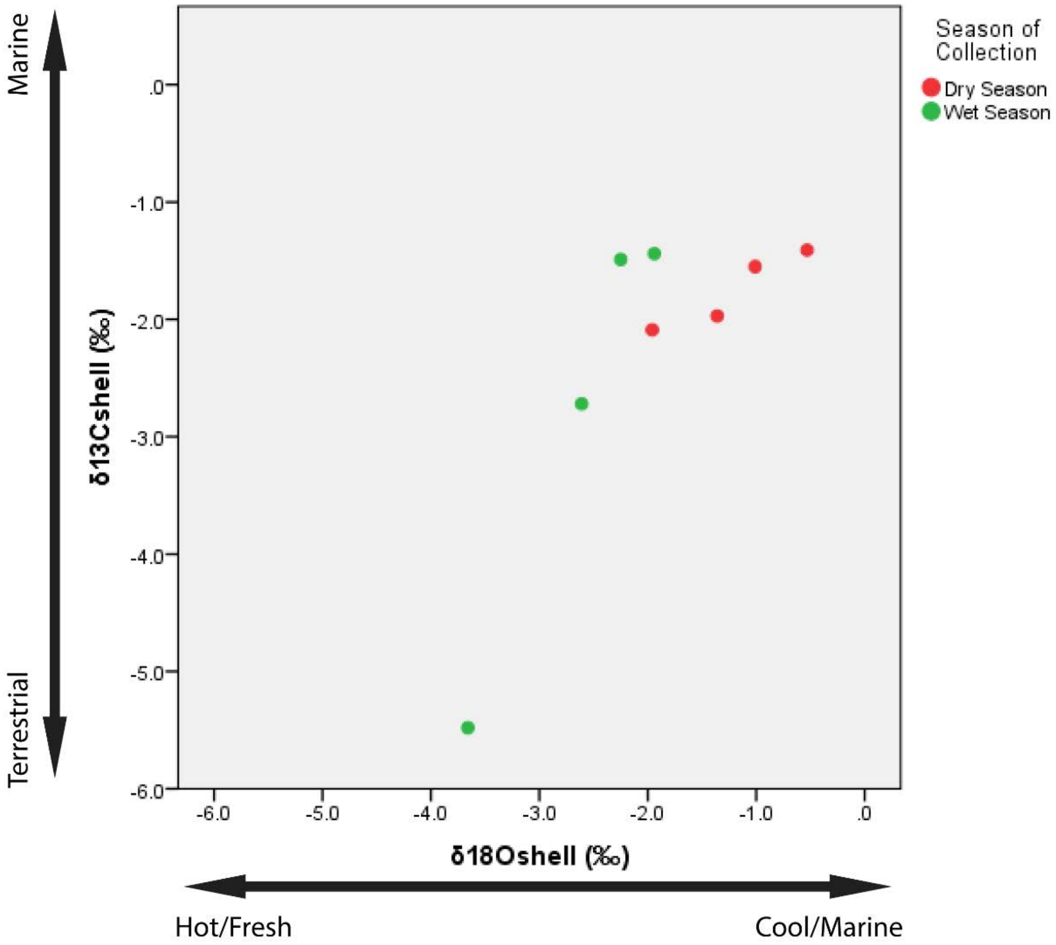

Figure 9.2 Edge margin values reveal minor variability between specimens live-collected from wet season and dry season contexts.

9.4.2 Micro-Drill Spot Sampling

9.4.2.1 Specimen 1/4

Specimen 1/4 was collected during the 2014 dry season from low intertidal flats south of Mirdidingki Creek. The paucity of studies focused on *M. hiantina* growth rates (see Chapter 4) makes estimating the age of Specimen 1/4 extremely difficult. However, given ethnographic accounts of Aboriginal foragers avoiding 'baby' *M. hiantina* (Meehan 1982:83) along with close correlations between this specimens length (34.1mm) and the average length of archaeological valves from sites such as Thundiy (36.4mm) (Peck 2016:159), it is suggested that Specimen 1/4 was sexually mature and thus at least 1 year of age. Carbonate samples (*n* = 20) were taken at an average resolution of 346µm (range = 204 – 532µm) across 6890µm of the section (Figure 9.3). Sampling ceased when the upper shell layer became too thin to reliably recover carbonate. Again due to a lack of information regarding growth rates the time period represented in this profile is unclear, however the isotopic profile detailed below suggests it may extend across less than one annual cycle. One carbonate sample (1/4-2) was discarded owing to material loss.

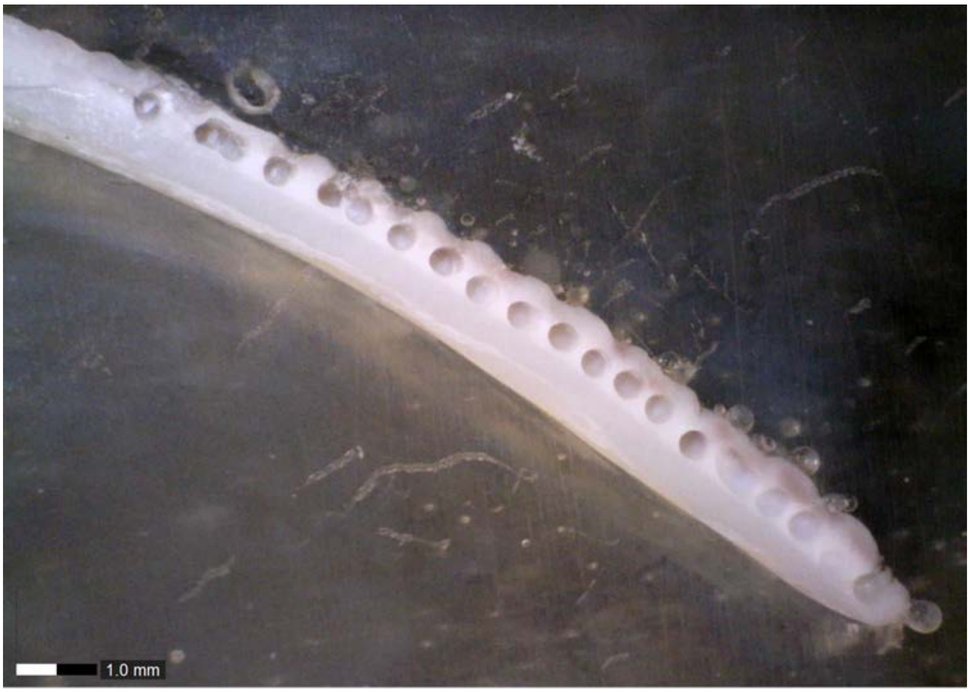

Figure 9.3 Specimen 1/4 was spot sampled by hand with samples taken at an average of 346µm.

Stable isotope analysis reveals an overall negative trend in $\delta^{18}O_{shell}$ values (mean = -3.9‰; range = -5.9‰ – -1.8‰) continuing through the profile (Figure 9.4). Similarly, plotted $\delta^{13}C_{shell}$ values display a largely negative trend (mean = -2.7‰; range = -3.5‰ – -1.8‰) that corresponds well to $\delta^{18}O_{shell}$ values. This is confirmed by linear regression analysis, which indicates a moderately strong relationship between stable oxygen and carbon isotopes (r^2 = .440). Overall, $\delta^{13}C_{shell}$ values remain relatively positive suggesting this specimen inhabited environments with little influence from terrestrial carbon sources, while $\delta^{18}O_{shell}$ values suggest a gradual negative shift owing to increased temperature and contact with freshwater.

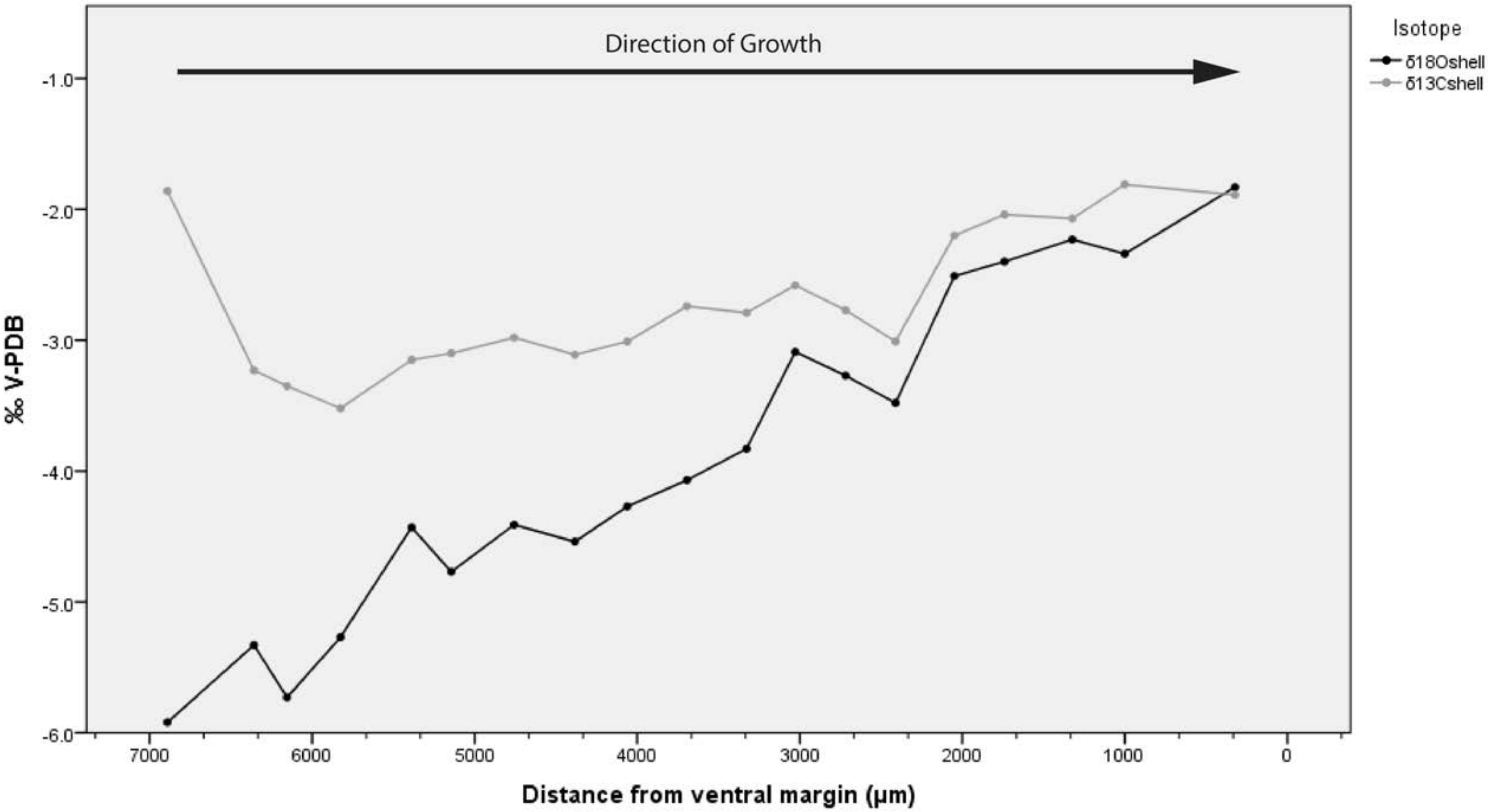

Figure 9.4 The isotope profile of *M. hiantina* specimen 1/4 extends across 6.89mm of the 36.4mm shell.

9.4.2.2 Specimen 31/1

Specimen 31/1 was collected from the northern coast of Fowler Island during the 2016 dry season. The precise age of this specimen remains unclear, however, as with Specimen 1/4, ethnographic accounts (Meehan 1982:83) combined with close correlations between this specimen's length (34.02mm) and the average size of archaeological material (Peck 2016:159) suggest it is at least 1 year of age. Carbonate samples (*n* = 15) were taken at an average resolution of 466µm (range = 288 – 601µm) (Figure 9.5). Sampling ceased when the upper shell layer became too thin. A lack of data regarding *M. hiantina* growth rates make estimating the time period represented in this profile difficult. No carbonate samples were discarded.

Figure 9.5 Specimen 31/1 was spot sampled by hand with samples taken at an average of 466µm.

Results of stable isotope analyses reveal variable ontogenetic $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values. $\delta^{18}O_{shell}$ values ranged between -2.5‰ and -0.9‰ with a mean of -1.8‰. While these values fluctuated through time, there is no discernible pattern (Figure 9.6). Moreover, a majority of the data (*n* = 14; 93%) are tightly grouped with 2.8‰ of the mean, with only a single value (7%) outside of this range. $\delta^{13}C_{shell}$ values displayed similar results with a range of -3.0‰ to -1.2‰ and a mean of -1.9‰. Again, data is largely grouped within 2.8‰ of the mean (n = 13; 87%), with 2 values (13%) remaining beyond this range. Oscillations in $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values correlated well with linear regression analysis reporting a moderately strong relationship between the two (r^2 = .402). Overall, results suggest this specimen inhabited an environment that primarily reflected marine conditions and had little contact with terrestrial carbon sources. Variations in $\delta^{18}O_{shell}$ suggest fluctuations in ambient temperatures or occasional contact with freshwater sources.

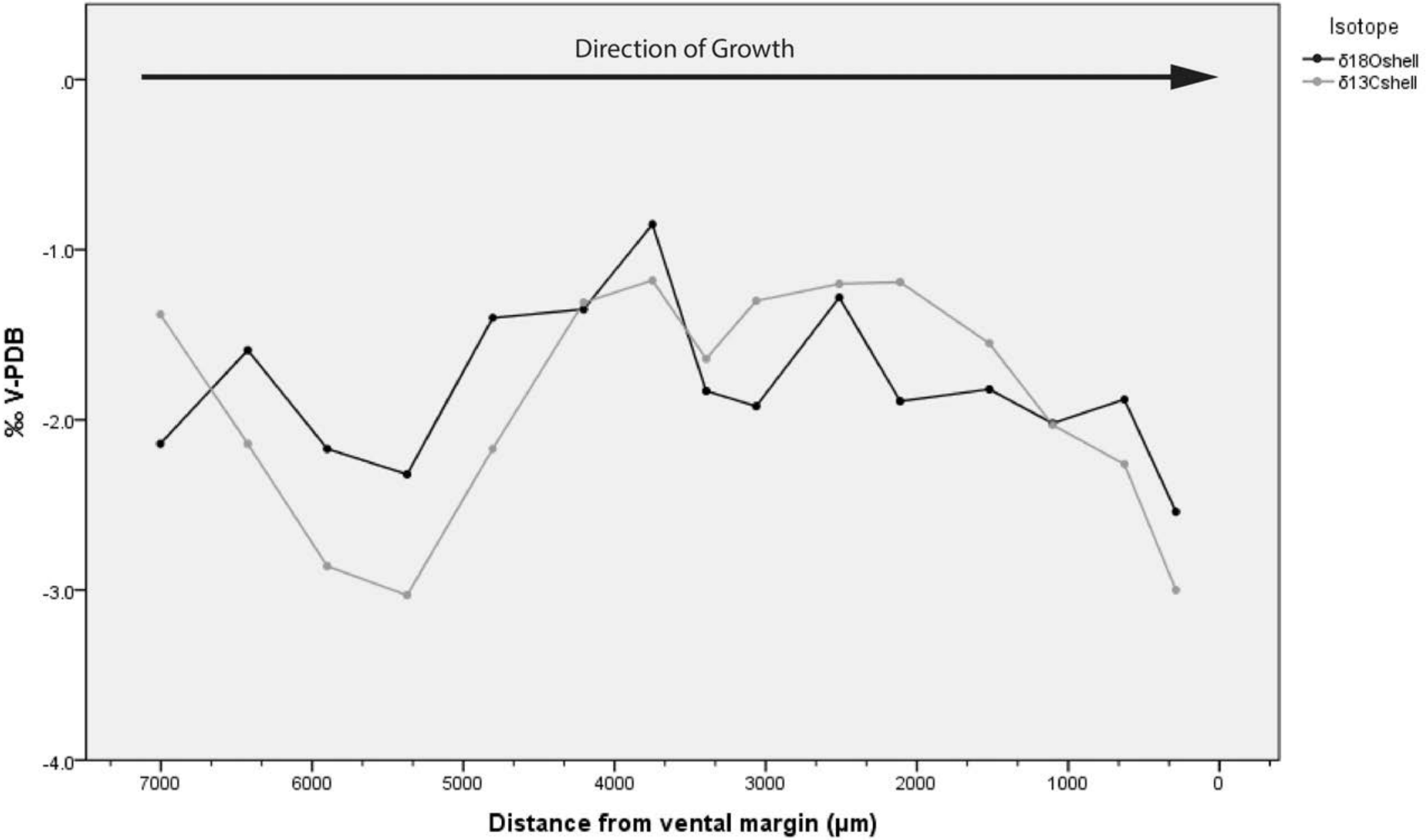

Figure 9.6 The isotope profile of *M. hiantina* specimen 31/1 extends across approximately 7.0mm of the 34.02mm shell.

9.5 Low-Shore and Subtidal Environments

Compared to the mangrove and rocky intertidal species discussed in previous chapters (see Chapters 7 and 8), characterising relationships shared by *M. hiantina* and its preferred low-shore/subtidal habitats is relatively simple. Environmental observations outlined in Chapter 6 revealed that intra-seasonal conditions in subtidal marine environments remain relatively stable, with substantial change triggered only by the onset of broader seasonal cycles. Moreover, when changes to oxygen isotope fractionation caused by water temperature and the oxygen content of water are taken into consideration, edge margin $\delta^{18}O_{shell}$ values are highly representative of the conditions they were collected from (Table 9.1). These results indicate that *M. hiantina* shell is precipitated in close isotopic equilibrium with the ambient environment during both wet and dry seasons.

Table 9.1 Using the palaeotemperature equation outlined in Chapter 5 (see Equation 5.1) the relationships between *M. hiantina* edge margin $\delta^{18}O_{shell}$ values and ambient conditions can be characterised. $\delta^{18}O_{shell}$ values are results of targeted ventral margin sampling (see Section 9.4.1). $\delta^{18}O_{water}$ values originate from water samples taken during live-collection of specimens. Measured temperatures are temperature highs from the day of collection as recorded by the Bureau of Meteorology station on Sweers Island (BOM 2016).

Collection Site	Season	$\delta^{18}O_{shell}$ (‰)	$\delta^{18}O_{water}$ (‰)	Predicted Temperature (°C)	Measured Temperature (°C)
Mirdidingki Intertidal	Dry	-2.0	-0.3	26.6	24.7
Mirdidingki Intertidal	Dry	-0.5	-0.3	20.4	24.7
Mirdidingki Intertidal	Dry	-1.4	-0.3	24.0	24.7
Fowler Island	Wet	-3.7	+1.0	39.6	36.4
Fowler Island	Wet	-2.6	+1.0	35.1	36.4
Fowler Island	Wet	-1.9	+1.0	32.2	36.4

Unfortunately, over the course of this research fluctuating environmental circumstances have somewhat complicated these normally straightforward relationships. The seasonal delineations displayed by $\delta^{18}O_{shell}$ values presented Section 9.4.1, while clearly present, appear relatively minor when compared to the substantial environmental differences observed between wet and dry seasons (see Chapter 6). Changes in broader climatic trends may explain these unexpected results. As outlined in Section 9.2, wet season specimens were collected during abnormal conditions as the region had experienced a substantial depression in the amount of rainfall over the two preceding years. The average wet season rainfall at Sweers Island between 2001 and 2013 was 1157mm, however data from the 2014/2015 and 2015/2016 wet seasons (up until early February 2016 when live-collection occurred) indicate severely diminished averages of 550mm and 444mm respectively. This pattern of decreased rainfall intensity is typical of the contemporaneous El Niño phase effecting the Australasian region (BOM 2015b). Without the input of freshwater from meteoric and terrestrial sources, water stable oxygen isotope content remained steady over wet and dry seasons, with water samples from the September 2015 and February 2016 demonstrating consistent $\delta^{18}O_{water}$, $\delta^{13}C_{DIC}$, and salinity values (Table 9.2). Thus, the surprisingly close relationship between wet and dry season edge margin values is linked with a lack of change in water composition, rather than *M. hiantina* failing to record wet season conditions.

Table 9.2 Water sampling exhibited few hydrological differences in 2015 and 2016.

	$\delta^{18}O_{water}$ (‰)	**$\delta^{13}C_{DIC}$ (‰)**	**Salinity (PSU)**
2015 (September)	+1.5	+0.2	38.4
2016 (February)	+1.0	-0.6	37.9

Applying the well documented temperature/$\delta^{18}O_{shell}$ conversion rate of 1‰ = 4.34°C (see Goodwin et al. 2001; Grossman and Ku 1986) to edge margin $\delta^{18}O_{shell}$ values, the average shift in $\delta^{18}O_{shell}$ between wet and dry season specimens (1.4‰) equates to approximately 6.1°C. This correlates to within 1°C of mean seasonal temperature differences in subtidal environments (7.1°C), as reported in Chapter 6. Moreover, as *M. hiantina* precipitates shell carbonates in isotopic equilibrium with its ambient environment, it can be assumed that any changes in $\delta^{18}O_{water}$ values would be recorded accurately. Regular seasonal variability in $\delta^{18}O_{water}$ (3.7‰, as reported in Chapter 6) can therefore be applied as a rough correction for 2016 wet season $\delta^{18}O_{shell}$ values, equating to a range of -7.4‰ to -5.6‰ with a mean of -6.3‰. These corrected values are indicative of modelled wet season values discussed in Chapter 6.

9.6 Ontogenetic Patterns

9.6.1 Seasonal Cycles

Isotopic patterning present in the ontogenetic profiles of Specimens 1/4 and 31/1 is variably linked with seasonal cycles. The abnormal wet season conditions associated with the collection and growth of Specimen 31/1 makes it difficult to link its isotopic profile with seasonal cycles. While isotopic oscillations are present, no trend or pattern appears to exist throughout the profile. Moreover, when compared to predicted seasonal ranges all data points appear indicative of dry season conditions despite live-collection during the wet season (Figure 9.7). As posited above this is caused by abnormally low rainfall during the 2014/2015 and 2015/2016 wet seasons (see Section 9.5). Given the assumed 1.5 to 2 year age of this specimen, it is likely that this mollusc has never been exposed to a 'normal' wet/dry season cycle. This may at least in part explain the lack of isotopic patterning in the profile of Specimen 31/1. While a rough correction for specimens collected during these conditions has been suggested (see Section 9.5), this cannot be utilised here as there is no way to accurately differentiate wet and dry season values. Thus, little information can be gleaned from this profile.

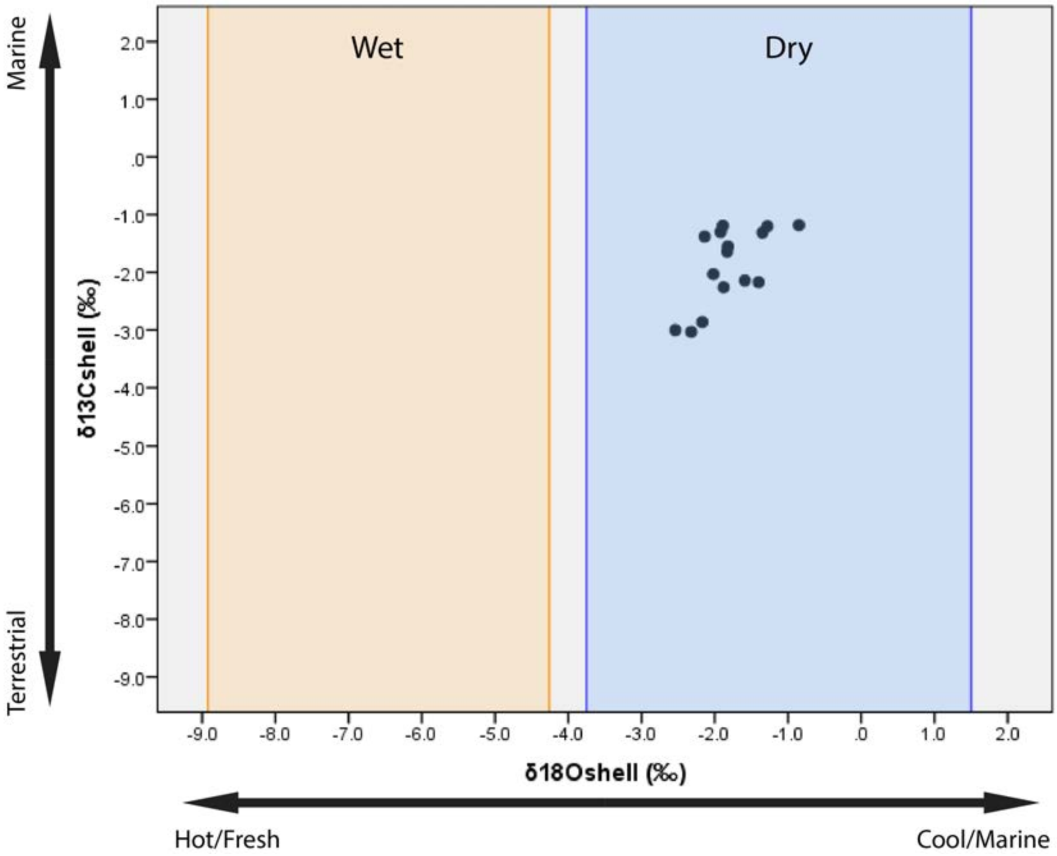

Figure 9.7 Low rainfall during wet season conditions throughout the life of Specimen 31/1 make accurately interpreting its isotopic profile extremely difficult.

The profile of Specimen 1/4 offers significant insight into the conditions under which *M. hiantina* records environmental conditions. Specimen 1/4 was collected at the peak of the dry season (July 2014), as $\delta^{18}O_{shell}$ values from the ventral margin suggest. What follows is a steady negative trend that extends from predicted dry season conditions into modelled wet season values (Figure 9.8). Moreover, as the trend remains steady throughout the profile it can be posited that no gaps were left by significant growth stoppages. When these findings are considered in combination with the knowledge that *M. hiantina* precipitate shell carbonates in equilibrium with the ambient environment, it can be confidently posited that Specimen 1/4 displays an isotopic profile reflecting ambient environmental conditions recorded over both wet and dry seasons.

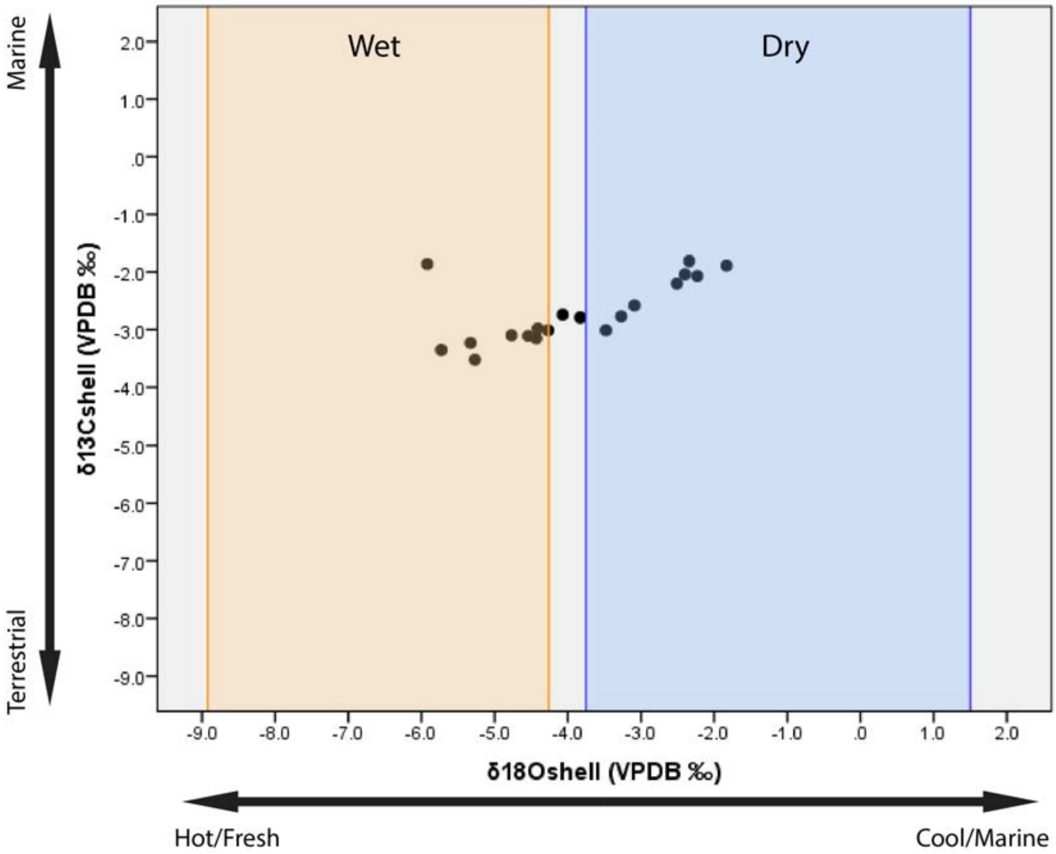

Figure 9.8 The isotopic profile of Specimen 1/4 demonstrates that *M. hiantina* record environmental conditions throughout both wet (shaded orange area) and dry (shaded blue area) seasons.

9.6.2 Relationships between Growth Features and Stable Isotope Values

Various factors made it impossible to explore relationships shared by growth features and stable isotopes in *M. hiantina* shell. As highlighted above the extremely tight spacing of visible growth features in this species makes targeted analysis particularly challenging. Refinement of micro-milling procedures may assist in characterising growth feature/isotope relationships, although this would require a different sampling strategy than that employed here. Moreover, growth features denoting seasonal change (e.g. broad lines indicating long periods of growth cessation) are essentially non-existent owing to environmental conditions remaining consistently within the tolerances of *M. hiantina* (see Chapter 6). It is suggested future research utilise additional analysis procedures capable of extremely high-resolutions, such as sensitive high resolution ion microprobe (SHRIMP), secondary ion mass spectrometry (SIMS), or laser ablation (e.g. Hanson et al. 2010; Long et al. 2014; Spötl and Mattey 2006; Stephens et al. 2008; Vihtakari et al. 2016; Weidel et al. 2007), to better characterise relationships between *M. hiantina* shell growth structures and geochemistry.

9.7 Palaeoenvironments and Seasonality

9.7.1 A Useful Proxy?

In previous sections the case was made for *M. hiantina* providing unambiguous and easily interpretable data that reflect ambient environmental and climatic conditions. However, lingering questions must be addressed before this research can recommend this taxa as a proxy for palaeoenvironmental and seasonality data. Most prevalent is whether results from the limited assemblage of modern *M. hiantina* are enough to justify this taxa's use as a marker for seasonality, particularly in light of wet season specimens producing $\delta^{18}O_{shell}$ values that do not adhere to predicted ranges. As demonstrated in Section 9.6, the isotopic profile of Specimen 1/4 encompasses $\delta^{18}O_{shell}$ values representative of both wet and dry seasons, however results from a single specimen cannot be accurately extrapolated over an entire species. As seasonal determinations from specimens live-collected during the 2015/2016 wet season reflect abnormal conditions (see Sections 9.5 and 9.5), other avenues of evidence are accessed to reinforce the usefulness of *M. hiantina*. Thus, results derived from archaeological material are considered (Figure 9.9).

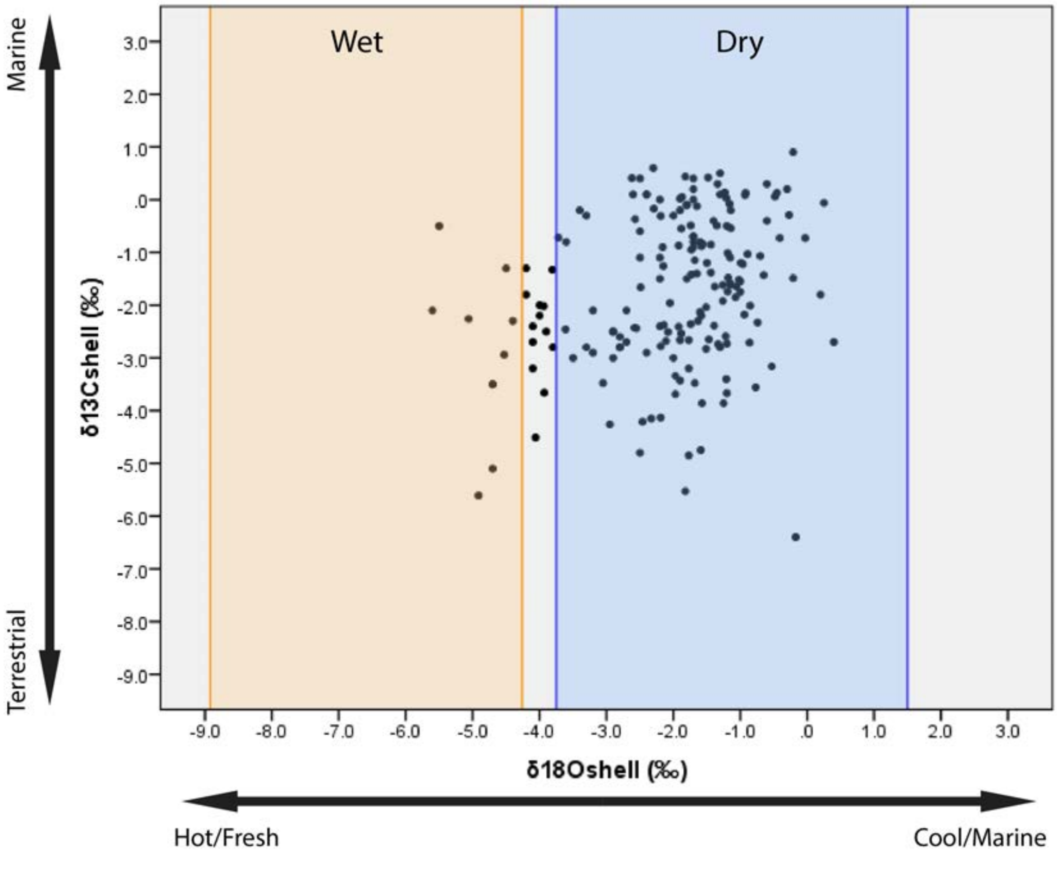

Figure 9.9 Isotopic values derived from the ventral margins of archaeological material indicate that *M. hiantina* records environmental conditions throughout the annual cycle, including both wet and dry seasons.

It must be noted that due to human decision-making processes and preferences archaeological isotopic values are skewed towards dry season collection (further discussed in Chapters 10 – 12), however this does not impact their usefulness in the context of the current chapter. While no archaeological interpretation is offered here (see Chapters 10 – 12), these data provide insight into relationships between *M. hiantina* shell and seasonal cycles. Results demonstrate that, as suggested by Specimen 1/4, *M. hiantina* shell carbonates contain representations of both wet and dry season conditions (Figure 9.9), indicating continuous recording of ambient environments over the course of the annual cycle.

9.7.2 Recommendation and Application to Archaeological Data

When the findings of modern environmental observations, water sampling, live-collected specimens, and archaeological material are combined, a convincing argument for the efficacy of *M. hiantina* as a proxy for palaeoenvironmental and seasonality determinations can be advanced. This taxa provides a continuous record of environmental conditions throughout the annual cycle that is constructed in close isotopic equilibrium with the ambient environment, requiring no corrections or offsets to characterise environmental trends associated with seasonal climatic change. Moreover, physiological and ecological issues prevalent throughout other molluscan taxa (see Chapters 7 and 8) do not effect *M. hiantina* populations, making relationships between environmental conditions and shell isotopes relatively straight-forward to characterise and interpret. This research therefore posits that out of the three target mollusc taxa, *M. hiantina* is the best candidate for further analysis as it is a reliable and effective proxy that can be used for palaeoenvironmental reconstruction as well as determining resource collection and occupation seasonality.

The application of modern findings to archaeological material largely relies upon the accuracy of the modelled seasonal ranges presented in Chapter 6. The predicted seasonal range for subtidal environments has been used throughout this chapter to assist in interpreting results, with findings indicating that data from known temporal contexts is largely congruous with modelled ranges. The exception to this is the 2015/2016 wet season catch cohort, however the source of this inconsistency was identified (see Section 9.5). When rough offsets were applied, corrected data points adhered closely to appropriate predicted ranges. While this hints at the efficacy of modelled ranges, it must be stressed that without further evidence from specimens with known temporal range, predicted wet season values can only be considered a preliminary guide for interpretation.

Improving understandings of fundamental attributes associated with this taxa would allow remaining questions to be meaningfully approached. Of particular importance is adding to currently sparse biological and ecological knowledge bases, including characterising growth rates, life span, age at sexual maturity, relationships between environmental conditions and macro-/micro-growth structures, and refined environmental tolerances. With this knowledge researchers could potentially approach more accurate/higher resolution seasonal determinations, beyond the dichotomous wet and dry seasons presented here. Moreover, further collection of live specimens during ‘normal’ wet season conditions would provide additional evidence for the efficacy of modelled ranges and consistent recording of environmental conditions. Findings associated with these improvements would likely serve to strengthen the assertion that *M. hiantina* is a powerful proxy that has the potential to be employed across Australia’s tropical north coast to fundamentally improve interpretation of past Aboriginal behaviour and culture.

9.8 Radiocarbon Dating

Researchers have long preferentially selected marine filter-feeding bivalves for radiocarbon dating, given their close associations with contemporary environments. This holds true for *M. hiantina*, which display few physiological or ecological attributes that should invalidate their use as a source of geochronological information based on radiocarbon. Section 9.5 demonstrated that this taxa precipitates its shell in isotopic equilibrium with the surrounding environment, a highly desirable characteristic for radiocarbon dating. Consistently positive $\delta^{13}C_{shell}$ values across the entire dataset indicate *M. hiantina* has little to no contact with terrestrial carbon sources, removing one major source of uncertainty impacting the accuracy of determinations. Results of water sampling at collection sites confirm this, with $\delta^{13}C_{DIC}$ values reflecting marine conditions throughout the annual cycle (see Chapter 6). While few concerns regarding the use of this species exist, it must be stressed that local ΔR corrections should continue to be applied. Thus, this research recommends that, where possible, *M. hiantina* shell be utilised for radiocarbon dating over the other species discussed as part of this research (see Chapters 7 and 8) owing to the close geochemical relationships it shares with its ambient marine environment.

9.9 Summary

Analysis of modern live-collected *M. hiantina* revealed isotopic records archived within this taxa’s shell carbonates are a reliable source of isotopic and seasonality data. Relationships shared between ambient environmental conditions and shell geochemistry are relatively straightforward, providing easily interpretable data despite complications presented by abnormal climatic events. However, a majority of current biological and physiological understandings related to this taxa are speculative, thus further research into these attributes would further strengthen the findings of this thesis. It is recommended that *M. hiantina* provide the foundation for the interpretation of Kaiadilt occupation patterns on Bentinck Island.

Chapter 10 Thundiy

10.1 Introduction

Archaeological excavations at the shell matrix site of Thundiy, north coast of Bentinck Island, reveal a dense cultural deposit dominated by marine bivalve shell. Previous studies have established a secure and detailed radiocarbon chronology for the formation and use of Thundiy (see Nagel et al. 2016). As a result, this site provides an exemplary context in which a high-resolution chronology of timing, periodicity, and seasonality of Kaiadilt occupation can be established. This chapter describes Thundiy and its stratigraphy in combination with results from stable isotope analyses of archaeological shell carbonates. Findings are then placed in the temporal framework provided by associated radiocarbon determinations. The implications of these results are discussed in relation to the history of Kaiadilt occupation at Thundiy and the surrounding area.

10.2 Site Description and Setting

A majority of the Thundiy cultural deposits are situated atop a long mid-Holocene beach ridge orientated parallel to the adjacent coastline. Elevations taken along the ridge’s surface place it 6.5m above the Australian Height Datum (AHD). A wide supra-tidal mudflat (c.160m wide) and broad, thick coastal mangrove fringe (c.120m wide) are found adjacent to the beach ridge, separating it from the open marine environment. Peak high tides not only inundate the mangrove fringe but also encroach upon the mudflat. Like the Mirdidingki area, mangrove forests associated with Thundiy are dominated by *Bruguiera exaristata* (orange mangrove) and *Rhizophora stylosa* (red stilt-root mangrove) along with *Avicennia marina* (grey mangrove) and *Ceriops togal* (yellow mangrove). Sediment supply to the site is derived from both natural (e.g. storm surge and wind) and cultural (e.g. disposal of food waste) actions. Vegetation surrounding the site is savannah, consisting of numerous species of tree (*Dolichandrone heterophylla*, *Premna acuminate*, and *Canarium australianum*), herb (*Grewia reusifolia*, *Trichodesma zeylanicum*, *Gomphrena canescens*, *Euphorbia mitchelliana*, *Tinospora smilacina*, and *Wrightia saligna*), and grass (*Chrysopogon* sp. and *Heteropogon contorus*). A large clay pan system borders much of the area to the northeast and east (Dururu) as well as to the south (Central Clay Pan), while the mouth of the Makarrki River is approximately 2km to the southwest (Figure 10.1). A four-wheel drive access track runs from the Dururu clay pan and along the length of the site before continuing southwest to the bank of the Makarrki River.

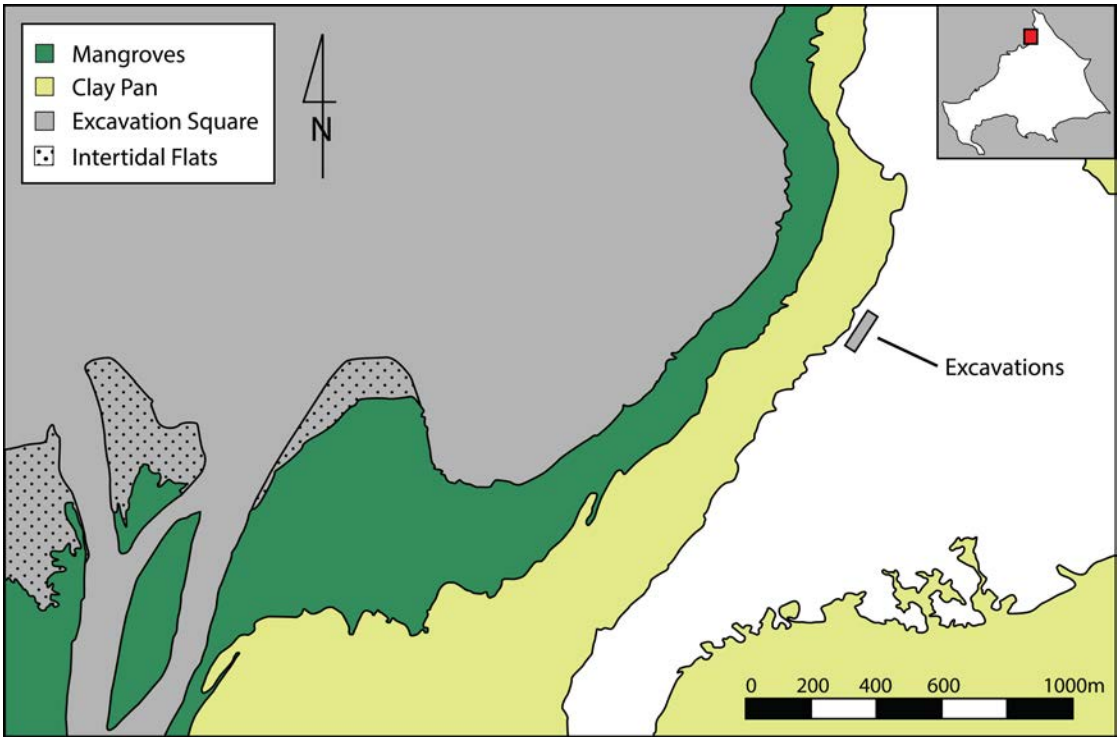

Figure 10.1 The area surrounding Thundiy consists of coastal mangrove forests (dark green), extensive clay pans (yellow), low lying savannah (white), intertidal flats (stippled), and a large estuarine system.

Archaeological deposits extend over an area c.4km long (SW – NE) and up to 150m wide (NW – SE), making Thundiy one of the largest sites of its type documented in the Australian tropical zone. A dense scatter of shell is visible across the surface of the site, denoting its extent. First recorded in 2009 during archaeological surveys across Bentinck Island, the site was initially excavated in 2010 using three 50cm x 50cm excavation squares (A, B, and C). Squares were placed at 50m intervals at the approximated centre of the site (Figure 10.2). These excavations revealed dense cultural shell deposits overlaying a natural shell-beach ridge that in turn rests upon beachrock. In 2014, two ancillary squares (D and E) were excavated to investigate geophysical features in a related study. While Square D followed procedures outlined in Chapter 5, Square E was excavated solely to examine a natural geophysical anomaly and thus a modified approach was taken. Arbitrary excavation units were discarded in favour of stratigraphic units, additionally sieving of sediments was not undertaken.

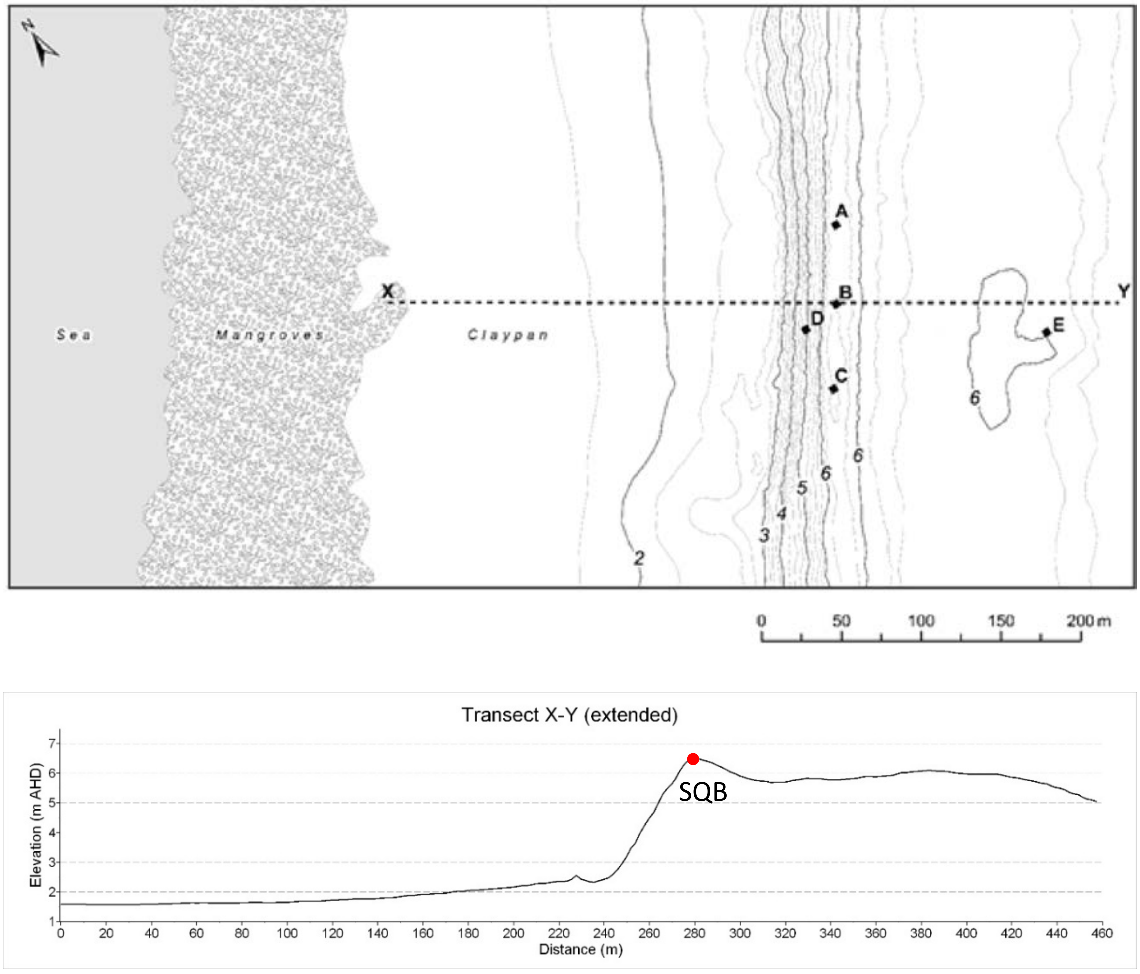

Figure 10.2 Top: Topographic map of the Thundiy area, showing excavations and elevation transect (Nagel et al. 2016: Figure 1). Bottom: Elevation transect extending through Square B (Nagel et al. 2016: Figure 1).

10.3 Cultural Deposit and Stratigraphy of Square B

This research focuses on Square B, which was excavated to a depth of c.60cm in 20 individual excavation units (XUs) averaging 3.2cm in thickness. The stratigraphic profile of Square B is characterised by a dense shell layer c.40cm deep, overlying c.20cm of natural beach ridge material at the base of the deposit (Figures 10.3 and 10.4). Stratigraphic profiles and ages available from Squares A, C, D, and E demonstrate a similar gross chronostratigraphic structure for the deposit (Table 10.1). Square B displays three major (I, II, III) stratigraphic units (SUs), with SUII further subdivided into IIa and IIb, based on difference in sediment colour and texture (Table 10.1). Roots and rootlets of various sizes were observed through much of the deposit, although were concentrated towards the surface. The archaeological assemblage is dominated by molluscan shell, especially the marine bivalve *Marcia hiantina*, although charcoal, stone (silcrete) and shell artefacts, and remains of marine vertebrate fauna (fish and turtle) were also recovered.

Figure 10.3 Top: The surface of Thundiy looking to the southwest (Photograph: Daniel Rosendahl, 2014). Bottom: Thundiy Square B final section photograph (west section) (Photograph: Sean Ulm, 2010).

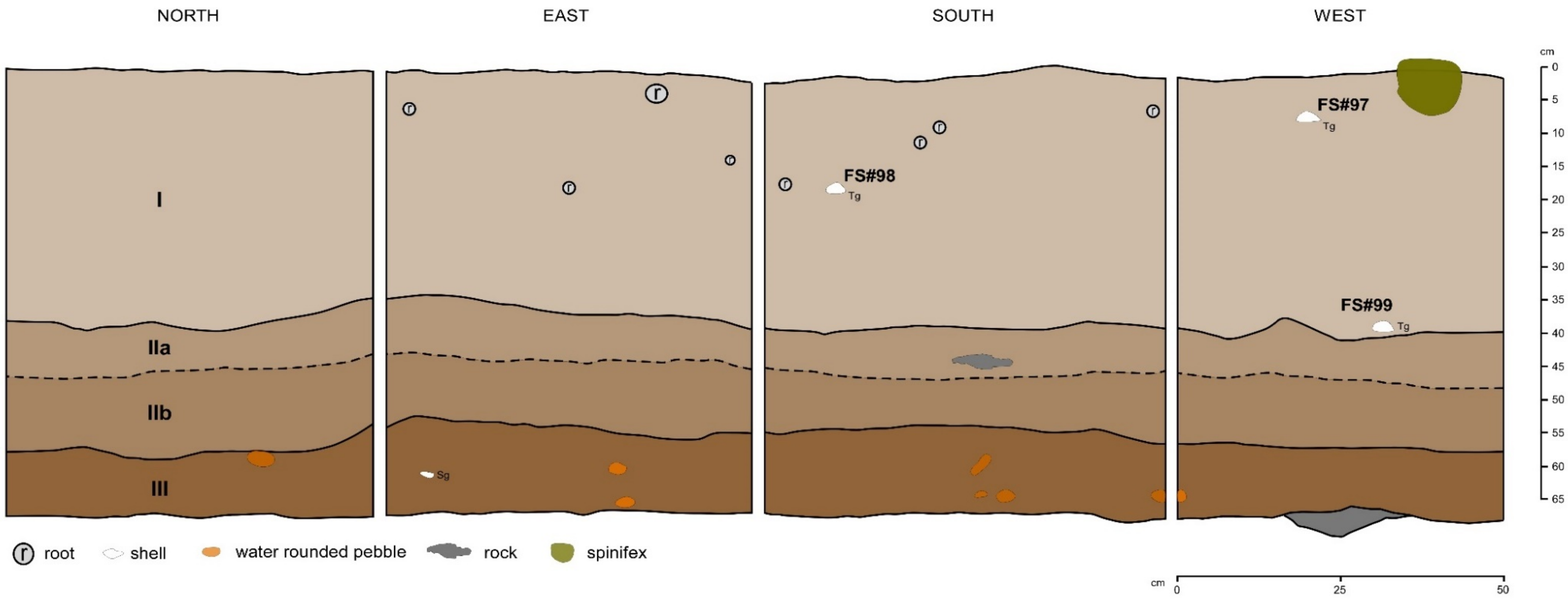

Figure 10.4 The stratigraphy of Thundiy Square B is divided into three units (I, II, and III) with SUII further divided into sub-units IIa and IIb (Section drawing: Michelle Langley and Sean Ulm, 2016).

Table 10.1 Stratigraphic unit descriptions for Square B, Thundiy (after Peck 2016).

SU	Description
I	Extends to depths below ground surface averaging 35cm. The unit is comprised of angular to subangular loosely consolidated sands with numerous spinifex grass rootlets. Sediments are dark brown (7.5YR-3/2) in colour. Some evidence of disturbance by insects present in the form of small burrows. Dense cultural matrix includes charcoal fragments, whole and fragmented *Marcia hiantina*, *Tegillarca granosa*, *Placuna placenta*, and *Saccostrea glomerata*. High alkalinity was observed with pH values of 9.5 – 10.0. Shell material appears to be reasonably well preserved.
II	SUII is a transitional unit between SUI and SUIII. As changes occur throughout the unit it has been divided into two sub-units IIa and IIb.
IIa	SUIIa, is a c.5cm thick unit of dark brown (7.5YR-3/2) humic sediments, decreased spinifex grass rootlets, and shell grit inclusions. Cultural material reduces in density with depth as large shells become scarcer while the number of small gastropods increases. Soils remain highly alkaline (pH 9.5 – 10.0).
IIb	Lower layers of the SUII transitional unit are described here as SUIIb. Sediments range from brown (7.5YR-5/3) to light brown (7.5YR-6/4) and consist of loosely consolidated coarse sands. Small (<10mm) gastropods and shell grit inclusions increase in thickness from 8cm. The unit contains water-rounded pebbles, and corals, and ironstone pisoliths. Overall this unit appears culturally sterile apart from occasional weathered shell that has filtered down the matrix through taphonomic processes. Like previous units sediments are highly alkaline (pH 9.5 – 10.0).
III	Very loosely consolidated coarse sands containing abundant shell grit, small gastropods commonly associated with natural beach ridge deposits, water-worn pebbles, and large pieces of coral. Sediments are light brown (7.5YR-6/4). The base of this unit is formed by a continuous layer of beachrock at c.60cm below surface. SUIII is culturally sterile and maintains high alkalinity (pH 9.5 – 10).

10.4 Radiocarbon Chronology

A total of 19 radiocarbon determinations have been obtained from marine shell and foraminifera across the five excavations (Table 10.2). Determinations were derived using a mix of accelerator mass spectrometry (AMS) and conventional (LCS) methods from shellfish taxa identified to species (*T. granosa*, *M. hiantina*, or *G. pectinatum*) or the *Elphidium* genus of foraminifera. Dates are reported at the 95.4% age range and corrected using the Gulf of

Carpentaria Δ*R* value of -49±102 ^{14}C years (see Nagel et al. 2016). Results from Squares A – D indicate cultural material was deposited between 104 – 793 cal BP with an abrupt chronostratigraphic disjunction to the sterile lower beach ridge dating 4717 – 5039 cal BP (Table 10.2). For the underlying beachrock, a *G. pectinatum* concreted to its surface excavated from Square D revealed a date of 5334 cal BP. The beachrock is comprised of nearshore sediments indurated by precipitation and cementation of calcium carbonate during the most recent marine transgression and highstand extending from 7000 cal BP until c.2000 years ago (Lewis et al. 2013; Reeves et al. 2008; Sloss et al. 2015). These dates suggest a >3000 year hiatus between the formation of the natural shelly-beach ridge and initiation of cultural deposition c.800 cal BP (Nagel et al. 2016). Analysis of foraminiferal abundance and dates undertaken by Nagel et al. (2016) further support the delineation between cultural and sterile units.

Work undertaken by Peck (2016) divided the Thundiy Square B assemblage into periods spanning 250 years based on analysis of the age-depth relationship of radiocarbon dates and the matrix stratigraphy, allowing excavation units to be assigned to temporal phases (Figure 10.5). This research further refines these temporal units into 100-year phases for the cultural deposit in Square B (XUs 1 – 13) (Figure 10.5). As 100-year phases provide a more nuanced view of site-use, they will be used as the core chronological framework to explore and characterise changes in the timing and periodicity of Kaiadilt occupation at Thundiy.

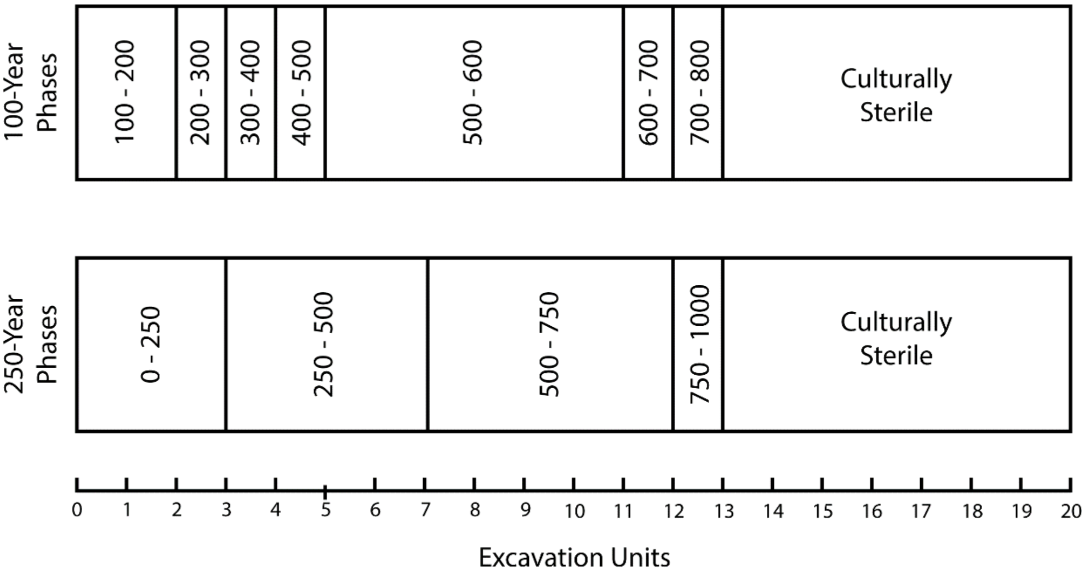

Figure 10.5 Square B XUs assigned to 250-year (bottom) and 100-year (top) temporal phase bins provide the framework for characterising changes in Kaiadilt use of Thundiy.

Table 10.2 Radiocarbon ages on marine shell from Thundiy, Squares A-D. Radiocarbon ages were calibrated using OxCal 4.2 (Bronk Ramsey 2009) and the Marine13 calibration dataset (Reimer et al. 2013), with a Δ*R* of -49±102 (Ulm et al. 2010). All calibrated ages are reported at the 95.4% age range. * = date may extend out of range (i.e. modern). # = $\delta^{13}C$ value is assumed based on the mean $\delta^{13}C$ of other measured *Marcia hiantina* samples. Greyed sections highlight Square B, which is targeted in this research. See Nagel et al. (2016) for foraminifera ages.

Square	**XU**	**Depth (cm)**	**Sample**	**Lab. No.**	**Method**	**$\delta^{13}C$ (‰)**	**CRA (BP)**	**Calibrated Age BP (95.4%)**	**Calibrated Age BP Median**
A	1	0-2.7	*Tegillarca granosa*	Wk-32135	Conventional	-1.6±0.2	428±36	0*-301	132
A	1	0-2.7	*Marcia hiantina*	OZP-186	AMS	-2.7±0.1	430±35	0*-302	133
A	6	14.5-18.0	*Tegillarca granosa*	Wk-32136	Conventional	-1.8±0.2	611±34	0*-490	298
B	1	0-2.5	*Marcia hiantina*	OZP-197	AMS	-3.3±0.1	370±30	0*-258	104
B	6	15.4-18.6	*Marcia hiantina*	Wk-34772	AMS	0±0.2	851±25	309-661	510
B	11	30.3-33.4	*Tegillarca granosa*	Wk-28560	AMS	-1.6±0.2	868±30	313-674	525
B	13	36.7-39.4	*Marcia hiantina*	Wk-37498	AMS	-2±0.2	1192±22	611-1006	793
B	20	57.5-60.4	*Marcia hiantina*	Wk-36175	AMS	1±0.2	4716±28	4795-5305	5039
C	1	0-2.7	*Marcia hiantina*	OZP-187	AMS	-1.6±0#	435±30	0*-304	135
C	11	31.4	*Tegillarca granosa*	Wk-28561	AMS	-1.3±0.2	1139±30	549-934	747
C	15	41.7-44.7	*Marcia hiantina*	Wk-36176	AMS	0.3±0.2	4484±29	4421-4985	4717
C	20	56.5-59.6	*Gafrarium pectinatum*	Wk-36177	AMS	2±0.2	4682±28	4724-5292	4997
D	13	35	*Gafrarium pectinatum*	Wk-40103	AMS	NA	4942±21	5036-5571	5334

While the radiocarbon assemblage suggests Aboriginal populations occupied Thundiy over a period of approximately 800 years, it is difficult to assess the timing and periodicity of use solely from radiocarbon data. Given the highly seasonal nature of ethnographic occupation and site-use throughout the broader region (see Chapters 1 and 3) it is posited Kaiadilt occupation of Thundiy saw similar patterning. Numerous cultural, environmental, and climatic variables likely impacted trajectories associated with how, when, and why people were occupying the area to form a complex history of site-use. Thus, it is imperative that a higher-resolution chronology be established to assist with accurate interpretation.

10.5 Square B Analysis

Stable isotope analysis was undertaken on archaeological shell material from XUs associated with cultural activity (XU1 – 13). Archaeological specimens were tested for recrystallisation prior to further carbonate collection. Subsequently, aragonitic carbonate samples were analysed using mass spectrometry (see Chapter 5 for procedures). Isotopic values are compared to modelled seasonal ranges (see Chapter 6) and modern analogues (see Chapter 9) to reach seasonal determinations. These determinations are combined with radiocarbon dates to produce a high-resolution chronology of the timing and periodicity of human activity at Thundiy.

10.5.1 Specimen Selection

The sampling regime detailed in Chapter 5 was employed to select 5% of total MNI counts from each XU for analysis. Between 1 and 11 *M. hiantina* specimens (mean = 6.69) were selected per XU and prepared for analysis (Figure 10.6). See Appendix G for a detailed overview of selected specimens.

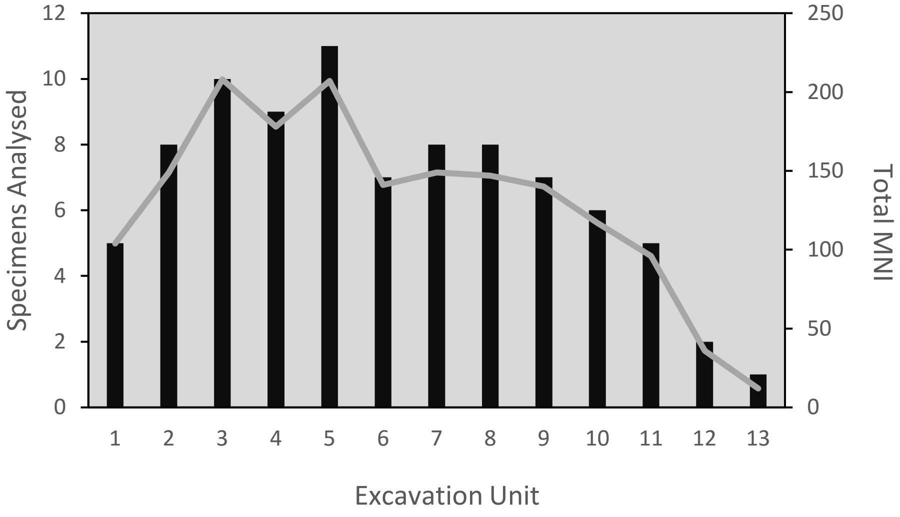

Figure 10.6 The number of *Marcia hiantina* specimens analysed (black bars) were selected at a rate of 5% of total MNI count (grey line) per XU. Minor variabilities exist owing to the availability of suitable specimens.

10.5.2 Testing for Recrystallisation

Archaeological specimens were tested for recrystallisation using FTIR (see Chapter 5 for procedures). All material from *M. hiantina* assemblages returned wavelength plots indicative of aragonite, indicating no instances of pre- or post-depositional recrystallisation were present. Consequently, no archaeological specimens were disqualified from stable isotope analysis.

10.5.3 Stable Isotopes

Overall $\delta^{18}O_{shell}$ values ranged between -5.1‰ and +0.3‰ with a mean of -1.7‰ (1σ = ±1.0‰). A majority of these data (80%; *n* = 69) are tightly grouped within 1σ of the overall mean, with 91% (*n* = 78) within 2σ. Only 8 data points (9%) remain outside the 2σ range. In this context, clustering of relatively positive values indicates analysed *M. hiantina* were consistently collected during cool marine conditions (Figure 10.7). Comparisons between seasonal $\delta^{18}O_{shell\text{-}predicted}$ ranges generated for subtidal environments (see Chapter 6), modern live-collected specimens (see Chapter 9), and archaeological shell values indicate close correlations between dry season values and archaeological edge margins (Figure 10.7). Only three specimens from XUs 3, 8, and 12 fall within the upper extremities of predicted wet season range. Moreover, four specimens from XUs 2, 3, 5, and 12 returned values between wet and dry season predicted ranges potentially indicating occupation during transitionary months outlined in Chapter 6 (April and/or September/October).

Similar levels of hydrological consistency are evidenced by $\delta^{13}C_{shell}$, with values ranging between -6.4‰ and +0.4‰ (mean = -2.9‰; 1σ = ±1.5‰). A majority of data points fall within 1σ of the mean (*n* = 56; 66%), with 95% (*n* = 81) within 2σ. According to Petchey et al. (2012, 2013) molluscs associated with marine reservoirs return $\delta^{13}C_{shell}$ values of approximately -4.0‰ or above, thus a substantive component of the assemblage was minimally influenced by terrestrial carbon (Figure 10.7). Broader fluctuations are likely linked with tidal forces drawing carbon from terrestrial sources surrounding the Thundiy coastline, such as fringing mangroves or the Makarrki River to the south, coupled with associated shifts in water productivity much like in the inter- and subtidal zones adjacent to Mirdidingki Creek (see Chapter 6).

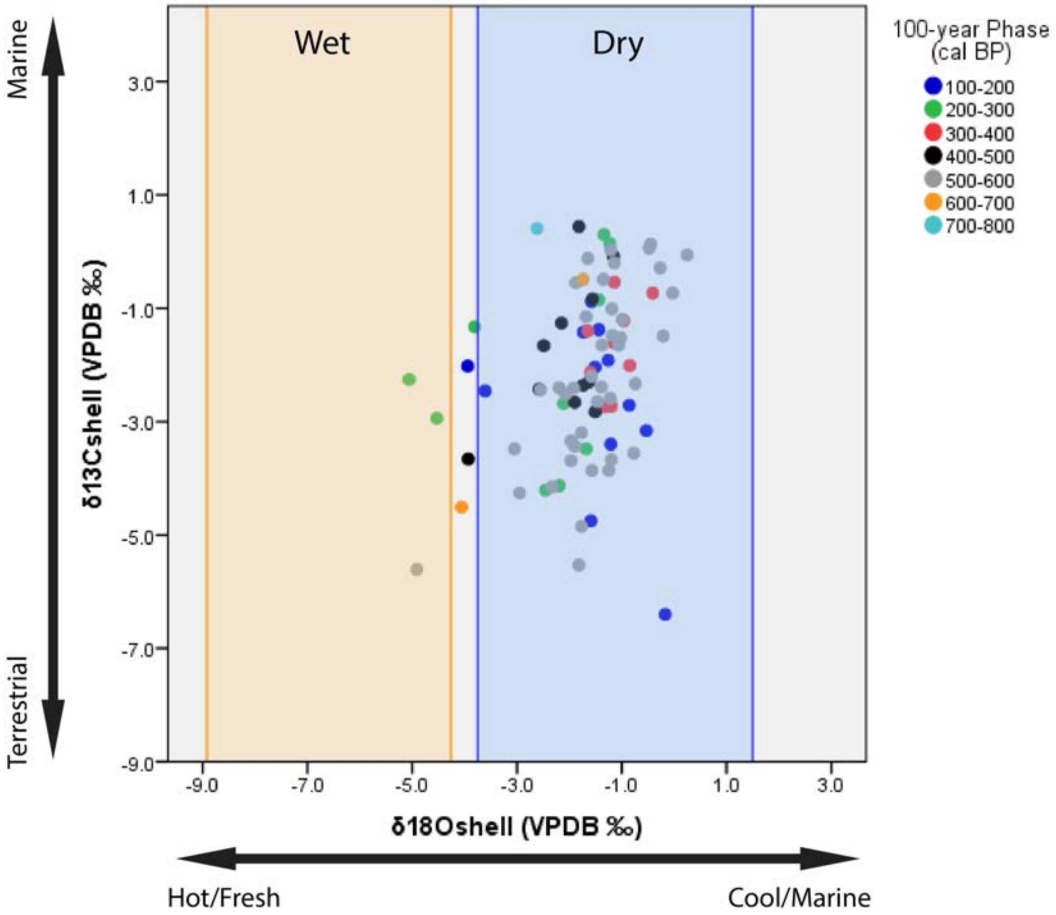

Figure 10.7 A majority of stable isotope values derived from archaeological *M. hiantina* at Thundiy are indicative of collection during cool marine conditions. Moreover, they fall within the dry season range for subtidal species (blue shaded area). A handful of values are indicative of wet season conditions (oranged shaded area) or a seasonal determination could not be reached, suggesting collection during transionary periods.

Comparing individual XUs reveals variability over the course of Kaiadilt occupation at Thundiy (Figure 10.8). Results of a One-Way ANOVA indicate the presence of statistical dissimilarities in $\delta^{18}O_{shell}$ values (*F*(12) = 2.034, *p* = .033), however a Tukey HSD post-hoc test reveals variability is primarily attributable to XU3 as it returned weak (although statistically congruous) links with a number of other XUs (e.g. *p* = 0.060 for XUs 3 and 7; *p* = 0.070 for XUs 3 and 4) owing to a high amplitude (3.8‰) and comparatively negative mean (-2.6‰). While XUs 2, 5, and 8 also display high amplitudes (3.1‰, 2.8‰, and 4.5‰, respectively), more positive means facilitate a closer association with remaining XUs. Relationships shared by remaining XUs vary in statistical strength, ranging between *p* = 0.415 (XUs 3 and 11) and *p* = 1.000 (e.g. XUs 1 and 4 among others). XU 13 is excluded from Tukey HSD post-hoc tests as it encompasses less than two values.

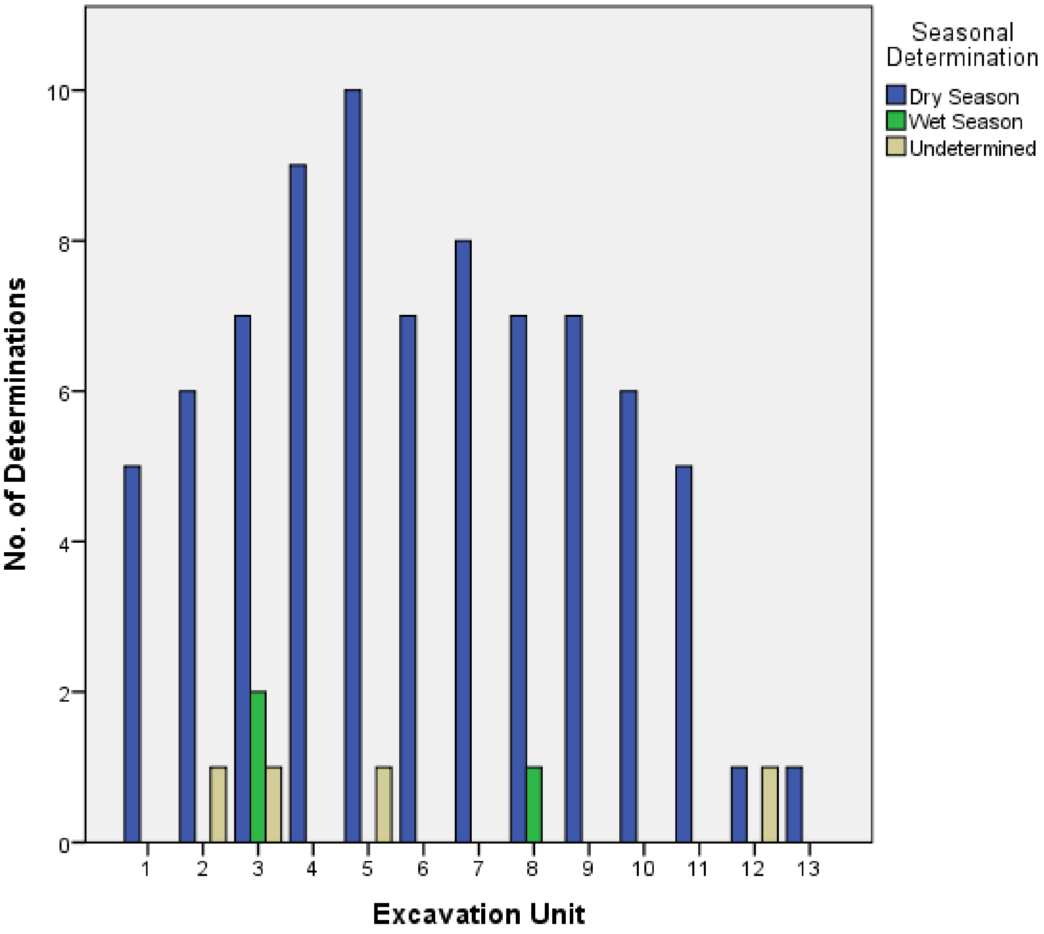

Figure 10.8 Number of seasonal determinations per excavation unit.

When $\delta^{13}C_{shell}$ values are compared between XUs using a One-Way ANOVA test statistical similarities are evident (*F*(12) = 1.252, *p* = .266). Results of a Tukey HSD post-hoc test demonstrate strong connections between all XUs (*p* >= .932) except XU1, which returned relationships varying between *p* = .308 (XUs 1 and 4) and *p* = .995 (XUs 1 and 12) owing to a comparatively high amplitude (5.0‰) and negative mean (-3.8‰). The widespread homogeneity of $\delta^{13}C_{shell}$ values throughout the Thundiy deposition suggests *M. hiantina* collection was focused around periods of relatively stable marine hydrology. XU13 is again excluded from Tukey HSD post-hoc tests as it encompasses less than 2 values.

Applying stable oxygen and carbon values to the 100-year temporal phases outlined above allows short-term occupation patterns associated with Thundiy to be couched within a secure temporal framework (Table 10.3). While a One-Way ANOVA test suggests a lack of significant similarities between phases for $\delta^{18}O_{shell}$ (*F*(6) = 3.121, *p* = .009), applying a Tukey HSD post-hoc test reveals numerous statistical similarities between individual phases. Exceptions to this are found in comparisons between 200 – 300 cal BP and 300 – 400 cal BP (*p* = .020) as well as 200 – 300 cal BP and 500 – 600 cal BP (*p* = .023). A significant relationship is revealed by an ANOVA run for $\delta^{13}C_{shell}$ values (*F*(6) = 1.046, *p* = .403). This is confirmed by a Tukey HSD post-hoc test, which found significant similarities between all phases. Phases spanning 0 – 100 cal BP and 700 – 800 cal BP were excluded from Tukey HSD post-hoc tests as they contained less than 2 values. A detailed discussion of the implications of these findings for Kaiadilt occupation of Thundiy and the surrounding area is presented in Section 10.6.

Table 10.3 Total number of specimens analysed per 100-year temporal phase.

Temporal Phase (cal BP)	0 – 100	100 – 200	200 – 300	300 – 400	400 – 500	500 – 600	600 – 700	700 – 800
Specimens	0	12	10	9	11	41	2	1

10.6 Timing and Periodicity of Occupation at Thundiy

10.6.1 Cycles of Occupation and Abandonment

The timing and periodicity of Kaiadilt occupation at Thundiy is closely linked with seasonal changes in climate and environment, with stable isotope analysis revealing a strong focus on dry season use. While it could be argued that this pattern is indicative of wet season cessations in *M. hiantina* exploitation, a combination of environmental, climatic, cultural, and ethnographic factors point towards a seasonally timed cycle of occupation and abandonment.

Periods of site-use associated with Thundiy are connected with favourable environmental and climatic conditions, resource availability, and landscape access. Thundiy is positioned on the leeward side of Bentinck Island during the dry season, protecting the area from strong southeasterly winds and rough seas. This provides favourable occupation conditions and facilitates access to a variety of intertidal and subtidal resources in the surrounding area, including marine, estuarine, and mangrove molluscs, fish, large aquatic vertebrates (e.g. dugong and turtle), as well as terrestrial resources (see Peck 2016). Ethnographies associated with Aboriginal groups living in similar contexts along Australia's tropical north coast highlight heightened mobility as a key dry season behaviour (e.g. Davies 1985; Meehan 1982; Memmott 2010:20-21). While there is currently no direct evidence of similar patterns associated with the Kaiadilt, the open low-lying landscape typifying the surrounding region expedites movement. Peck (2016) posits Thundiy was utilised as a central-place camp, suggesting it may have acted as a locus for resource gathering. This suggests dry season occupation at Thundiy does not preclude contemporaneous use of other sites, with the surrounding region seeing regular use, visitation, or occupation. For example, the northern tip of the island contains permanent freshwater sources, which were likely frequently utilised by the Kaiadilt during dry season conditions (Sean Ulm, pers. comm., 2016; personal observation, July 2013, 2014).

Changes in environment and climate associated with the Australian monsoonal cycle signal the onset of wet season conditions and the temporary abandonment of Thundiy. Strong northeasterly winds blow directly onto the now windward coastline adjacent to Thundiy, where the low largely bare ridgeline and sparsely forested surrounds offer little relief. Storms, cyclonic activity, and monsoonal rainfall accompany wet season winds, leading to inclement ocean conditions and restricted access to coastal resources. Instances of Aboriginal groups abandoning windward coastlines during inclement conditions are present throughout numerous ethnographies (Meehan 1977, 1982; Memmott 2010:21), suggesting similar strategies may be enacted by Kaiadilt populations. Moreover, the flooding of low-lying areas surrounding Thundiy largely isolate the site for the duration of the wet season, making abandonment a time-sensitive activity. Estimates for the timing of abandonment can be reached via a combination of stable oxygen isotope results and environmental data. As a majority of $\delta^{18}O_{shell}$ values are indicative of cool marine conditions, temperature and rainfall increases typifying the transitionary period of September/October were likely a key trigger signalling abandonment. Likewise, Thundiy likely saw reoccupation subsequent to the onset of dry season conditions, when rainfall, flooding, and temperatures subside.

10.6.2 Patterns through Time

The timing and periodicity of occupation at Thundiy remains relatively consistent throughout its use, displaying only minor fluctuations. Detailed analysis of the archaeological assemblage undertaken by Peck (2016) reveals shifts in material density that can assist in characterising site-use over 250-year temporal phases. Further, pollen and charcoal analysis by Moss et al. (2014) allow patterns of human occupation to be contextualised against palaeoenvironmental change. When these findings are reconfigured to adhere to 100-year phases a number of changing behavioural patterns are revealed.

Radiocarbon determinations suggest the earliest human presence at Thundiy occurred c.793 cal BP. Analysis undertaken by Peck (2016) suggests a period of ephemeral occupation between 750 – 1000 cal BP, owing to a sparse cultural assemblage that consists of only 10% of total taxa numbers based on MNI. When this is considered in the context of 100-year phases it appears that ephemeral use may have continued for an additional c.150 years, extending from initial occupation until c.600 cal BP (Figure 10.9). Three seasonal determinations were obtained during this period, two dry seasons and one undetermined. While seasonality determinations suggest primarily dry season use, understandings of seasonally timed occupation during this initial period are limited by the small assemblage size.

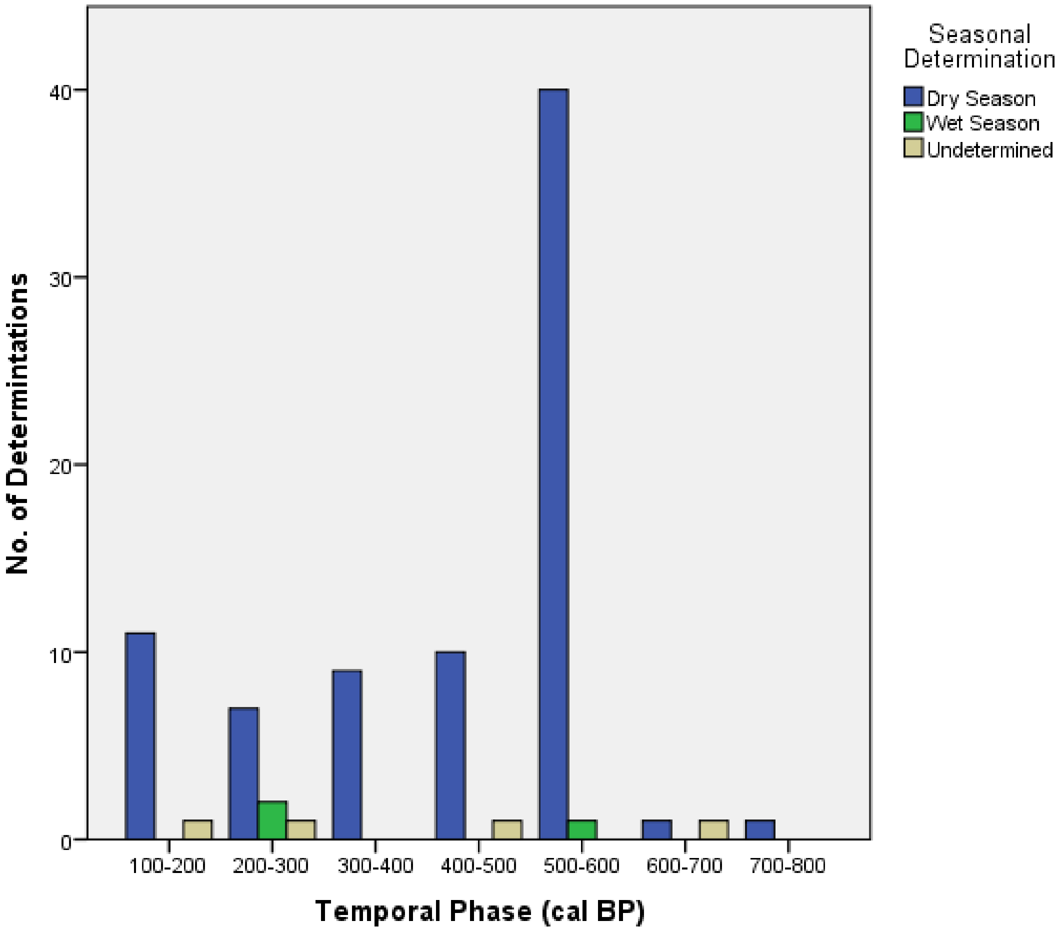

Figure 10.9 Seasonal determinations for Thundiy delineated into 100-year temporal phases.

Peck (2016) identifies a substantial increase in the density of material occurring through 250 – 750 cal BP, potentially reflecting a period of intense use and occupation. Deposition rates were exceptionally high between 500 – 600 cal BP, agreeing with the notion of intense occupation. Palynological analysis reveals this temporal phase coincides with an open coastal phase at Thundiy, evidenced by increased quantities of chenopods and Convolvulaceae (Moss et al. 2014). The timing of occupation during this period is largely focused on the dry season, with only one specimen returning a wet season determination (Figure 10.10). The single wet season determination indicates that site-use at Thundiy may have infrequently extended beyond its regular pattern of dry season occupation and wet season abandonment. Given the apparent intensity of use during this period, foragers may have found it necessary to intermittently continue exploiting resources at Thundiy for longer periods of time to adequately provision the population.

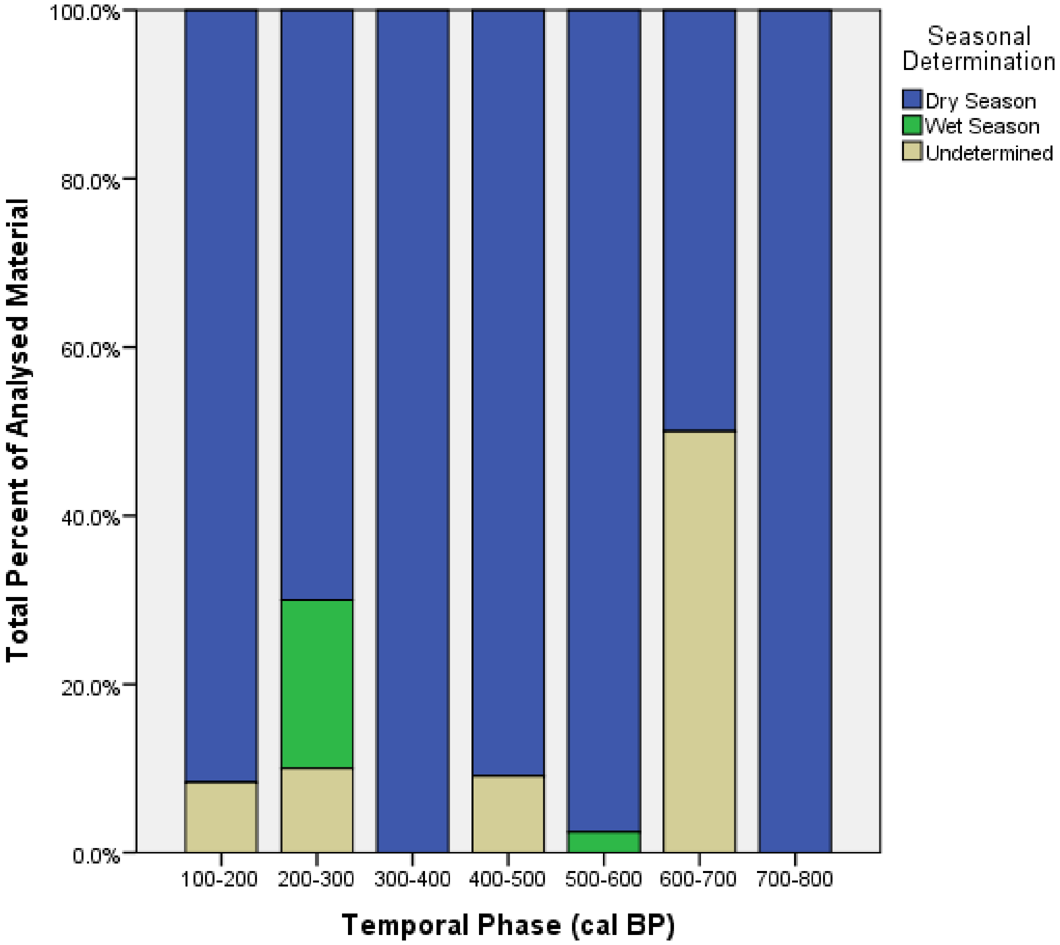

Figure 10.10 Total percent of seasonal determinations per 100-year temporal phase. Note that quantity of analysed material differs per phase. See Table 10.3 for specimens per phase.

The timing of occupation at Thundiy remained firmly focused on the dry season during the period between 300 – 500 cal BP (Figures 10.9 and 10.10). However, deposition rates and material density declined sharply between 400 – 500 cal BP before stabilising by 300 – 400 cal BP. This is accompanied by a substantial reduction in charcoal inclusions, which returned to earlier levels (Moss et al. 2014). The combination of reduced charcoal and deposition rates suggest a period of behavioural change, including reduced site-use and modified burning regimes. Reasons for this apparent decline in activity at Thundiy are currently unclear, however it is likely linked with a broader environmental change evidenced locally and across Bentinck Island. Just prior to this period (510±25 cal BP) a major vegetation change is evident, with grass and arboreal taxa becoming dominant and mangrove species declining (Moss et al. 2014). Peck (2016) posits that this was a driver for a concurrent shift in exploitation focus away from mangrove shellfish towards taxa inhabiting sandy-mud and rocky substrates. Further contemporaneous changes are evidenced by a peak in charcoal abundance at Thundiy (Moss et al. 2014) and the establishment of mangrove communities at Marralda Swamp, on the south coast of Bentinck Island (Moss et al. 2015). When considered in unison, these findings allude to a broader pattern of environmental change, commencing c.500 cal BP, which likely contributed to the modification of established behaviours evidenced at Thundiy.

The most substantial shifts in occupation at Thundiy appear within the last 300 years. Most striking are changes to the, until now, relatively stable timing of use. Seasonal determinations from for 200 – 300 cal BP indicate movement towards more frequent use during conditions indicative of transitionary months and the early/late wet season (Figure 10.10). While not as prevalent, a similar pattern is revealed between 100 – 200 cal BP. Moreover, changes in subsistence are evident with a decreased reliance on shellfish taxa from mangroves, mudflats, and rocky reefs (Peck 2016). Further declines in charcoal inclusions may also indicate a shift in fire regimes (Moss et al. 2014).

The modification of these long-standing behaviour patterns correspond broadly to periods of contact with both Macassan and European parties (see Memmott 1982b; Oertle et al. 2014; Tindale 1962a). The Macassan site at Kalinda is located c.2km northeast of Thundiy along the Kalint River (Oertle et al. 2014), giving a degree of plausibility to the notion that changes to occupation patterns at Thundiy were a Kaiadilt response to the presence of Macassans. While excavations at Kalinda yielded no datable material, making its temporal association with Thundiy difficult to discern, dates from the western Gulf of Carpentaria indicate the most intensive phase of Macassan contact occurred from the 1780s when trepanging operations were at their peak (Macknight 1972, 1986, 2008, 2013; Oertle et al. 2014; Wesley et al. in press). Moreover, oral histories suggest the well at Oak Tree Point (northern tip of Bentinck Island) was '…dug long ago by people from a three-masted ship, no engine, which one tied up in the river estuary' (Tindale 1963:180), a description matching Macassan praus (see Macknight 1972; Wesley et al. in press). There is little direct evidence of Kaiadilt-European contact on north Bentinck Island, although a brief interaction somewhere near the islands northern extremity is described by Landsborough (Laurie 1866; see also Memmott 1982b). Despite the scarcity of direct links between Macassan or European contact and Kaiadilt behaviour, the potential impact of these external forces should not be discounted owing to influences demonstrated in similar contexts (Macknight 1972, 1986). Moreover, disruptions to traditional lifeways from the settlement of Carnarvon in the 1860s (Laurie 1866), increased presence of European ships in the early 20th century (Tindale 1962a), and violent clashes with pastoralists around the turn of the 19th century (Kelly and Evans 1985; Stubbs 2005; Tindale 1962a, 1962b) cannot be ignored.

The evidence presented above suggests the Kaiadilt occupation of Thundiy fluctuated between periods of stability and substantial change. To this end four phases of occupation are suggested for Thundiy (Table 10.4). The ephemeral phase encompasses initial occupation (c.800 cal BP) until c.600 cal BP and is typified by a sparse assemblage, low rate of material deposition, focused exploitation of mangrove shellfish, and largely dry season use. A phase of intense seasonal use followed (500 – 600 cal BP) with rapid deposition of a dense archaeological assemblage, shift in focus away from mangrove shellfish gathering, and dry season occupation with occasional wet season use. The interface between this and the next phase (c.500 cal BP) saw substantial environmental shifts, which likely played a key role in the behavioural change to come. Following this period of change Thundiy saw a sharp decrease in use before stabilising (c.300 – 500 cal BP) into moderate dry season occupation. Finally, the most recent phase extends 0 – 300 cal BP. Substantial changes in the timing of occupation, subsistence, and contact with European and Macassan parties typify this era. Thus, Kaiadilt use and occupation of Thundiy was variable and multidirectional, punctuated by periods of behavioural and environmental stability as well as intense change. The broader implications of this chronology are discussed in Chapter 13.

Table 10.4 Four phases of occupation can be identified in Thundiy Square B – after Kelly and Evans 1985; Laurie 1866; Macknight 1972, 1986; Moss et al. 2012, 2014; Oertle et al. 2014; Peck 2016; Stubbs 2005; Tindale 1962b.

Occupation Phase (cal BP)	**Assemblage Density**	**Seasonality**	**Local Landscape and Palynology**	**Shellfish Exploitation**	**Other Factors**
Ephemeral 600 – 800	Sparse	Majority dry season with occasional undetermined	NA	Focused on mangrove species	Initial occupation
Intense Seasonal 500 – 600	Sharp increase, dense	Majority dry season with occasional wet season	Open coastal	Decrease in mangrove species, sharp increase in sandy-mud taxa	NA
Environmental Shift c.500	NA	NA	Sharp charcoal spike, increase in grasses and arboreal taxa	NA	Contemporary changes in Marralda Swamp
Moderate Seasonal 300 – 500	Sharp decrease before stabilising	Majority dry season with occasional undetermined	Decline in charcoal and mangrove species	Steady exploitation of sandy-mud species, increase in rocky taxa	NA
Variable 0 – 300	Stable	Primarily dry season with some wet season and undetermined	Decline in charcoal and arboreal taxa, increase in grasses	Moderate increase in sandy-mud taxa, decrease in rocky species	Period of Macassan visitation and European contact

10.6.3 Mobile Landscape Use

The periodic abandonment of Thundiy proffers an obvious, although important, question – where were inhabitants of Thundiy relocating to during wet season conditions? Approaching a satisfying answer requires aspects of Kaiadilt culture and demography to be considered. As discussed in Chapter 3, Tindale (1962a, 1962b, 1963, 1977) posits the Kaiadilt population was divided into eight family groups or *dolnoro*, each of which held rights over separate estates of land and resources. Thundiy is located in *dolnoro* S, which encompasses the entirety of Bentinck Island's northern peninsula (Figure 10.11). Strict rules governed rights of access between family groups (Evans 1995), suggesting Kaiadilt occupying Thundiy would remain within the boundaries of *dolnoro* S subsequent to wet season abandonment.

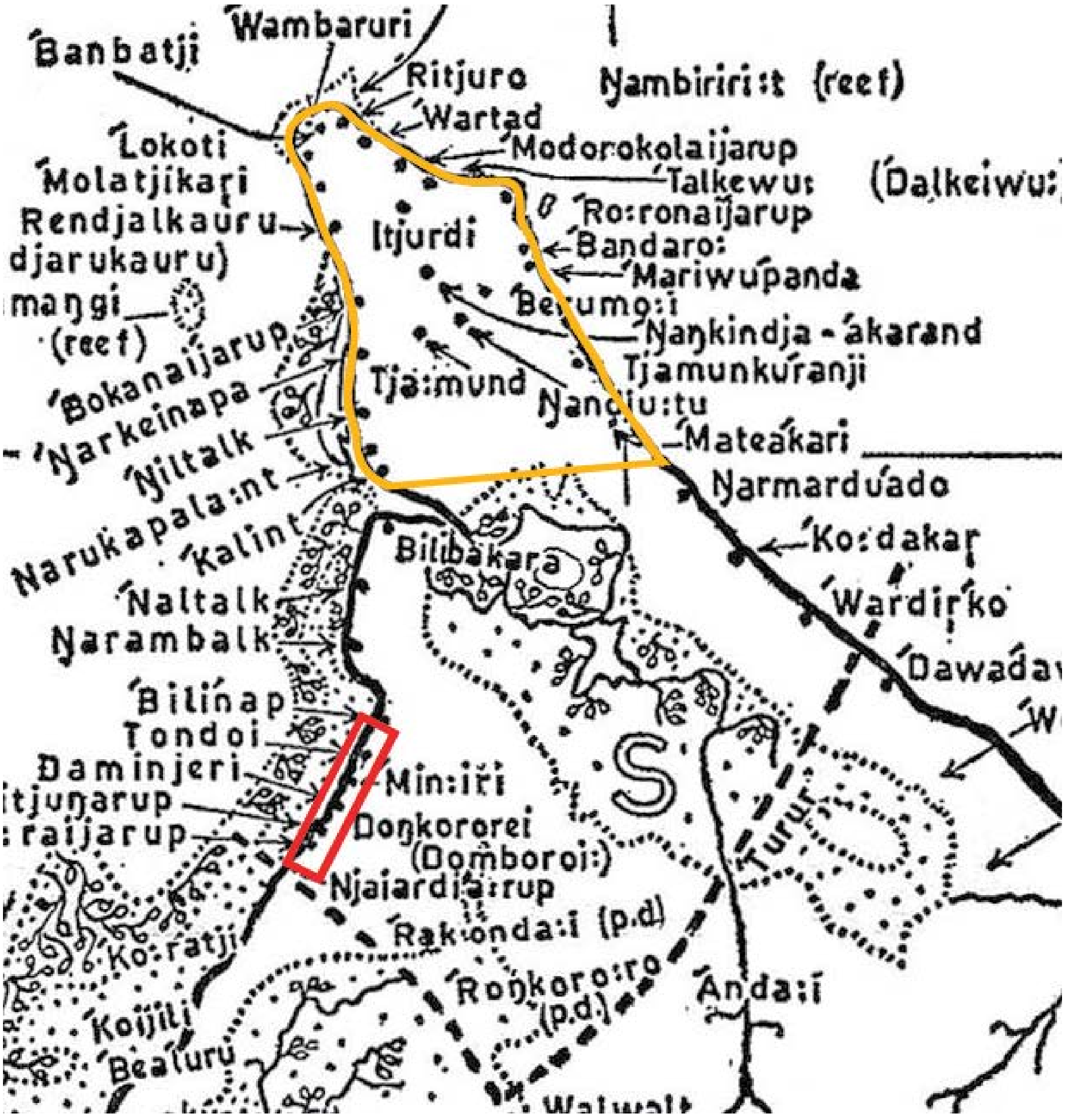

Figure 10.11 Bentinck Island is divided into eight family estates, or *dolnoro*. Thundiy (spelt here as Tondoi and highlighted in red) and the area known as Rukathi (labelled by Tindale with a variety of placenames and highlighted here in yellow) are located in *dolnoro* S (modified from Tindale 1962).

As many fundamental aspects of Kaiadilt culture and identity are closely linked with seascapes (Memmott and Trigger 1998; Tindale 1977; discussed in Chapter 3), there exists a high likelihood that people abandoning Thundiy would relocate to a similar coastal context for the duration of the wet season. The coastal area known as Rukathi, located on the north coast of Bentinck Island (Figure 10.11), displays a range of characteristics that make it ideal for wet season occupation. The landscape is dominated by high dune systems, pandanus trees, rocky intertidal platforms, and open grasslands (Figure 10.12). Dunes offer shelter from winds and other forms of inclement weather originating from any direction. The rocky intertidal zone facilitates the construction of rock walled fish traps, another important component of Kaiadilt culture (Memmott et al. 2006; Rowland and Ulm 2011; discussed in Chapter 3). A majority of fish traps associated with Rukathi are located in the wet season lee of the island, sheltering them from the worst winds and allowing their continued use (Tindale 1962a). Moreover, the surrounding landscape contains numerous easily exploitable resource zones, including the Kalint River and surrounding mangrove stands, intertidal and subtidal zones, open sclerophyll savannah, freshwater swamps, and clay pan systems. It should be noted occupation at Rukathi may not have been exclusively timed with the wet season. Mobile groups potentially exploited this area in conjunction with Thundiy and other sites during the dry season, with the abandonment of Thundiy serving to periodically increase the intensity of use. However, further research into the timing and periodicity of use at Rukathi is required to meaningfully approach this question.

Figure 10.12 The landscape of Rukathi is dominated by large coastal dune systems (Photograph: Sarah Slater, 2014).

Aboriginal use of Rukathi is evidenced by numerous surface scatters of various shellfish taxa and stone artefacts. The earliest radiocarbon determination associated with cultural material suggests occupation commencing from c.1318 cal BP, however there are few subsequent dates until 102 – c.290 cal BP. While there is the potential for this to be interpreted as a long break in occupation, the nature of the landscape provides an alternative explanation. Highly mobile sand dune systems typifying the area have caused substantial deflation of archaeological deposits (Figure 10.13), compromising the security of temporal and stratigraphic contexts as well as the validity of undertaking excavations. The current chronology is therefore restricted to material collected from surface scatters, thus leaving the extent of Aboriginal activity at Rukathi largely unknown as potentially older deposited material cannot be incorporated without introducing avoidable inaccuracies. It is therefore necessary to make assumptions regarding the timing and periodicity of occupation at Rukathi, although the strong contemporary Kaiadilt attachment to the area, presence of multiple rock walled fish traps, a native well, large silcrete source, and evidence of use extending across much of the area strongly suggests that Rukathi was repeatedly occupied over an extended period of time. While the evidentiary basis for these conclusions is clearly lacking in detail, future research could assist in evaluating their validity.

Figure 10.13 A majority of archaeological deposits around Rukathi have undergone severe deflation owing to highly mobile dune systems (Photograph: Sarah Slater, 2014).

10.7 Summary

Stable isotopic analysis of archaeological *M. hiantina* from the shell matrix site of Thundiy revealed highly seasonal occupation extending throughout the archaeological record. Stable oxygen values indicate a majority of analysed shellfish were collected in conjunction with cool marine conditions indicative of the dry season. A cycle of seasonal occupation and abandonment linked with environment and climatic factors was suggested, with the onset of wet season conditions signalling a relocation of Kaiadilt to Rukathi on the east coast for its duration. Site-use at Thundiy can be divided into four distinct phases delineated by multidirectional shifts in occupation intensity, burning regimes, exploitation strategies, landscape changes, and contact with European and Macassan parties. This high-resolution chronology provides important insight into Kaiadilt seasonality and how relationships between Aboriginal populations and island environments developed through time.

Chapter 11 Dangkankuruwuru

11.1 Introduction

Excavations at Dangkankuruwuru, a shell matrix site on the southwest coast of Bentinck Island, reveal a substantial cultural deposit dominated by marine bivalve remains. A high-resolution chronology of the timing, periodicity, and seasonality of site-use is established via stable isotopic analysis of archaeological mollusc shell. This chapter describes the site and its stratigraphy as well as oxygen and carbon stable isotope values derived from archaeological shell carbonates. The implications of these findings for Kaiadilt occupation and resource-use at Dangkankuruwuru are considered.

11.2 Site Description and Setting

Located on the southwest coast of Bentinck Island, the shell matrix site of Dangkankuruwuru (also Dankonarupai) is situated on the crest of a steep ridge c.700m northwest of the present-day coast (Figure 11.1). Elevations taken along the ridge indicate the site rests c.10m above the Australian Height Datum (AHD). The western edge of Dangkankuruwuru abuts an extensive low-lying clay pan. The landscape to the north contains a dense, although relatively thin, mangrove forest lining the banks of a small unnamed creek extending to the southeast coastline. The coastline southeast of Dangkankuruwuru is a north-south orientated tidal flat bordered by a coastal mangrove fringe, both of which stretch from the small creek in the north to Kirk Point on the southern tip of the island. Mangrove forests are dominated by *Rhizophora stylosa* (red stilt-root mangrove), *Ceriops togal* (yellow mangrove), *Bruguiera* spp. (orange mangrove), and *Avicennia marina* (grey mangrove). Vegetation surrounding the site itself is principally savannah, consisting of eucalypts on the south and west of the ridge, pandanus, grevillea, and acacia trees.

Archaeological deposits extend over an area c.150m long (NNE – SSW) and up to c.20m wide (NW – SE) (Figures 11.2, 11.3, and 11.4). A moderately dense shell scatter dominated by *M. hiantina*, *S. glomerata*, and *Glauconome virens* (*G. pectinatum*, *T. granosa*, *Volema cochlidium, T. telescopium*, and nerites are also present) is visible across the surface of the site with occasional high density patches. Some deflation is evident with winnowing of sand around some shells in combination with pedestalling of some valves. Dangkankuruwuru was recorded and subsequently excavated in 2013 as part of an extensive archaeological survey of the surrounding region. Initially, excavations were undertaken using two 50cm x 50cm excavation squares (A and B) placed c.12m apart where surface material displayed minimal deflation. Excavations around Square A were later expanded to incorporate three additional 50cm x 50cm squares (B1, C, and

D) to allow access to cultural deposits below a depth of 70cm. These excavations continued until a depth of c.105cm. No unambiguous cultural material was recovered below 67cm. Square B was excavated to a depth of c.72cm. All excavations followed procedures outlined in Chapter 5.

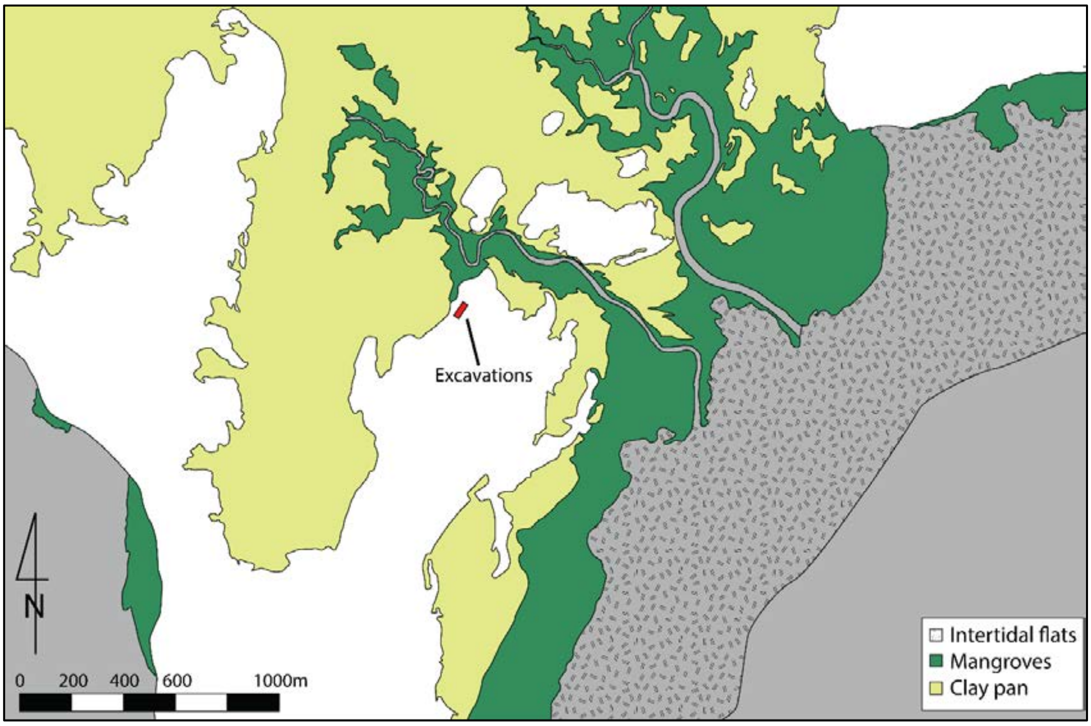

Figure 11.1 The area surrounding Dangkankuruwuru consists of expansive clay pans, mangrove forests, estuarine systems, intertidal flats, and low-lying savannah.

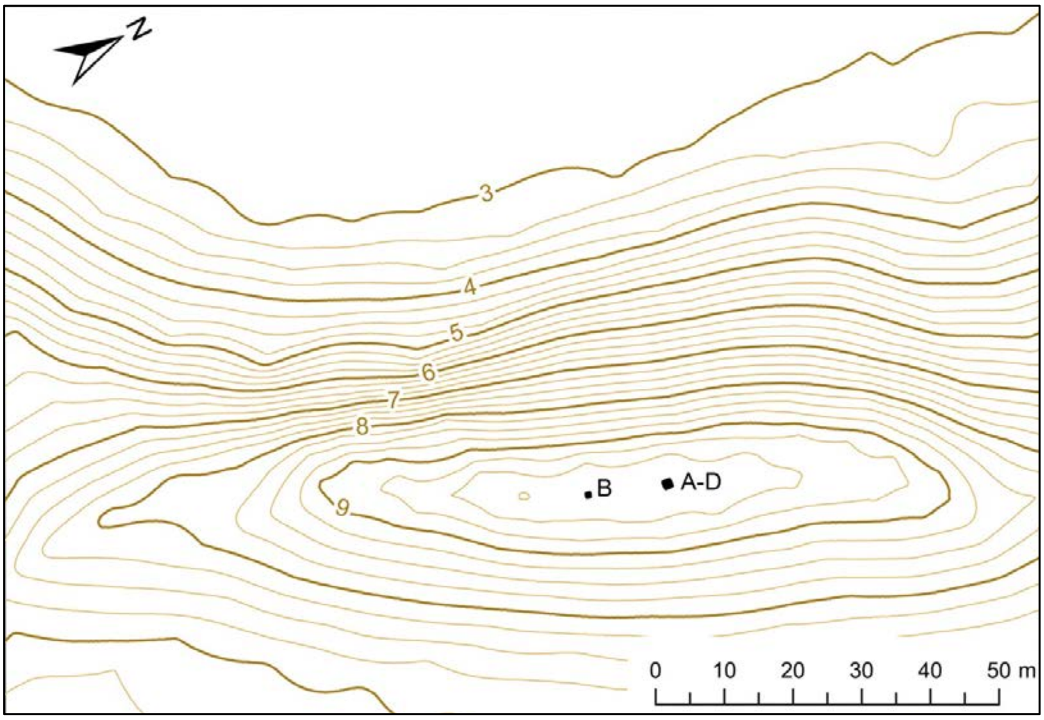

Figure 11.2 Topographic map of Dangkankuruwuru showing the positioning of excavations (Map: Lincoln Steinberger and Sean Ulm, 2013).

Figure 11.3 The ridgeline Dangkankuruwuru is located on facing to the west (Photograph: Helene Peck, 2013).

Figure 11.4 The 1 x 1m excavation undertaken at Dangkankuruwuru (Squares A – D) (Photograph: Sean Ulm, 2013).

11.3 Cultural Deposit and Stratigraphy of Squares A, B1, C, and D

This research focuses on the amalgamated excavation of Squares A, B1, C, and D, all of which were excavated to a depth of c.105cm in 37 individual excavation units (XUs) averaging 2.6cm in thickness. The contiguous stratigraphic profile of the four squares is characterised by a dense cultural deposit c.67cm deep at the lowest point in Square B1 (Figures 11.5 and 11.6). Three distinct (I, II, III) stratigraphic units (SUs) are present, SUIII also displays a sub-unit (IIIa), based upon difference in sediment colour and texture (Table 11.2). Roots and rootlets were observed throughout much of the deposition, concentrated near the surface before decreasing in quantity with depth. The archaeological assemblage was dominated by molluscan shell, particularly the marine bivalve *M. hiantina*, however charcoal and fishbone were also commonly recovered (Peck 2016).

Figure 11.5 End of excavation photograph of Dangkankuruwuru Squares A-D (Photograph: Sean Ulm, 2013).

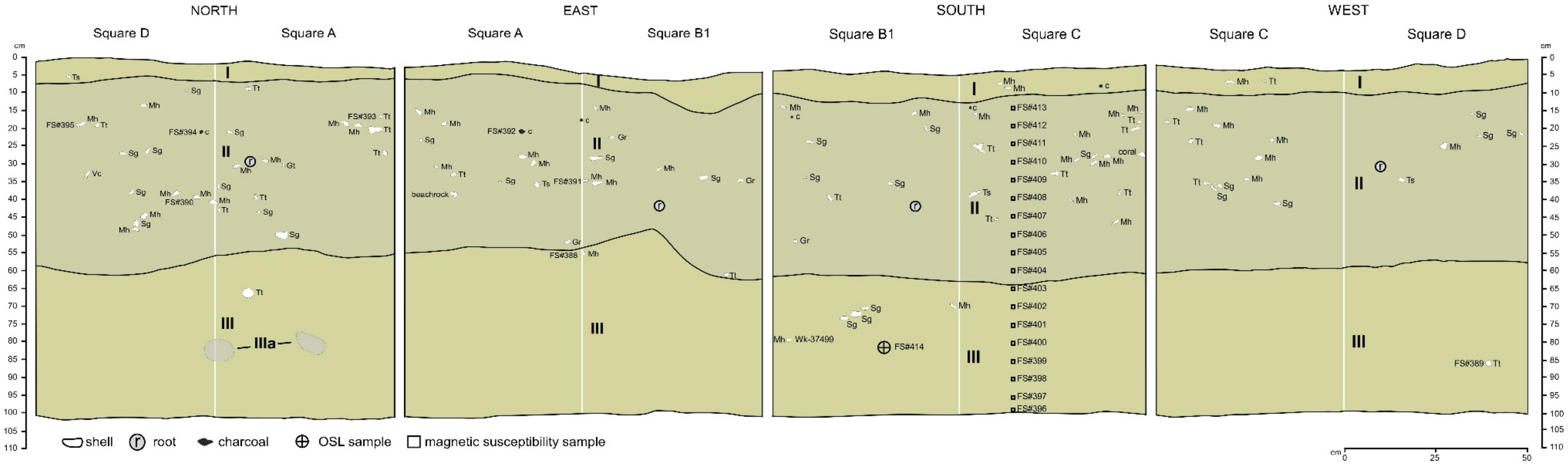

Figure 11.6 The stratigraphy of Dangkankuruwuru. Squares A-D is divided into three units (I, II, and III) with unit III displaying a sub-unit IIIa in Squares A and D (Section drawing: Michelle Langley and Sean Ulm, 2016).

Table 11.1 Descriptions of stratigraphic units (SU) for Dangkankuruwuru Squares A-D (after Peck 2016).

SU	Description
I	SUI extends across Squares A-D with depths ranging from 5 – 10 cm below the surface. The unit is comprised of angular to subangular dry and loosely consolidated sands that become more consolidated with depth. These sediments are brown (7.5YR-4/3 to 7.5YR-5/4) to dark yellowish brown (10YR-4/4) in colour. Coarse shell grit is interspersed throughout the SU. This SU contains occasional grass roots. Cultural materials include charcoal fragments, whole and fragmented mollusc shells (*M. hiantina*, *S. glomerata*, and telescope snails), crab fragments, fish bones, and otoliths. Sediments are somewhat acidic (pH 6.0 – 7.5). Shell and bone materials appear to have reasonable preservation levels.
II	Transitional unit grading from dark yellowish brown (10YR-4/4) to brown (7.5YR-4/3) to light brown (7.5YR-6/4 to 10YR-6/3). In Squares A-D this unit spans 45 – 55 cm. The matrix consists of less consolidated sands with numerous beach rock and gravel inclusions throughout. Large quantities of whole and fragmented mollusc shells (*M. hiantina*, *S. glomerata*, *T. telescopium*, *Terebralia sulcata*, nerites, and mangrove-mud mussels) are present throughout as are occasional small and blocky fragments of charcoal. Sediments are highly alkaline (pH 8.5 – 10.0). Insect burrows suggest minor disturbance of materials from insects.
III	There is a distinct change in sediment colour between SUII and SUIII from yellow and brown hues to pink (7.5YR-7/4) coarse sands and shell grit. Larger shell fragments are present but in much lower quantities than previously. Beach rock fragments were also recovered. The basal XUs (lowest 5 –10 cm) appear to be culturally sterile. Sediments are acidic (pH 5.5).

11.4 Radiocarbon Chronology

Five AMS radiocarbon determinations were obtained from *M. hiantina* marine shell across the five excavation squares (Table 11.2). Dates are reported at the 95.4% age range and corrected using the Gulf of Carpentaria ΔR value of -49±102 ^{14}C years (see Ulm et al. 2010). Results from Squares A – D indicate that the bulk of cultural material was deposited between 99 – 1537 cal BP, suggesting use of Dangkankuruwuru extends over c.1500 years. This means that site-use continued through multiple occupation phases postulated for Bentinck Island (see Memmott et al. 2016; Peck 2016). Thus, there exists the potential to better characterise Kaiadilt occupation not only on seasonal timescales but also through key transitional periods.

Table 11.2 Radiocarbon ages on marine shell from Dangkankuruwuru, Squares A-D. Radiocarbon ages were calibrated using OxCal 4.2 (Bronk Ramsey 2009) and the Marine13 calibration dataset (Reimer et al. 2013), with a Δ*R* of -49±102 (Ulm et al. 2010). All calibrated ages are reported at the 95.4% age range. * = date may extend out of range (i.e. modern).

Square	**XU**	**Depth (cm)**	**Sample**	**Lab. No.**	**Method**	**δ^{13}C (‰)**	**CRA (BP)**	**Calibrated Age BP (95.4%)**	**Calibrated Age BP Median**
A	1	0 – 1.6	*Marcia hiantina*	Wk-38692	AMS	-0.6±0.2	399±24	0*-271	115
B1	5	9.38	*Marcia hiantina*	Wk-39328	AMS	NA	360±25	0*-253	99
B1	11	24.3 – 27.4	*Marcia hiantina*	Wk-39329	AMS	NA	1502±25	895-1301	1104
B1	20	47.58 – 50.1	*Marcia hiantina*	Wk-39330	AMS	NA	1569±25	940-1362	1168
B1	29	74.6	*Marcia hiantina*	Wk-39499	AMS	-0.1±0.2	1927±25	1306-1782	1537

Peck (2016) divided the Dangkankuruwuru Squares A – D assemblage into 250-year periods based on analysis of the age-depth relationship of radiocarbon dates and the matrix stratigraphy, allowing excavation units to be assigned to one of eight temporal phases (Figure 11.7). As in Chapter 10, this research refines these temporal units into 100-year phases encompassing the cultural deposit in Squares A – D (XUs 1 – 25) to provide a more nuanced chronology of site use. It must be noted that due to periods of changing rates of deposition and probable hiatuses some phases are not represented by any XUs. 100-year phases are used as the chronological framework for interpreting and discussing Kaiadilt occupation at Dangkankuruwuru.

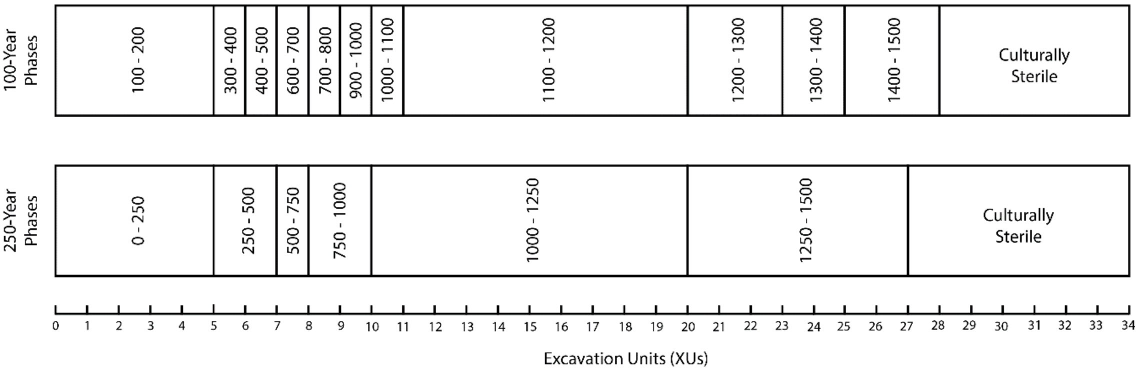

Figure 11.7 Squares A - D XUs assigned to 250-year (bottom) (after Peck 2016) and 100-year (top) temporal phase bins provide the framework for characterising changes in Kaiadilt use of Dangkankuruwuru.

The radiocarbon chronology associated with Aboriginal occupation at Dangkankuruwuru suggests the site was occupied over a period of approximately 1500 years, however the timing and periodicity of occupation remains unclear. As behavioural patterns have been linked with seasonal climatic trends at local (see Chapter 10) and regional (see Chapters 1 and 3) scales, Dangkankuruwuru may display a similar history of use reflecting a range of behaviours. Thus, establishing a high-resolution chronology will assist in better characterising decision-making processes and the permanency of Kaiadilt occupation in this area.

11.5 Squares A – D Analysis

Stable isotope analysis was undertaken on archaeological shell carbonates collected from specimens associated with cultural activity (XUs 1 – 28). All specimens were tested for recrystallisation prior to carbonate extraction and analysis. Those specimens returning aragonitic signals, indicating an absence of carbonate recrystallisation, were analysed using mass spectrometry (see Chapter 5 for procedures). Isotopic values are compared to modelled seasonal ranges (see Chapter 6) and modern analogues (see Chapter 9) to reach seasonal determinations. When combined with the established radiocarbon chronology seasonal determinations allow a high-resolution history of the timing and periodicity of Kaiadilt activity at Dangkankuruwuru.

11.5.1 Specimen Selection

Procedures outlined in Chapter 5 were used to select 5% of total MNI counts from each XU for analysis. While selecting specimens all squares were treated as separate entities, however as XUs of Squares A – D are at equivalent depth and stratigraphic position, allowing for interpretation to encompass multiple squares, specimens were recombined for analysis. Between 1 – 4 *M. hiantina* specimens (mean = 2.8) were selected per XU and prepared for analysis, however not all XUs contained usable specimens owing to post-depositional damage. See Appendix H for a detailed description of selected specimens.

11.5.2 Testing for Recrystallisation

Archaeological specimens were tested for recrystallisation using FTIR (see Chapter 5 for procedures). All material returned wavelength plots indicative of aragonite, indicating no pre- or post-depositional recrystallisation. Therefore, no archaeological material was discarded from stable isotope analysis.

11.5.3 Stable Isotopes

Overall $\delta^{18}O_{shell}$ values range between -5.6‰ and -0.3‰ with a mean of -2.7‰ (1σ = ±1.2). A majority of these data (68%; *n* = 68) are grouped within 1σ of the overall mean, with 98% (*n* = 97) within 2σ. Two $\delta^{18}O_{shell}$ data points (2%) remain outside 2σ. The patterning of data suggests analysed *M. hiantina* were collected from environments that shifted between cool marine and warm fresher conditions (Figure 11.8). Comparisons between seasonal $\delta^{18}O_{shell\text{-}predicted}$ ranges generated for subtidal environments (see Chapter 6), modern live-collected specimens (see Chapter 9), and archaeological shell values indicate a mix of both dry season, wet season, and undetermined values (Figure 11.8). While a majority of values are indicative of dry season conditions (n = 52), wet season (*n* = 7) and undetermined (*n* = 9) values are evident intermittently throughout the assemblage. All undetermined values fell between wet and dry season ranges, suggesting collection of *M. hiantina* during transitionary periods (April or September/October).

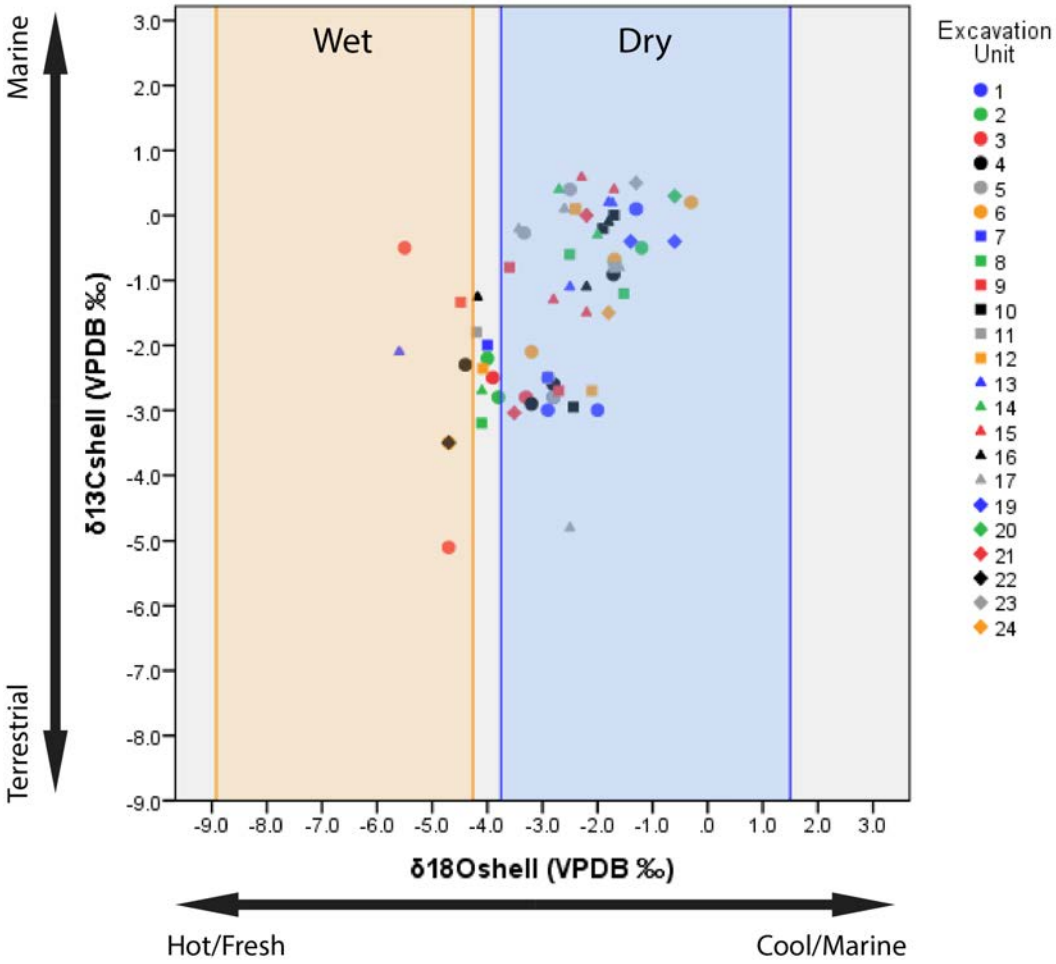

Figure 11.8 Stable isotope values derived from archaeological *M. hiantina* at Dangkankuruwuru are indicative of collection during conditions indicative of cool marine and warm fresh environments. Moreover, the values fall within dry (blue shaded area) and wet (orange shaded area). Seasonal determinations for some specimens could not be reached, suggesting collection during transitionary periods.

A similar pattern is evident in $\delta^{13}C_{shell}$ values, which range between -5.1‰ and +0.6‰ (mean = -1.4‰; 1σ = ±1.4‰). Just over half (*n* = 40; 59%) the data points fall within 1σ of the mean, while 97% (*n* = 66) of values remain within 2σ. A majority of $\delta^{13}C_{shell}$ values are indicative of carbonates being constructed from marine carbon sources (following Petchey et al. 2013), suggesting minimal interaction with terrestrial carbon reservoirs (Figure 11.8). The more negative $\delta^{13}C_{shell}$ values evident in some specimens may be linked with tidal forces or wet season flood run-off transferring carbon from terrestrial sources surrounding the nearby coastline, such as the fringing mangrove system or small estuarine system to the east, much like that observed in the Mirdidingki Creek area (see Chapter 6).

Comparisons of $\delta^{18}O_{shell}$ values between individual XUs reveal relative stability over the course of Kaiadilt occupation at Dangkankuruwuru (Figure 11.9), with results of a One-Way ANOVA demonstrating statistical similarities between all XUs (*F*(22) = 1.281, *p* = .236). Augmenting this with a Tukey HSD post-hoc test reveals a majority of variability is attributable to XU3, which returned changeable relationships with other XUs (e.g. *p* = .102 for XUs 3 and 19; *p* = 1.000 for XUs 3, 7, and 9) owing to its comparatively negative range (-5.5‰ – -3.3‰) and mean (-4.4‰). Similarities shared by remaining XUs were strong, ranging between *p* = .548 (XUs 9 and 19) and *p* = 1.000 (e.g. XUs 1 and 2 among others). XUs 20, 22, 23, and 24 were excluded from Tukey HSD post-hoc tests as they encompassed less than 2 values.

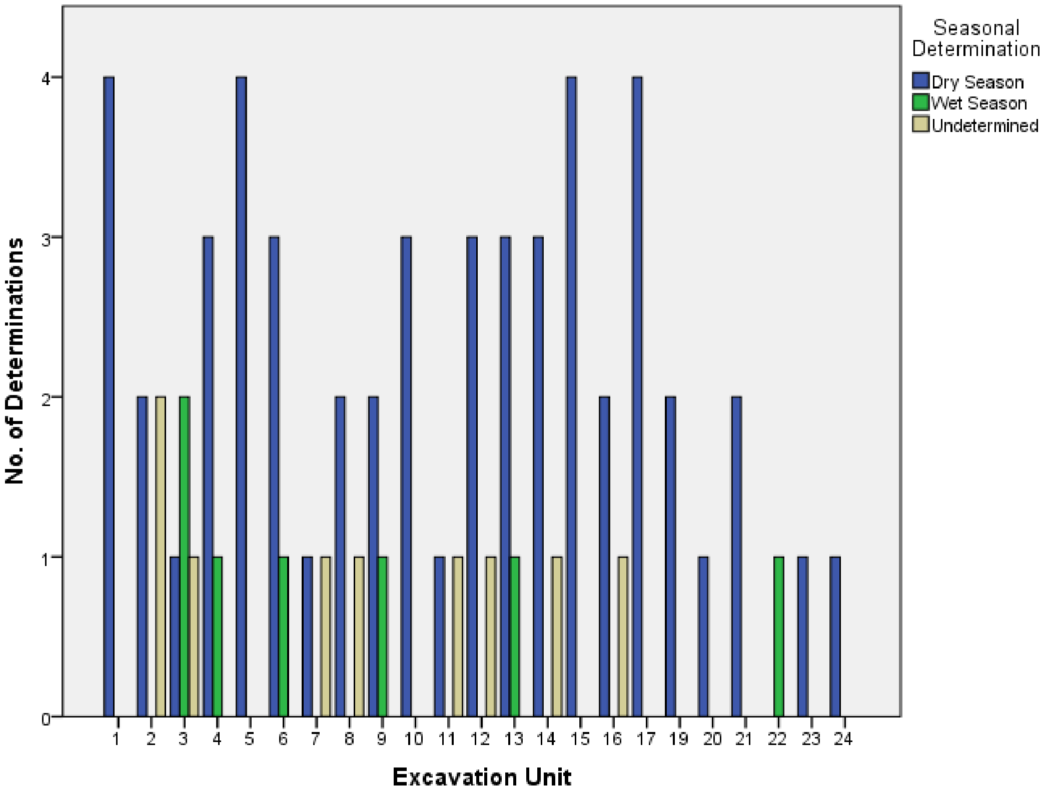

Figure 11.9 Number of seasonal determinations per excavation unit.

Strong similarities are evident when $\delta^{13}C_{shell}$ values are compared between XUs using a One-Way ANOVA (*F*(22) = .799, *p* = .711). Likewise, a Tukey HSD post-hoc test demonstrates significant connections between all XUs (*p* >= .548) except XU3, which returned variable relationships ranging between *p* = .102 (XUs 3 and 19) and *p* = 1.000 (XUs 3, 7, and 10) likely owing to its wide range of $\delta^{13}C_{shell}$ values (-5.1 to -0.5‰). XUs 20, 22, 23, and 24 were again excluded from Tukey HSD post-hoc tests as they encompassed less than 2 values.

While relationships found in $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values are statistically significant throughout the Dangkankuruwuru assemblage, a number of patterns of change are evident. Most noticeably, values form two distinct data point clusters. These clusters are delineated by both $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values, with *Group 1* typified by more positive values and *Group 2* more negative values (Table 11.3). Moreover, a One-Way ANOVA indicates no significant relationship between groups for $\delta^{18}O_{shell}$ (*F*(1) = 68.131, *p* = .000) and $\delta^{13}C_{shell}$ (*F*(1) = 168.746, *p* = .000) values.

When compared to predicted seasonal ranges, *Group 1* remains entirely within dry season conditions while *Group 2* is relatively evenly split between dry season and wet season/undetermined values (Figure 11.8). Despite this, $\delta^{13}C_{shell}$ appears to be the primary factor separating the clusters with some overlap occurring in $\delta^{18}O_{shell}$ values. The potential ramifications of these groups are discussed in the context of temporal phases in Section 11.6.2.

Table 11.3 Isotopic values from the Dangkankuruwuru assemblage cluster in two well delineated groups.

	Group 1		**Group 2**	
	$\delta^{18}O_{shell}$ (‰)	**$\delta^{13}C_{shell}$ (‰)**	**$\delta^{18}O_{shell}$ (‰)**	**$\delta^{13}C_{shell}$ (‰)**
Range	-3.6 – -0.3	-1.5 – +0.6	-5.6 – -2.0	-5.1 – -0.5
Mean	-2.0	-0.3	-3.6	-2.7
1σ	±0.7	±0.6	±0.9	±0.9

Applying the 100-year temporal phases outlined above to stable oxygen and carbon values allows short-term occupation patterns associated with Dangkankuruwuru to be considered within a secure temporal framework (Figure 11.10). A One-Way ANOVA suggests significant relationships are shared by $\delta^{18}O_{shell}$ values across all phases ($F(9) = .821$, $p = .599$). This is confirmed by a Tukey HSD post-hoc test, which found strong relationships between all phases. Similar patterning is evident in $\delta^{13}C_{shell}$ values with an ANOVA highlighting significant connections between all phases ($F(9) = 1.082$, $p = .390$). While a Tukey HSD post-hoc test found that a majority of significant relationships were strong (*p* values ranged between .879 – 1.000), variability is attributable to phases spanning 100 – 200 cal BP and 1100 – 1200 cal BP ($p = .112$). This is unlikely to be skewed by the sample as 5% of all material is represented. One phase (1300 – 1400 cal BP) was excluded from both Tukey HSD post-hoc tests as it contained less than two values. A detailed discussion of the implications for Kaiadilt occupation at Dangkankuruwuru and the surrounding area is presented in Section 11.6.

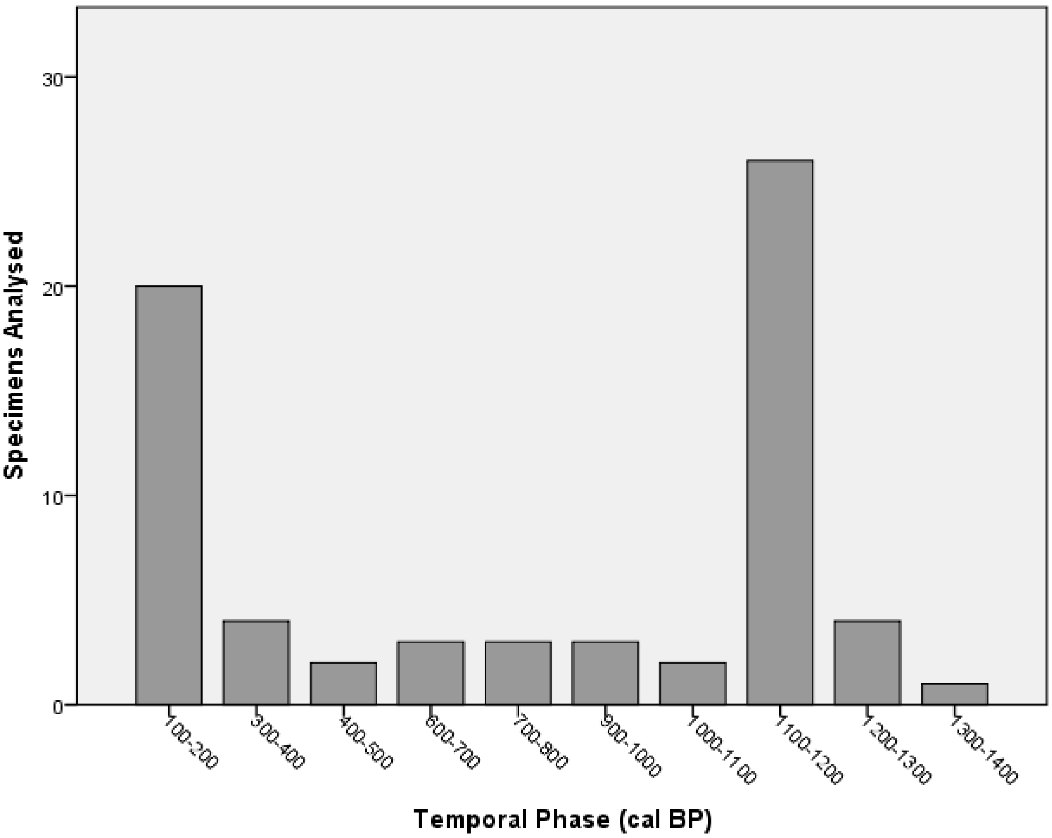

Figure 11.10 Total number of specimens analysed per 100-year temporal phase.

11.6 Timing and Periodicity of Occupation at Dangkankuruwuru

11.6.1 A High-Resolution Chronology of Site-Use

Patterns of occupation associated with Dangkankuruwuru underwent significant changes over the course of its use. Analyses of the archaeological assemblage undertaken by Peck (2016) highlighted shifts in material density that assist in understanding occupation intensity and the progression of site-use through time. Palaeoenvironmental trends and conditions characterised by Moss et al. (2014, 2015) further contextualise human decision-making processes against broader patterns of environmental change. Moreover, sea-level curves suggested by Sloss et al. (2015) indicate that access and use of important littoral resource bases, including stone-walled fish traps at Kirk Point, commenced after c.800 cal BP, likely 500 – 600 cal BP, as the surrounding rocky platform become increasingly intertidal. When these findings are combined with seasonality data and placed within 100-year phases a number of changing behavioural patterns are evident.

Radiocarbon determinations suggest that the earliest human presence at Dangkankuruwuru occurred c.1537 cal BP during a period of occupation described by Peck (2016) as ephemeral in nature, owing to its sparse assemblage and low number of economically important taxa. This coincides with a broader pattern of discontinuous occupation proposed for the South Wellesley region (Memmott et al. 2016; Peck 2016; Ulm et al. 2010), suggesting short-term sporadic use. Seasonality determinations indicate this period was typified by dry season use with occasional wet season occupation. Thus, occupation was likely timed to coincide with periods of predictable wind conditions and low storminess. This initial period of ephemeral use terminated c.1200 cal BP (Figure 11.11).

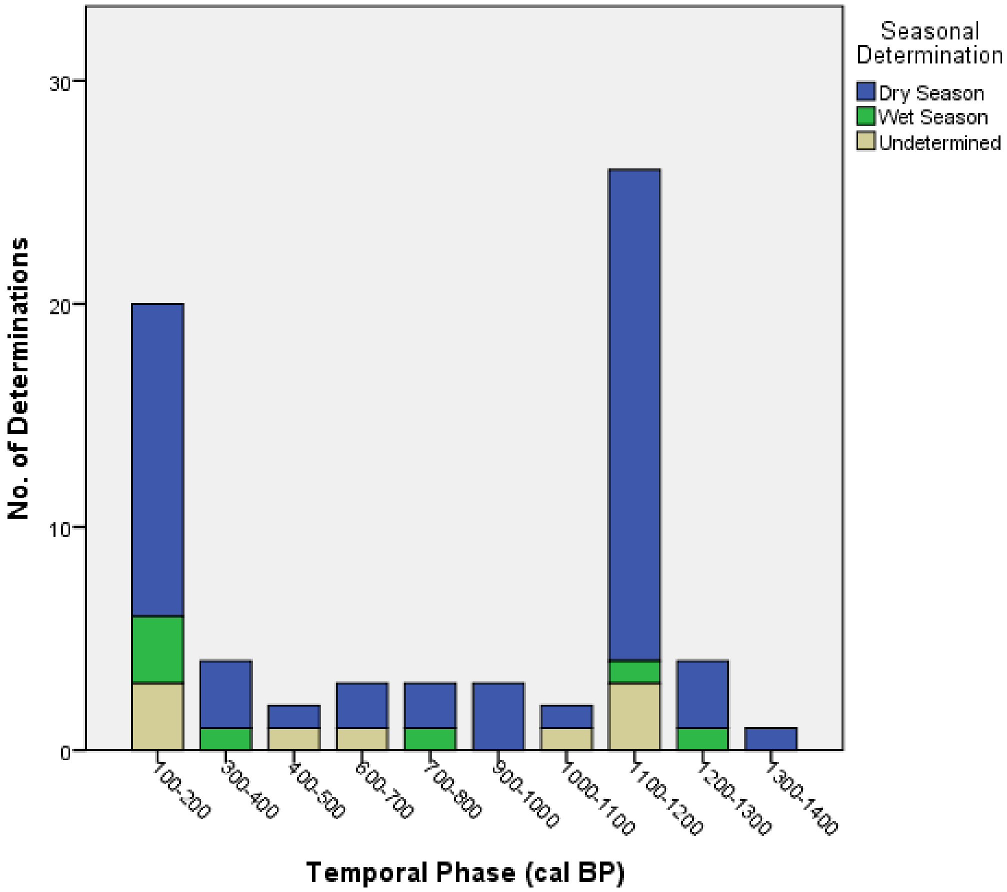

Figure 11.11 Seasonality determinations for Dangkankuruwuru divided into 100-year phases.

In the 100 years (1100 – 1200 cal BP) that followed occupation intensity increased substantially, as evidenced by the rapid deposition of a dense archaeological assemblage dominated by important economic shellfish taxa (Peck 2016). Seasonality determinations indicate a focus on dry season occupation, with a majority of data points falling within the more positive *Group 1* (see Section 11.5.3). Further, while wet season and transitionary period use is evidenced, the small number of these signals suggests limited site-use during these times (Figure 11.12). When compared to regional patterns of occupation it is interesting to note that this period occurs approximately 300 years before occupation in the South Wellesley Islands is thought to significantly intensify (see Memmott et al. 2016; Peck 2016; Ulm et al. 2010). Thus, questions regarding the origin of people occupying Dangkankuruwuru as well as the nature and permanency of this use are raised. These questions are approached in detail in Section 11.6.2 and Chapter 13.

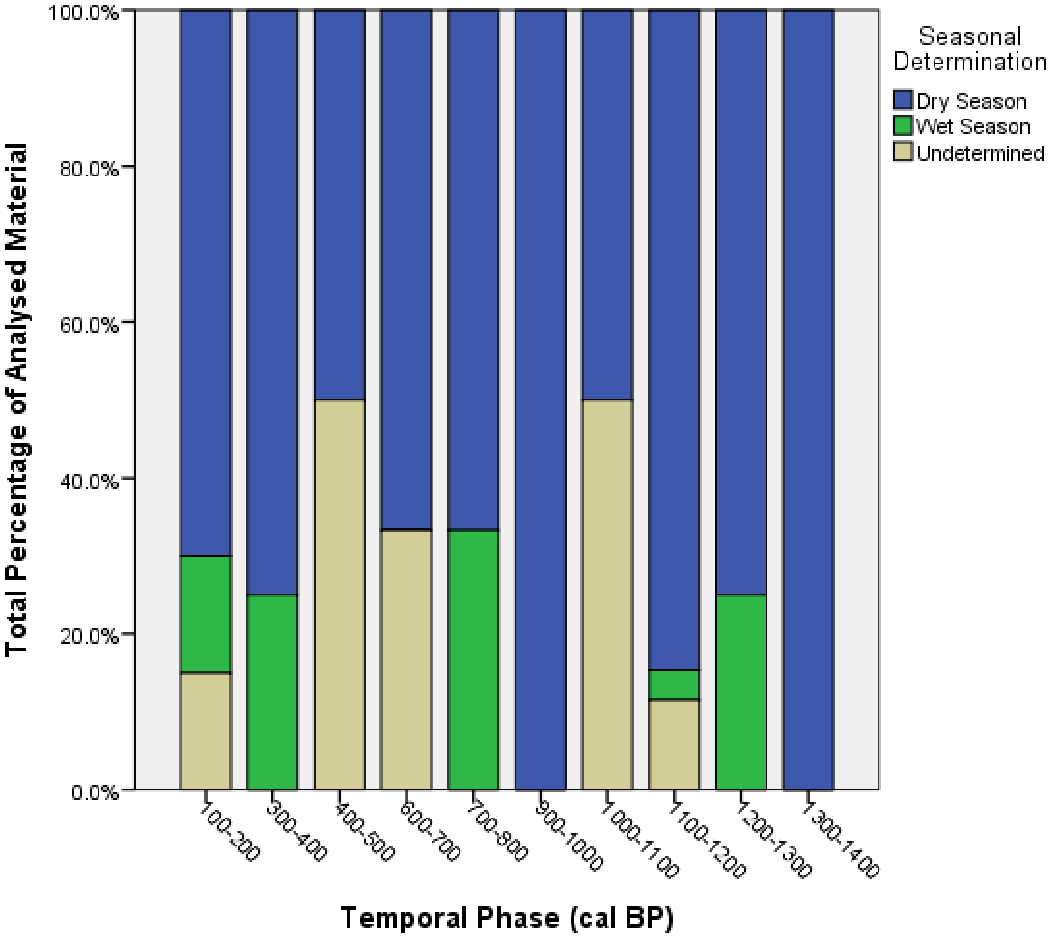

Figure 11.12 Total percent of seasonal determinations per 100-year temporal phase. Note that quantity of analysed material differs per phase. See Figure 11.11 for specimens per phase.

A significant reduction in material density and species richness follows (Peck 2016), suggesting occupation returned to levels indicative of earlier ephemeral or low-intensity use. After an initial decrease (c.1100 cal BP), occupation stabilises with evidence of low-level use persisting until c.200 cal BP. This is largely congruous with the chronology suggested by Peck (2016), which highlights a similar depression in use 250 – 1000 cal BP. Additionally, although Peck (2016) posits that an occupation hiatus occurred between 500 – 750 cal BP, this is not evidenced within 100-year phases. While analysis of seasonality again suggests a focus on dry season use, wet season and transitionary period determinations are common throughout this period. Moreover, the diverse range of isotopic values suggests that site-use may again be opportunistic. At broader geographic scales this period encapsulates substantial environmental and behavioural shifts from c.500 cal BP (see Chapters 10 and 12; Moss et al. 2014, 2015; Sloss et al. 2015) as well as an overall trend of intensifying occupation across the South Wellesley Islands from c.800 cal BP (see Memmott et al. 2016; Peck 2016; Ulm et al. 2010). The arrival of Macassan trepangers in the 1700s followed by European settlers in the 1800s also disrupted behavioural patterns throughout the archipelago (Chapters 10 and 12; see also Kelly and Evans 1985; Laurie 1866; Oertle et al. 2014; Stubbs 2005; Tindale 1962a, 1962b). Similarly timed shifts are not displayed by the Dangkankuruwuru assemblage, likely owing to minimal occupation signals, geographic removal from European and Macassan settlements, the periodic nature of site-use, large extent of the site, or the employed sampling strategy which may not have identified specific occupation episodes. Although, a slight upturn in occupation during the final 200 years of this period (200 – 400 cal BP) signals the commencement of a second period of intense occupation from c.200 cal BP.

Evidence coinciding with the most recent period of occupation at Dangkankuruwuru (100 – 200 cal BP) suggests more intense use, as evidenced by a dense assemblage, increases in diet diversity, and decreases in the size of the dominant economic bivalve *M. hiantina* (Peck 2016). Moreover, while a majority of seasonality determinations returned dry season signals, timing and periodicity shifts towards a less seasonal pattern with increases in wet and transitionary season values. In combination these findings indicate high-levels of sustained occupation that continue through seasonal climatic cycles. Given the intensity of occupation across the South Wellesley Islands continued to increase after c.800 cal BP (see Memmott et al. 2016; Peck 2016; Ulm et al. 2010), the late more intensive use of Dangkankuruwuru is likely a component of this broader pattern with groups looking to exploit a wider array of areas and resources to support increasing populations. Moreover, the recent stabilisation of sea levels (Sloss et al. 2015) likely facilitated the construction and use of extensive fish trap complexes on the intertidal rocky platform surrounding Kirk Point, evidenced by a significant increase in fish remains occurring within the record (Peck 2016). The construction and continued management of these new resource bases likely encouraged more regular use of nearby Dangkankuruwuru (see Section 11.6.2 for further discussion on the implications of fish trap use).

The evidence presented above indicates occupation at Dangkankuruwuru saw significant fluctuations through time. To better characterise this, four phases of occupation are suggested (Table 11.4). The first ephemeral phase (1200 – c.1537 cal BP) begins with initial occupation and is typified by opportunistic use during both wet and (primarily) dry seasons, a sparse archaeological assemblage, and low numbers of economically important shellfish taxa. An early intense phase (1100 – 1200 cal BP) followed, displaying a strong focus on dry season use, dense assemblage dominated by economic species, and temporal correlations to broader patterns of discontinuous occupation in the South Wellesley Island region. Subsequent to this, occupation decreased significantly to form a long second ephemeral phase (200 – 1100 cal BP), typified by reduced material density and species diversity, mixed seasonality signals, opportunistic use, and a potential occupation hiatus. The most recent period of occupation, the late intense phase (100 – 200 cal BP), saw a resurgence in the use of Dangkankuruwuru with higher rates of material deposition, increases in use outside of the dry season, a focus on sandy-mud flat mollusc species, and increases in inclusions of fish bone. Thus, occupation patterns at Dangkankuruwuru exhibit a complex multidirectional chronology that extends throughout numerous phases of Kaiadilt presence in the South Wellesley Islands.

Table 11.4 Four phases of occupation can be identified for Dangkankuruwuru Squares A-D – after Kelly and Evans 1985; Laurie 1866; Macknight 1972, 1986; Moss et al. 2012, 2014; Oertle et al. 2014; Peck 2016; Stubbs 2005; Tindale 1962b.

Occupation Phase (cal BP)	Assemblage Density	Seasonality	Local Landscape and Palynology	Shellfish Exploitation	Other Factors	Broader Patterns of Occupation
First Ephemeral c.1537 – 1200	Sparse	Dry season with occasional wet season	NA	Low number of economic taxa	Initial occupation	Discontinuous occupation across South Wellesley Islands
Early Intense 1200 – 1100	Sharp increase; Dense	Strong dry season focus with wet and transitionary season	Prograded coastline provided productive littoral resources	Decrease in sandy-mud taxa and increase in mangrove species	NA	Discontinuous occupation across South Wellesley Islands
Second Ephemeral 1100 – 200	Sharp decrease then stable; Sparse; Slight increase in later 100 years	Mix of wet, dry, and transitionary seasons	Sea-level stabilisation causing Kirk Point rocky platform to become highly intertidal (c.800 cal BP)	Decrease in species richness; Steady exploitation from rocky reef, sandy-mud flat, and mangrove environments	Appearance of mangroves at nearby Marralda Swamp and sharp charcoal spike, increase in grasses and arboreal taxa at Thundiy (c.500 cal BP); Arrival of Macassans and Europeans	Increases in occupation across South Wellesley Islands (from c.800 cal BP)
Late Intense 200 – 100	Sharp increase; Dense	Dry season with increased numbers of wet and transitionary seasons	NA	Significant decrease in rocky reef and mangrove species with increase in sandy-mud flat taxa	Kirk Point fish traps; Continued presence of Europeans	Permanent occupation across South Wellesley Islands

11.6.2 Changing Patterns of Seasonal Occupation

It has been posited that prior to c.800 cal BP the South Wellesley Islands were sporadically exploited by wide-ranging maritime foragers from outside the immediate region (Memmott et al. 2016; Peck 2016), suggesting that occupation during this time was largely ephemeral in nature. After c.800 cal BP occupation signals increase dramatically, suggesting a move towards intensified, permanent island use with the establishment of more sites and larger populations (Memmott et al. 2016; Peck 2016; Tindale 1962b). These broader patterns assist interpretations at Dangkankuruwuru, providing valuable context for the changing relationships between site-use and seasonal cycles outlined in Section 11.6.1. The behavioural patterns leading to the deposition of the Dangkankuruwuru assemblage can therefore be divided into two periods, early (pre-c.800 cal BP) and late (post-c.800 cal BP).

As the early period coincides with evidence of sparse, discontinuous occupation at other sites (see Memmott et al. 2016; Peck 2016), it is argued that Dangkankuruwuru was periodically visited by groups from outside the South Wellesley Islands (e.g. the mainland or other nearby islands). Moreover, evidence of focused dry and, to a lesser extent, transitionary season use suggests that seasonally timed cycles of occupation and abandonment were present during the early period. These patterns are potentially linked with seasonal shifts in wind direction facilitating travel to and from Bentinck Island. Assuming groups utilised Horseshoe and Albinia Islands as stepping stones to minimise open water crossings (Figure 11.13), the northeasterly winds that typify the late wet season and wet-dry transition likely eased open water crossings from the mainland while late dry season or dry-wet transitions southwesterly winds assisted return journeys (see Anderson and White 2001; Davies 1985; McNiven 2015 for other examples of wind assisted travel in Australia). While evidence of the motives and decisions that led groups to make this often dangerous journey is largely absent, seasonal use of offshore island environments for subsistence or cultural purposes is well documented (e.g. Davies 1985; Jones and Allen 1979; McNiven et al. 2014; Sullivan 1982).

Within this period of otherwise low-level site visitation is an occupation peak, suggestive of intense dry season site-use (see Section 11.6.1). This may be representative of either a period of repeated targeted use or a colonisation attempt, however distinguishing between these two possibilities is not possible with the data available. Factors leading to the sudden decrease in site-use subsequent to this peak are also unclear. Although, as the archaeological record displays concurrent increases in *M. hiantina* quantities and reductions in valve length (Peck 2016), a resource depression linked with rapid and intense exploitation may have contributed to lessening use. Other studies have suggested broader changes in climate and environment as primary drivers behind island abandonment (e.g. Sim and Wallis 2008), however no evidence of these were found at Dangkankuruwuru. Moreover, it must be remembered that Dangkankuruwuru is a single site on a highly active archaeological landscape, thus its discontinued use cannot be taken to signal the abandonment of Bentinck Island or the South Wellesley Islands as a whole as other sites were likely simultaneously brought into use.

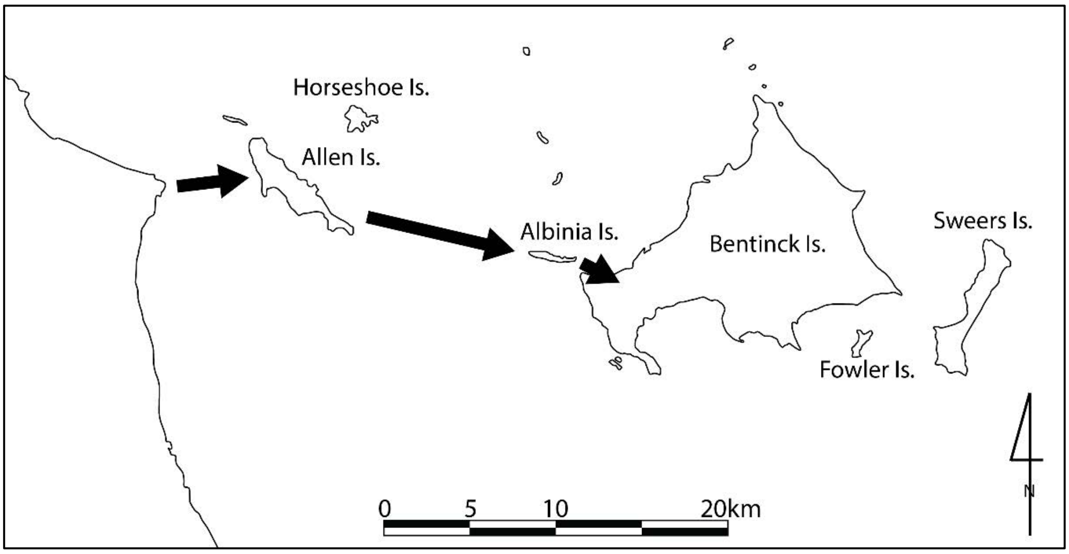

Figure 11.13 Voyaging from the mainland to Bentinck Island requires a number of extended open ocean crossings.

After c.800 cal BP increasing evidence of intense use across numerous sites suggests that Bentinck Island had undergone successful colonisation and was now permanently occupied by Kaiadilt groups (Memmott et al. 2016; Peck 2016). At Dangkankuruwuru, this coincided with continuing low-level occupation, although seasonality determinations indicate use was not focused upon one season and was instead scattered throughout the year. When considered together, these factors suggest that Dangkankuruwuru was no longer used by foragers traveling from outside the island group but rather was opportunistically occupied by permanent inhabitants of Bentinck Island. A second period of intense occupation is also evident, although unlike the earlier peak this period displays increasing use across seasonal boundaries (see Section 11.6.1).

The position of Dangkankuruwuru on the landscape is an important factor in understanding why this site saw occupation that persisted throughout seasonal climatic and environmental change. Located on the southern coast of Bentinck Island, the site is protected from inclement conditions that accompany the wet season northwesterly winds. Conversely, Dangkankuruwuru was exposed to southeasterly winds for the duration of the dry season, however their intensity is lessened by the dune systems and mangrove fringes that lay between the open marine environment and the site itself. Wet season rainfall likely caused extended periods of flooding across the clay pan and low-lying landscape to the north of Dangkankuruwuru, potentially isolating it from much of the island. However, a wide array of resources – including fish traps, mangrove forests, estuarine systems, littoral zones, and various terrestrial resources – likely remained in use, accessible via nearby dune systems or intertidal reaches. Similar resource bases were likely available during the dry season.

11.6.3 Fish Traps and Site-Use

The extensive stone-walled fish trap complexes located around much of Kirk Point, particularly the lower eastern coast, southern tip, and south coast (Figure 11.14), may provide salient insight into recent patterns of occupation observed at Dangkankuruwuru. As highlighted above sea levels would not have allowed the construction of fish traps at Kirk Point until after c.800 cal BP (Sloss et al. 2015), with use likely not commencing until c.500 – 600 cal BP. The positioning of trap systems across the marine landscape provides differential protection from seasonal winds and rough conditions, e.g. traps on the east and south are protected during the wet season while traps on the west a shielded during the dry season. Fish traps can therefore remain in use year round, facilitating pan-seasonal exploitation of associated resources.

Figure 11.14 Dense fish trap complexes are found surrounding Kirk Point, Bentinck Island (Photograph: Anna Kreij, 2015).

As wet and transitionary season determinations are not as prevalent as their dry season counterparts during the most recent occupation peak (25%, *n* = 5 and 75%, *n* = 15 respectively), there may exist a shift in resource focus timed to coincide with wet season conditions. This notion is supported by a majority of fish traps being positioned to make use of Bentinck Island as a natural barrier against wet season winds (e.g. complexes on the east, south, and some on the west of Kirk Point), although it must be stressed that this does not preclude their use during the dry season. Moreover, the traditional calendar of the Lardil suggests that wet season conditions saw increased availability and exploitation of fish as well as numerous vegetables and fruits (Rosendahl 2012:60; see also Chapter 3), allowing the seasonally timed diversification of diets that may signal a temporary decrease in the importance of shellfish.

This interpretation can be elaborated upon to suggest the presence of seasonal shifts in occupation intensity at Dangkankuruwuru. Assuming subsistence behaviours are being modified concurrent to seasonal resource availability, as outlined above, allows for the possibility of an equivalent change in the locus of occupation. Dangkankuruwuru has been characterised as a central-place camp from which residents launched foraging expeditions (Peck 2016). This interpretation is more salient to dry season use, owing to the large quantity of material reflecting dry season conditions. However, a number of factors suggest the nature of occupation at Dangkankuruwuru may change with the onset of wet season conditions. The smaller assemblage of archaeological material with links to the wet season suggests reduced use at this time of year. Moreover, as Dangkankuruwuru is geographically removed from Kirk Point (requiring a minimum of c.3.2km travel to the nearest fish traps), although it is the closest known site, a seasonal increase in the exploitation of fish coupled with a potential shift towards more sedentary behaviour (as suggested for similar regions by Davies 1985; Meehan 1982; Memmott 2010) would likely result in the relocation of central-place camps closer to active resource bases. It is therefore suggested that occupation focus may have shifted away from Dangkankuruwuru for the duration of the wet season before populations returned at the onset of dry season conditions, although further archaeological evidence is required to confirm this.

However, this does not account for evidence of wet season use at Dangkankuruwuru. Three potential explanations are suggested. Firstly, seasonally timed demographic changes lead to lower-intensity occupation as smaller groups exploited a more diverse range of environments (see Meehan 1982 for an example of this). Alternatively, wet season signals originate from early or late in the season, prior to abandonment or subsequent to reoccupation respectively. Finally, Dangkankuruwuru may undergo infrequent or sporadic use during wet season conditions. Unfortunately testing the efficacy of these interpretations requires understandings of the timing and periodicity of occupation at archaeological sites in the surrounding region, which are currently uncertain. Whatever the reason, it is clear that recent changes in decision-making processes associated with occupation and subsistence practices at Dangkankuruwuru are driven by a complex interplay of environmental and cultural factors.

11.7 Summary

Analysis of archaeological *M. hiantina* shell from Dangkankuruwuru revealed changing patterns of occupation. Stable oxygen values indicate a majority of early use was scheduled to concurrent with the dry season. This coincides with a broader period of discontinuous use by wide-ranging foragers, suggesting initial periods of occupation were associated with regular voyaging from the mainland. Shifting seasonal conditions, particularly wind direction and storminess, likely restricted open water access to the South Wellesley Islands to the dry season. Thus, a cycle of occupation and abandonment, not just of Dangkankuruwuru but the region as a whole, may have been in place. Later periods of seasonal use corresponding with the broader permanent occupation phase are more indicative of opportunistic occupation by groups moving across the local landscape. A final period of intensive use saw a shift towards occupation outside of the dry season, suggesting increases in residency times and sedentary behaviours. This high-resolution chronology provides insight into the changing importance of seasonality and will allow higher-order questions of mobility to be addressed in later chapters.

Chapter 12 Murdumurdu

12.1 Introduction

The shell matrix site known as Murdumurdu is located on the south coast of Bentinck Island approximately 2.5km east-northeast of Mirdidingki Creek. Excavations undertaken in 2012 revealed a stratified cultural deposit dominated by marine bivalve remains. A high-resolution chronology of timing, periodicity, and seasonality of Kaiadilt use is established through stable isotopic analysis of associated archaeological mollusc shell. This chapter describes Murdumurdu and its surrounding area, stratigraphy, and oxygen and carbon stable isotope values derived from archaeological shell carbonates. Findings are then used to discuss implications for Kaiadilt occupation and resource-use at the site.

12.2 Site Description and Setting

Murdumurdu (also known as 'Modomodo') is a shell matrix site located on the south coast of Bentinck Island, c.2.5km west of the township of Njinjilki. Positioned c.10 – 20m south of the southern border of the Marralda swamp system (Figure 12.1), Murdumurdu is low-lying with elevations placing it 5m above the Australian Height Datum (AHD). A small dune system (c.200m wide) running adjacent to the coastline and swamp system separate the site from the open marine environment, providing some shelter from winds and other inclement conditions. The surrounding area contains vegetation including mangrove stands dominated by *Bruguiera exaristata* (orange mangrove) and *Rhizophora stylosa* (red stilt-root mangrove) along with *Avicennia marina* (grey mangrove) and *Ceriops togal* (yellow mangrove), and coastal savannah consisting of *Melaleuca* and *Pandanus* forest as well as *Typha* and spike-rush corms of *Eliocharis dulcis*. A large clay pan system abuts the eastern end of Marralda Swamp, while Mirdidingki Creek is found at its western extremities. A major four-wheel drive access track, originating at Njinjilki, terminates c.300m to the east of Murdumurdu with lesser-used tracks continuing past the site to the south. North of Marralda Swamp is a second major vehicle track.

Archaeological shell material is evident in a surface scatter across much of Murdumurdu (Figure 12.2). The site was first recorded in 2012 as part of a pedestrian survey before being excavated the same year. Two 50cm x 50cm excavations (Squares A and B) were undertaken at a 10m interval. Excavations revealed a dense lens of archaeological shell material at depths of c.9 – 18cm in Square A and c.10 – 28cm in Square B. Assemblages for both squares were dominated by *M. hiantina* with occasional *G. tumidum* inclusions in Square A. Both excavations followed procedures detailed in Chapter 5.

Figure 12.1 The region surrounding Murdumurdu consists of low-lying coastal savannah, mangrove swamps, clay pans, and intertidal flats.

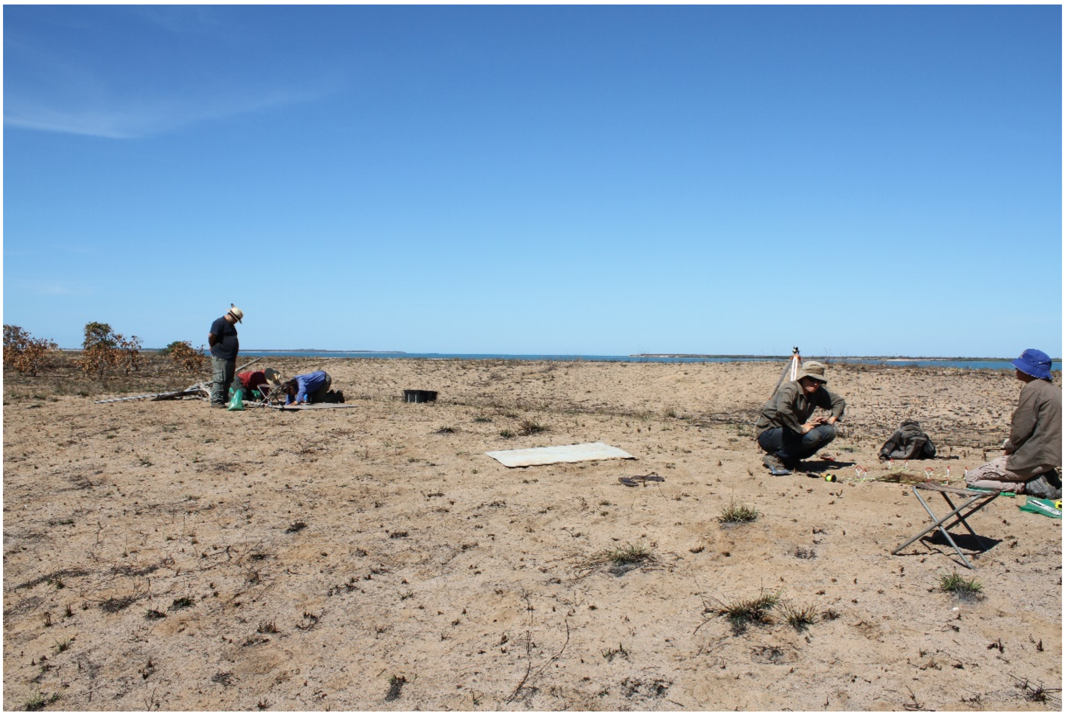

Figure 12.2 Murdumurdu is located on a low dune on the southern edge of Marralda Swamp, Bentinck Island (Photograph: Daniel Rosendahl, 2012).

12.3 Cultural Deposit and Stratigraphy

Excavations revealed a 30 – 40cm thick cultural deposit resting on degraded beach sands. The bulk of material was recovered from dense lenses of cultural shell material extending in Square A from XU2-7 (c.6 – 22cm depth) and XU3-8 (c.6.5 – 24.5cm) in Square B (Figures 12.3, 12.4, 12.5, 12.6, and 12.7). The stratigraphic profile in both squares is characterised by three stratigraphic units (I, II, III), with SUI divide into two subunits (Ia and Ib), identified based upon sediment colour and texture (Table 12.1). Roots and rootlets were observed throughout much of the site, with rootlets concentrated towards the surface and more robust roots at greater depths. The archaeological assemblage was dominated by molluscan shell, principally the marine bivalve *M. hiantina*, however charcoal, crustacean, and fish bone was also recovered.

Figure 12.3 Murdumurdu Square A end of excavation photograph. Note the small collapse in the north section and dense lens of *M. hiantina* visible in the north and east sections (Photograph: Sean Ulm, 2012).

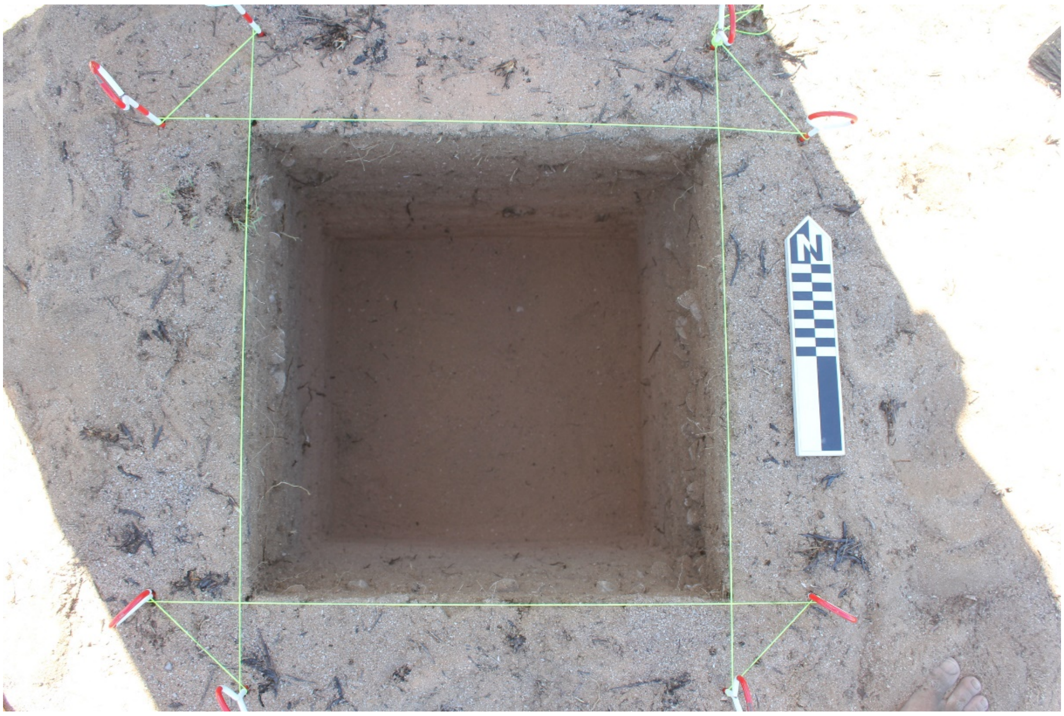
Figure 12.4 Murdumurdu Square B end of excavation photograph. Note the dense lens of *M. hiantina* visible in the east, west, and south sections (Photograph: Sean Ulm, 2012).


Figure 12.5 The dense lens of *M. hiantina* that extends across both Square A and B (Photograph: Sean Ulm, 2012).

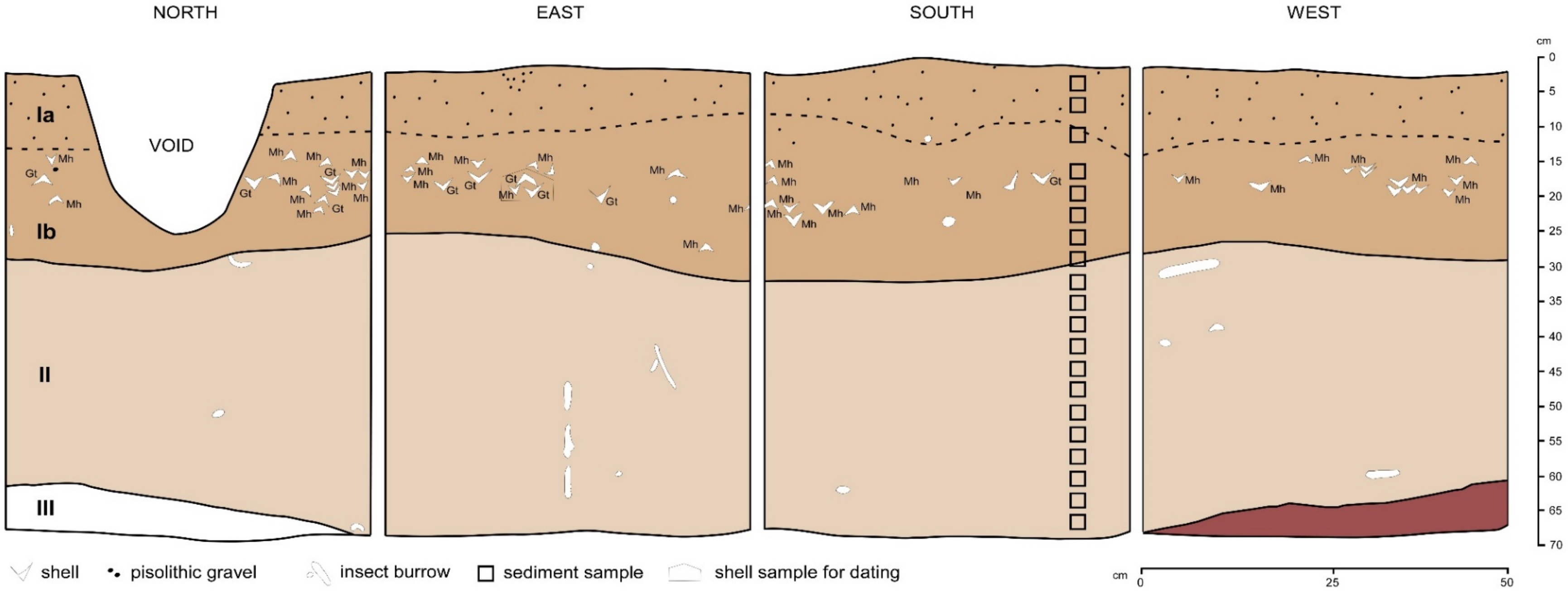

Figure 12.6 The stratigraphy of Murdumurdu Square A is divided into three units (I, II, and III) with SUI further divided into sub-units Ia and Ib (Section drawing: Michelle Langley and Sean Ulm, 2016).

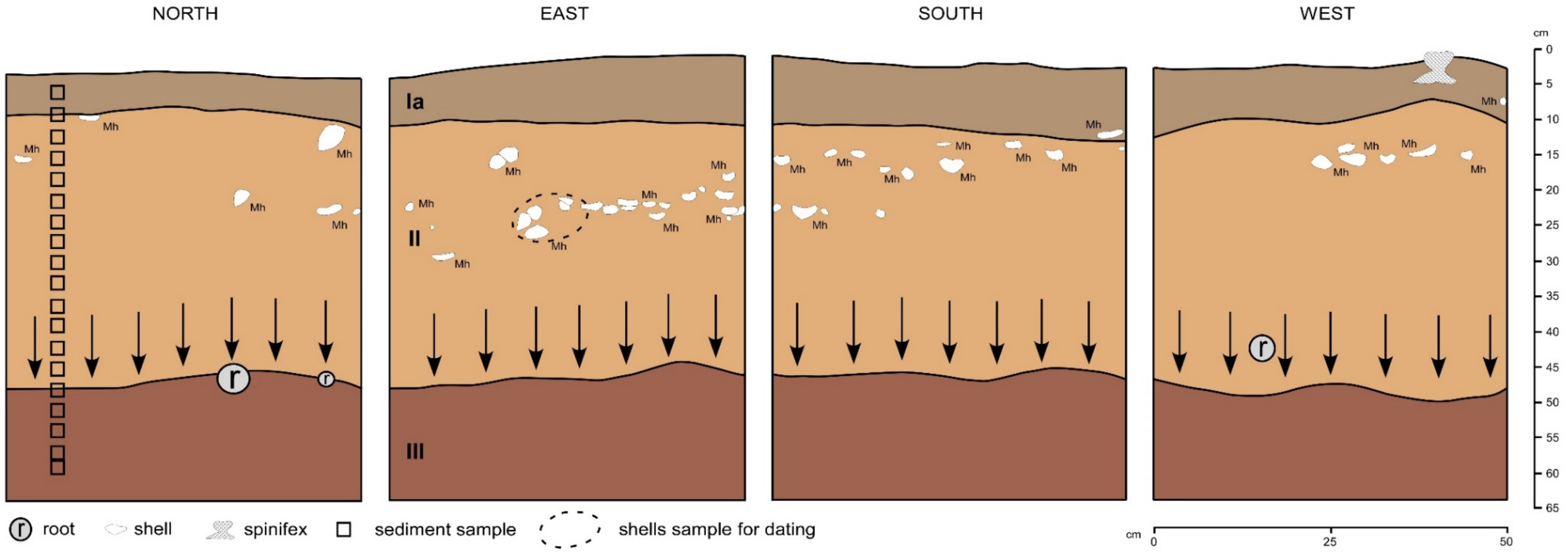

Figure 12.7 The stratigraphy of Murdumurdu Square B is divided into three units (I, II, and III) with SUI further divided into sub-units Ia and Ib (Section drawing: Michelle Langley and Sean Ulm, 2016).

Table 12.1 Stratigraphic unit descriptions, Murdumurdu, Squares A and B (after Peck 2016).

SU	Description
Ia	Extends across both squares with depths ranging between 10 – 15cm below ground surface in Square A and 5 – 10cm in Square B. The unit is comprised of angular to subangular loosely consolidated coarse sands with numerous spinifex grass rootlets. The sediments are brown (7.5YR-5/4) in colour with coarse shell grit interspersed throughout the SU. Small insect burrows are evident, suggesting insect disturbance. Cultural materials include charcoal fragments as well as whole and fragmented *M. hiantina* and *G. pectinatum*. Sediments are highly alkaline (8.5 – 10.0 pH). Shell material appears reasonably well-preserved.
Ib	More consolidated coarse brown (7.5YR-5/4) sands with fewer spinifex grass rootlets and shell grit inclusions. For Square A SUIb, is found 10 – 25cm below the surface. In Square B, SUIb is 5 – 30cm below the surface. Sediment pH is alkaline (7.5 – 9.0). High concentration of shell between 15 cm and 25cm, comprised of *M. hiantina* and G. *pectinatum* as well as other cultural material (e.g. fishbone and charcoal).
II	Transitional unit grading from brown (7.5YR-5/4) to light brown (7.5YR-6/4) loosely consolidated coarse sands. Few roots but numerous and larger insect burrows. Shells found in this unit are likely cultural in origin but are unlikely to be *in situ*, with insect bioturbation and other taphonomic factors causing shell fragments to move down the profile. For Square A SUII rests between 25cm and 55cm below the surface. In Square B SUII is found 30 – 45cm below the surface. Sediments are highly alkaline (8.5 – 9.5 pH).
III	Very loosely consolidated reddish yellow (7.5YR-6/6) sands in Square A and pink (7.5YR-7/4) coarse sands in Square B. SUIII in both squares contains plentiful shell grit and small molluscs, including *Calliostoma* sp. A continuous layer of beach rock forms the base of this unit at c.45 – 60cm below the surface. This SU is culturally sterile. Sediments remain highly alkaline (8.0 – 9.0 pH).

12.4 Radiocarbon Chronology

Two radiocarbon determinations were obtained from marine shell for the deposits at Murdumurdu. These mollusc specimens were recovered from the base of the major cultural shell in each square. Dates are reported at the 95.4% age range and corrected using the Gulf of Carpentaria Δ*R* value of -49±102 ^{14}C years (Ulm et al. 2010). This limited radiocarbon chronology suggests Murdumurdu has been used for at least 300 years (Table 12.2), placing occupation at Murdumurdu after Marralda Swamp entered its mangrove phase c.500 cal BP (Moss et al. 2015). Dates on shell from the sterile beach layer below by Sloss et al. (2015) of up to 1494±25 BP suggest the associated dune system formed after c.2400 cal BP in conjunction with falling sea levels. These dates suggest an approximate 2000 year hiatus between the formation of the shelly-beach ridge and initial occupation.

Table 12.2 Radiocarbon ages on marine shell from Murdumurdu, Squares A and B. Radiocarbon ages were calibrated using OxCal 4.2 (Bronk Ramsey 2009) and the Marine13 calibration dataset (Reimer et al. 2013), with a Δ*R* of -49±102 (Ulm et al. 2010). All calibrated ages are reported at the 95.4% age range.

Square	**XU**	**Depth (cm)**	**Sample**	**Lab. No.**	**Method**	**δ^{13}C (‰)**	**CRA (BP)**	**Calibrated Age BP (95.4%)**	**Calibrated Age BP Median**
A	5-6	14-17	*Gafrarium pectinatum*	Wk-34780	AMS	1.7±0.2	640±25	67-508	328
B	7-8	20-24	*Marcia hiantina*	Wk-34776	AMS	0.9±0.2	634±27	67-504	322

Peck (2016) utilised analysis of the age-depth relationship of radiocarbon dates and the matrix stratigraphy to divide the Murdumurdu assemblage into 250-year temporal phases (Table 12.3). The limited radiocarbon assemblage associated with this site, particularly the absence of a termination date (here assumed to be 0 cal BP), means the associated chronology is potentially problematic and should therefore be approached with caution. For this reason, along with the constrained nature of the deposit, 100-year phases are not applied to this site. Instead data will be discussed using the chronology suggested by Peck (2016).

Table 12.3 Square A and B XUs assigned to 250-year temporal phase bins as per Peck (2016).

Temporal Phase (cal BP)	0 – 250	250 – 500	500 – 750	750 – 1000	1000 – 1250
Square A XUs	1 – 3	4 – 8	9 – 11	12 – 15	16 – 20
Square B XUs	1 – 5	6 – 11	12 – 17	18 – 20	

12.5 Squares A and B Analysis

12.5.1 Specimen Selection

Using procedures outlined in Chapter 5, 5% of total MNI counts from XUs containing cultural material were selected for stable isotope analysis. Between 1 and 5 *M. hiantina* specimens were selected per XU (mean = 2.1). Given that Peck (2016) suggests material deposited at Murdumurdu prior to 500 cal BP is largely non-cultural and that the most recent XUs contained sparse assemblages, severely limiting the number of usable valves, specimen selection focused primarily on XUs 3 – 10 for Square A and 2 – 8 in Square B. See Appendix I for a detailed overview of selected specimens.

12.5.2 Testing for Recrystallisation

Archaeological specimens were tested for recrystallisation using FTIR (see Chapter 5 for procedures). All material returned wavelength plots indicative of aragonite, indicating no instances of pre- or post-depositional recrystallisation. Therefore, no archaeological material was discarded from stable isotope analysis.

12.5.3 Stable Isotopes

As excavations were undertaken in separate pits, XU depths are not directly comparable. Therefore, results are initially presented on a per square basis. In subsequent discussion, once XUs have been placed within an overarching temporal framework, all results are amalgamated and assessed as a single assemblage.

12.5.3.1 Square A

Overall $\delta^{18}O_{shell}$ values returned a mean of -1.5‰ with a range of -3.7‰ to -0.2‰ ($1\sigma = \pm 0.9‰$). A majority of these values (87%; $n = 13$) are grouped within 1σ of the overall mean, with 94% ($n = 14$) within 2σ. The remaining value was more than 2σ from the Square A mean (6%). These closely grouped, relatively positive values suggest *M. hiantina* were gathered during cool marine conditions throughout the occupation of Murdumurdu (Figure 12.8). Comparisons with seasonal $\delta^{18}O_{shell\text{-}predicted}$ ranges indicate close links between expected dry season values and analysed archaeological edge margins (Figure 12.8). No specimens fall outside the dry season, although the value from XU8 was on the lower border of the dry season range.

Similarly consistent results were evidenced in $\delta^{13}C_{shell}$ values, which range between -2.7‰ and +0.9‰ (mean = -1.3‰; $1\sigma = \pm 0.9‰$). However, data are less tightly grouped than oxygen with 67% ($n = 10$) within 1σ and 94% ($n = 14$) within 2σ. Relatively positive $\delta^{13}C_{shell}$ values suggest little interaction with terrestrial carbon sources, with carbonates being built primarily from marine reservoirs (see Petchey et al. 2013).

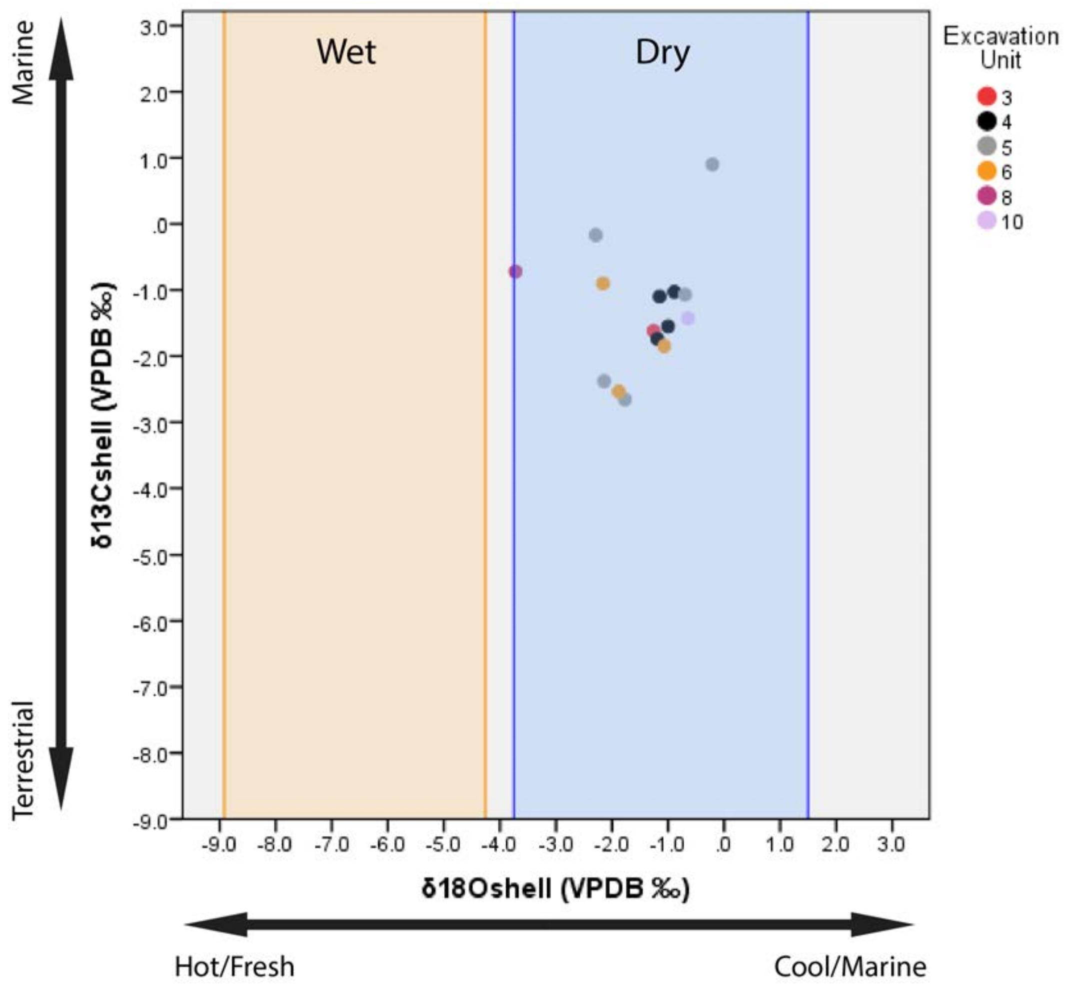

Figure 12.8 Stable isotope values from archaeological *M. hiantina* at Murdumurdu Square A are indicative of collection during cool marine conditions, with all values falling within the predicted dry season range (blue shaded area).

Comparisons between XUs reveal little variability throughout Square A. A One-way ANOVA demonstrates significant relationships in δ^{18}O$_{shell}$ and δ^{13}C$_{shell}$ values between all XUs (δ^{18}O$_{shell}$: *F*(5) = 2.928, *p* = .077; δ^{13}C$_{shell}$: *F*(5) = .229, *p* = .940). As only three XUs contained two or more specimens, applying a Tukey HSD post-hoc test requires XUs 3, 8, and 10 to be removed. Results derived from the remaining XUs reveal a close association in δ^{18}O$_{shell}$ values with *p* values ranging from .453 (XUs 4 and 6) to .838 (XUs 4 and 5). Likewise, δ^{13}C$_{shell}$ values see significant relationships across XUs with *p* values of .674 (XUs 5 and 6) to .923 (XUs 4 and 5). Close correlations suggest all material was collected from environments exhibiting highly similar conditions (Figure 12.9).

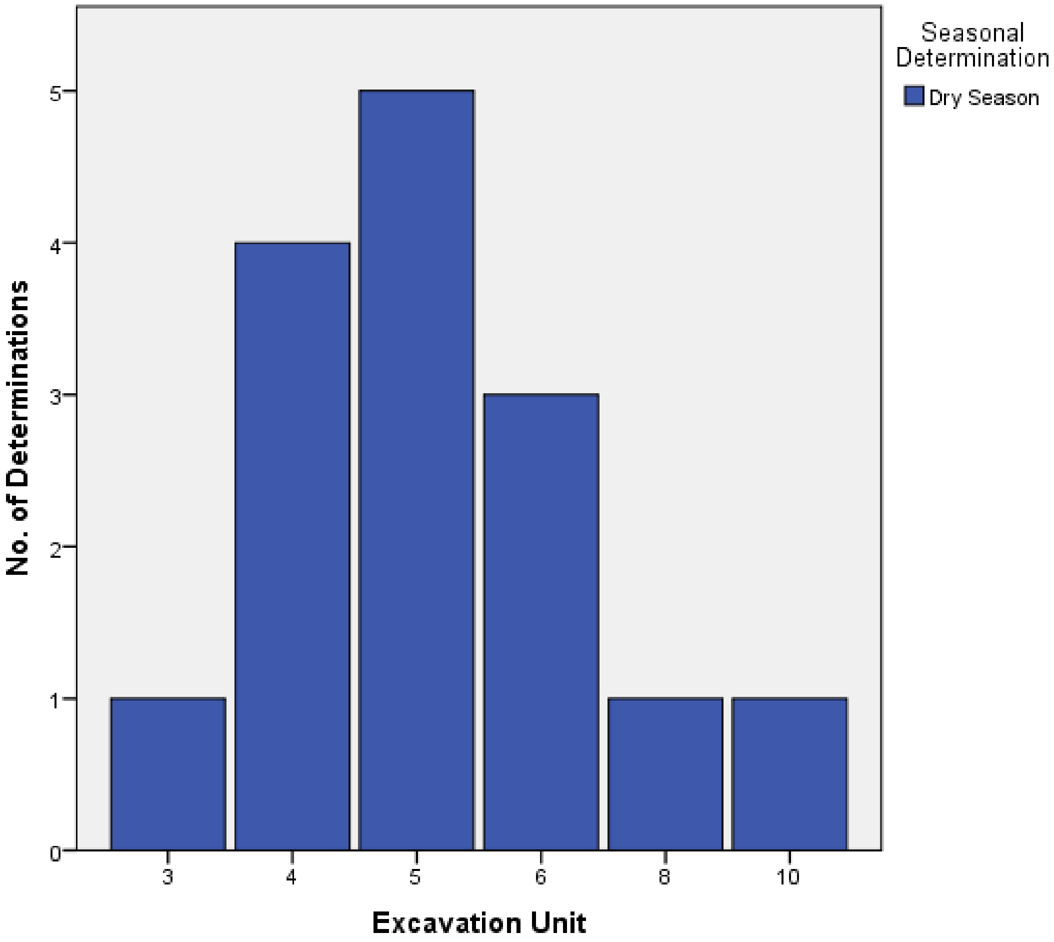

Figure 12.9 Seasonal determinations delineated by excavation unit for Square A, Murdumurdu. Note that all determinations returned values indicative of dry season conditions.

12.5.3.2 Square B

$\delta^{18}O_{shell}$ values from Square B appear similar to those derived from Square A, with a mean of -0.8‰ and a range of -2.8‰ to +0.4‰ (1σ = ±1.0‰). Values are not as tightly clustered, spread equally across 1σ (*n* = 7; 54%) and 2σ (*n* = 6; 46%) ranges. Despite this, data grouping and consistently positive values suggest that, much like Square A, *M. hiantina* from Square B were collected during cool marine conditions (Figure 12.10). Applying seasonal $\delta^{18}O_{shell\text{-}predicted}$ ranges confirms this, with all values remaining within the dry season range.

Stable conditions are also evidenced in $\delta^{13}C_{shell}$ values, which are grouped between -2.6‰ and -0.9‰ (mean = -1.6‰; 1σ = ±0.6‰). These values are evenly scattered throughout the entire range with 38% (*n* = 5) within 1σ and 62% (*n* = 8) within 2σ, while the remaining 38% (*n* = 5) are outside 2σ. Despite this spread, $\delta^{13}C_{shell}$ values are relatively positive suggesting that carbonates were primarily constructed from marine DIC (Figure 12.10).

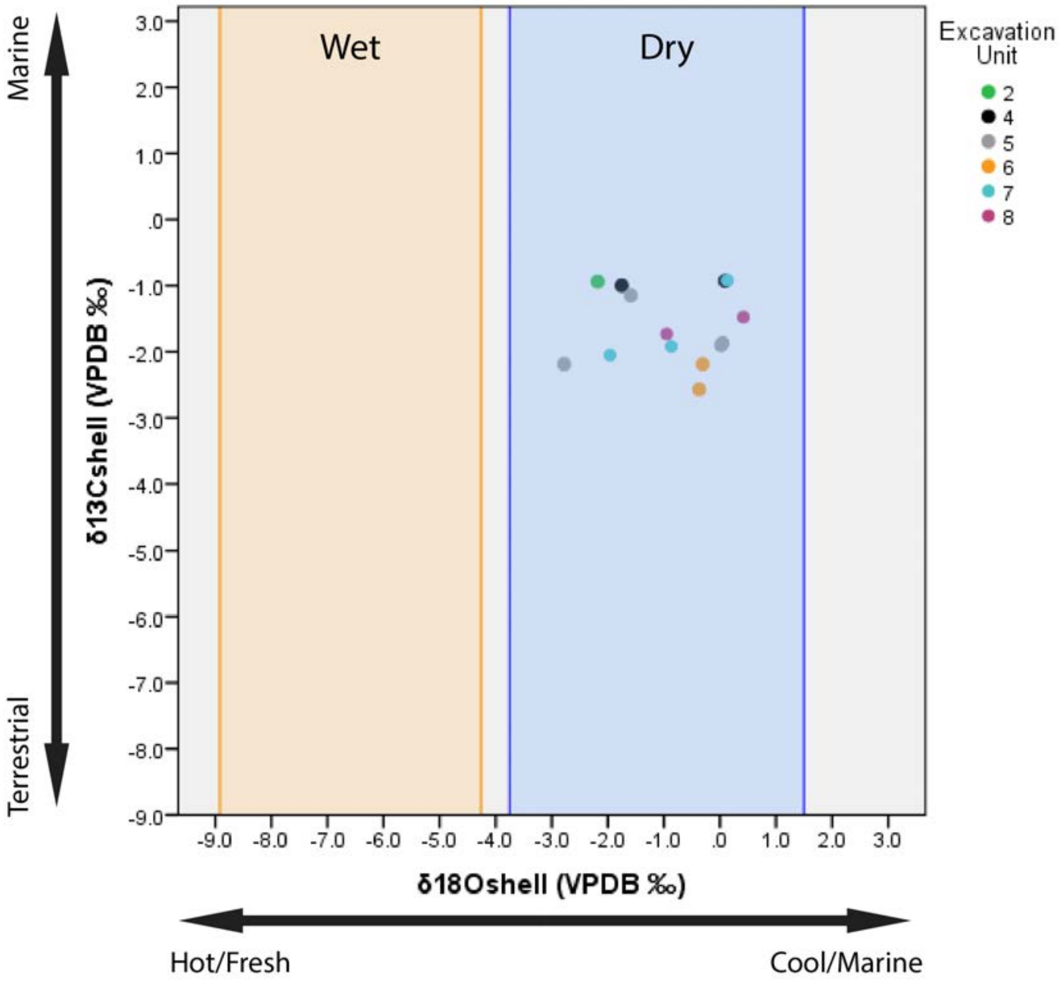

Figure 12.10 Stable isotope values from archaeological *M. hiantina* at Murdumurdu Square B are indicative of collection during cool marine conditions, indicating that, like Square A, occupation occurred exclusively during the dry season (blue shaded area).

Statistical comparisons between XUs exhibit only minimal variability throughout the occupation of Square B (Figure 12.11). A One-way ANOVA demonstrates significant relationships in $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values between all XUs ($\delta^{18}O_{shell}$: $F(5) = .487$, $p = .778$; $\delta^{13}C_{shell}$: $F(5) = 2.825$, $p = .093$). Augmenting these results with a Tukey HSD post-hoc test reveals consistent associations in $\delta^{18}O_{shell}$ across all XUs with *p* values of between .918 (XUs 5 and 8) to 1.000 (XUs 4 and 7 as well as 5 and 7). $\delta^{13}C_{shell}$ returned substantially more variable *p* values, which ranged from .061 (XUs 4 and 6) to 1.000 (XUs 7 and 8). The variable, although consistently significant, relationships observed in $\delta^{13}C_{shell}$ values is caused by the spread of data points across 3σ despite their small range. XU2 was excluded from post-hoc testing as it encompasses less than two values.

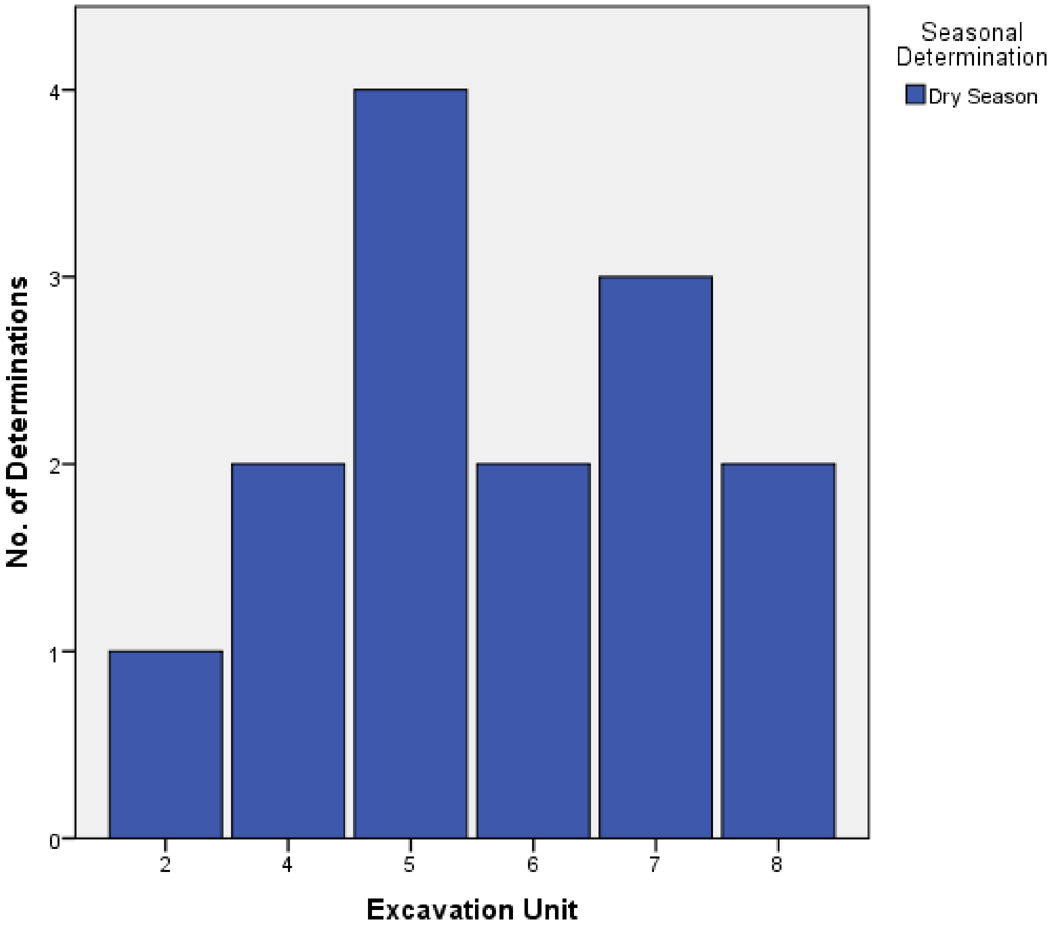

Figure 12.11 Seasonal determinations delineated by excavation unit for Square B, Murdumurdu.

12.5.3.3 Amalgamated Data in 250-year Temporal Phases

Employing the 250-year temporal phases generated by Peck (2016) couches seasonal determinations within a chronological framework (Table 12.4), allowing changes in short-term patterns of occupation to be characterised. However, unlike Thundiy and Dangkankuruwuru, the timing of occupation appears to remain stable throughout Murdumurdu's use (Figure 12.12). A One-way ANOVA highlights strong relationships through time in both $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values ($\delta^{18}O_{shell}$: *F*(2) = .142, *p* = .868; $\delta^{13}C_{shell}$: *F*(2) = .006, *p* = .994). While a Tukey HSD post-hoc test could not be applied as there were fewer than three usable groups (500 – 750 cal BP could not be incorporated as it encompasses less than two values), it is unlikely that this would have revealed any additional variability between temporal phases. The implications of these findings for Kaiadilt occupation at Murdumurdu is presented in Section 12.6.

Table 12.4 Total number of specimens analysed per 250-year temporal phase.

Temporal Phase (cal BP)	0 – 250	250 – 500	500 – 750
Specimens	8	20	1

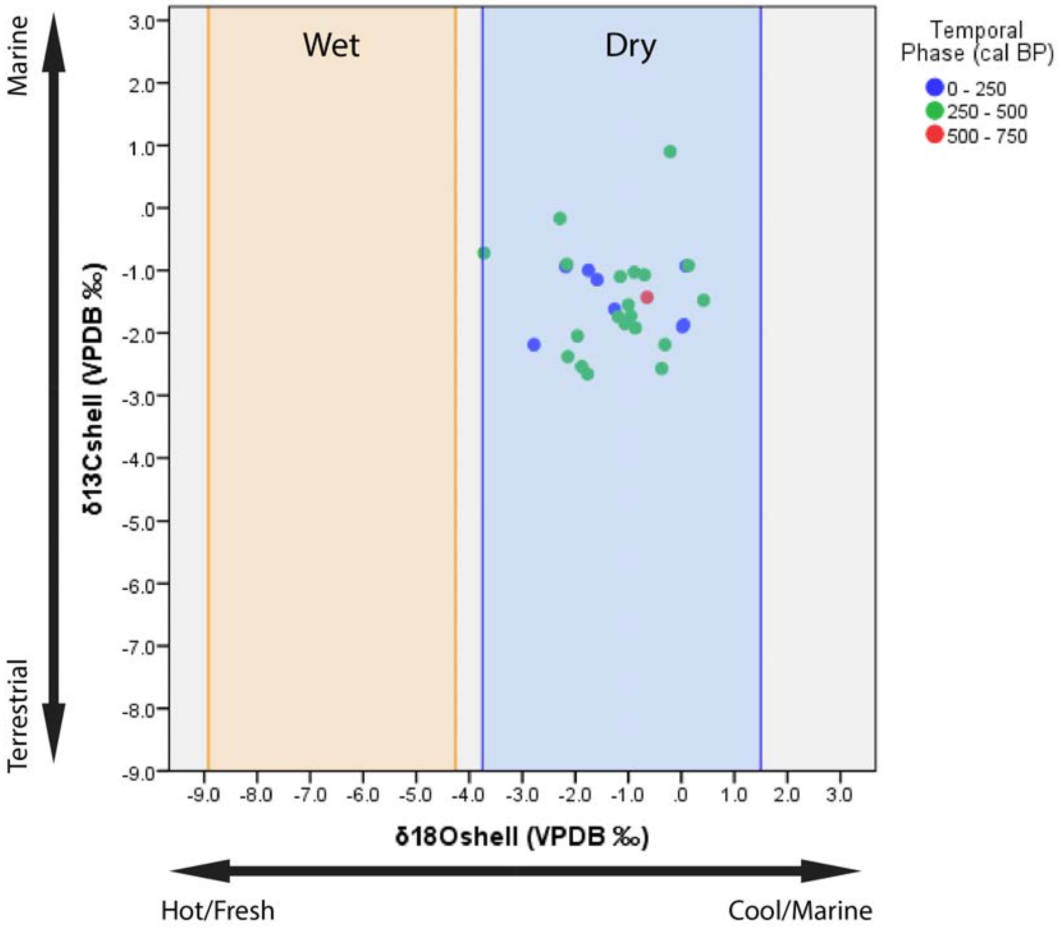

Figure 12.12 The collection of *M. hiantina* at Murdumurdu remains consistently timed with cool marine conditions over a period of at c.750 years, suggesting occupation was focused on the dry season throughout the entirety of this sites use.

12.6 Timing and Periodicity of Occupation at Murdumurdu

12.6.1 Defying Expected Patterns of Occupation

Patterns of occupation at Murdumurdu appear closely connected to season cycles, with stable isotope analyses indicating the site was used exclusively during the dry season. However, factors leading to this decision are not as immediately obvious as with other previously discussed sites (see Chapter 10 and 11). In particular as Murdumurdu is located on Bentinck Island's windward side for the duration of the dry season, periods of occupation coincide with the site being exposed to strong southeasterly winds and rough water conditions. Given ethnographic and archaeological evidence of periodic site abandonment during similar conditions (see Chapter 10; Memmott 2010:21), it was somewhat unexpected that this site was occupied exclusively during the dry season. Therefore, it is posited that patterns of Kaiadilt occupation at Murdumurdu were driven by the interplay of various climatic, environmental, and cultural influences.

Unlike sites exhibiting highly diverse assemblages (see Chapters 10 and 11), cultural material excavated from Murdumurdu is overwhelmingly dominated by two bivalve species – *M. hiantina* and to a lesser extent *G. pectinatum* (Peck 2016). The subtidal nature of *M. hiantina* necessitates collection to be undertaken primarily at low tide, requiring foragers to carefully time their collections and traverse up to 600m of intertidal flats to reach shellfish beds (personal observation, 2014, 2016; see also Meehan 1982:81-86). It must therefore be assumed that the exploitation of this species was deliberate and targeted rather than opportunistic. Conversely, *G. pectinatum* are found on the surface of intertidal flats (Baron and Clavier 1992; Kurihara 2003), with archaeological specimens constrained to Square A (Peck 2016). This suggests *G. pectinatum* was collected opportunistically upon encounter rather than being explicitly targeted. Given these findings it is probable that Murdumurdu was occupied sporadically for short periods of time by people exploiting local littoral resources. This lessens the importance of highly effective shelter, as the exploitation of low-intertidal/subtidal taxa is unlikely to occur during rough seas. Furthermore, groups occupying the site for limited periods of time could easily relocate if conditions became too severe, for example to the northern protected side of Marralda Swamp. Murdumurdu is therefore more closely related to the dinnertime camps documented by Meehan (1982) than a central locus of exploitation as represented by Thundiy or Dangkankuruwuru (Peck 2016; see also Chapters 10 and 11).

Decision-making leading to the suspension of cultural activities at Murdumurdu during wet season conditions was likely influenced by an assortment of cultural, behaviour, and environmental factors. Isolation may have played a role with monsoonal rainfall causing extensive seasonal flooding in surrounding low-lying savannah, swamp systems, and clay pans. However, it was found that Murdumurdu remains easily accessible via nearby beach and dune systems, even at the height of the wet season (personal observation, 2014). An alternative explanation sees substantial increases in mosquito and other insect populations, which thrive in wet season conditions in Marralda Swamp causing great discomfort to anyone residing nearby. However, it seems unlikely that this alone would have caused the seasonal abandonment of Murdumurdu, although the Lardil of the North Wellesley Islands make note of increased mosquito activity in their traditional calendar confirming its importance to decision-making processes (see Rosendahl 2012:60; Chapter 3).

Broader changes in mobility may also impact the cyclical abandonment of Murdumurdu. Several ethnographic accounts have documented seasonal change in mobility across Australia's tropical north coast, highlighting increases in sedentary behaviour for the duration of the wet season (e.g. Davies 1985; Meehan 1982; Memmott 2010:21; Rosendahl 2012:60). Thus, as groups establish more permanent wet season camps and begin limiting foraging ranges, it follows that sites that were only intermittently occupied during the dry season would be among the first to fall into disuse. Similar changes in subsistence practices, owing to temporary shifts in resource availability, mobility, demography, or exploitation patterns, may lead to abandonment not just of Murdumurdu but also of the surrounding area in order to access other seasonally available resources.

12.6.2 Changing Patterns of Use through Time

While Murdumurdu exhibits evidence of stable dry season occupation, the intensity of use varies significantly through time. To better characterise and interpret these changes, seasonality determinations are considered within the framework of 250-year phases in combination with a palaeoenvironmental and archaeological foundation established by previous research (Moss et al. 2014, 2015; Peck 2016). Radiocarbon determinations indicate that Murdumurdu was occupied from at least 328 cal BP. However, analysis of the archaeological assemblage suggests an earlier period of ephemeral use between 500 – 750 cal BP, as evidenced by a sparse archaeological assemblage and limited numbers of economic species (Peck 2016). A single dry season determination was reached for this period (Figure 12.13). While this suggests the presence of seasonal behaviours, characterisations of the timing and periodicity of site-use are severely limited by the small assemblage size and the lack of radiocarbon dates from this part of the deposit. The ephemeral nature of activity at Murdumurdu during this initial phase has been linked with potentially low productivity of local resource bases (Peck 2016), which undergo significant changes from 500 cal BP.

The period between 250 – 500 cal BP exhibits a substantial rise in assemblage density (Figure 12.13), encompassing almost half the total MNI of deposited material, and concurrent change in exploitation focus towards sandy-mud species such as *M. hiantina* (Peck 2016). This coincides with substantial environmental change in nearby Marralda Swamp, which entered a contemporaneous mangrove phase (Moss et al. 2015). Similarly timed vegetation changes are evident at Thundiy, where a peak in charcoal abundance was accompanied by declining mangrove species and increases in grass and arboreal taxa (Moss et al. 2014). In combination these factors suggest that changing environmental conditions may have facilitated increasing use of Murdumurdu. In particular, if decreases in coastal mangrove fringes suggested for Thundiy also occurred along the coastline adjacent to Murdumurdu, the subsequent formation and expansion of littoral resource bases – such as marine shellfish populations – would have provided newly accessible productive environments for exploitation.

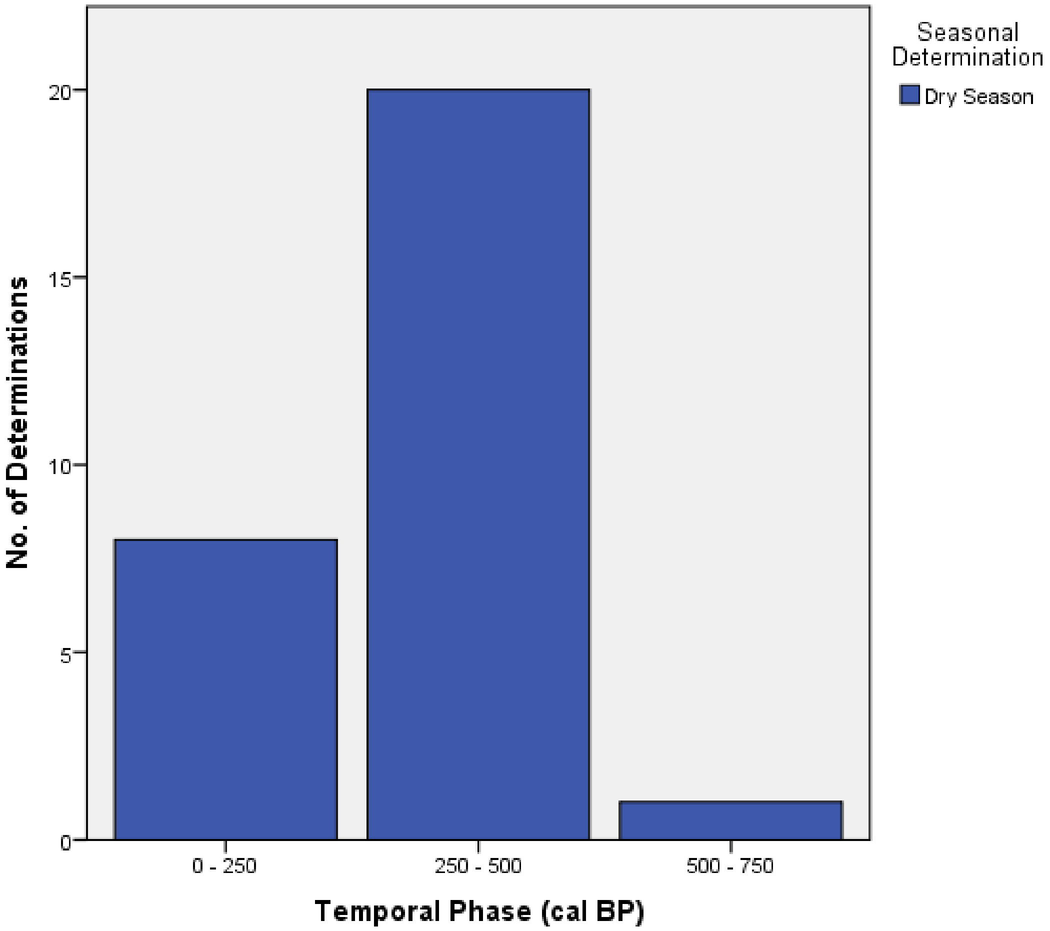

Figure 12.13 Stable isotopic analysis of archaeological *M. hiantina* from Murdumurdu suggest that Kaiadilt activity at this site was focused on dry season use.

Archaeological material associated with more recent occupation at Murdumurdu (0 – 250 cal BP) indicates a decrease in the intensity or frequency of use, as evidenced by a reduction in assemblage density (Peck 2016). This change coincides broadly with the arrival of Macassan and then European parties (see Memmott 1982b; Oertle et al. 2014; Tindale 1962a). The lifeways of Kaiadilt living along the south coast of Bentinck Island likely saw significant change during this period, given the close proximity of Macassan trapanging operations on Fowler Island (Oertle et al. 2014) and the well-documented European occupation of Fowler, Sweers, and Bentinck Islands (Kelly and Evans 1985; Laurie 1866; Memmott 1982b; Stubbs 2005; Tindale 1962a, 1962b). Murdumurdu is exposed and visible from the sheltered anchorages of Fowler Island and Inscription Point on Sweers Island. Thus, the reduction in use of Murdumurdu may be part of a larger change to decision-making processes and associated behaviours in order to negotiate the presence of external groups.

The evidence presented above suggests that while the occupation of Murdumurdu was relatively short and remained seasonally stable, the intensity of use fluctuated through time. To this end three key phases of occupation are suggested (Table 12.5). The ephemeral phase (500 – 750 cal BP) encompasses initial occupation until c.500 cal BP and is typified by a sparse assemblage, high numbers of non-economic molluscan taxa, and dry season use. The termination of this phase (c. 500 cal BP) saw substantial environmental shifts, which are linked with environmental and behavioural changes evidenced across Bentinck Island. What followed was a period of intense dry season use for Murdumurdu (250 – 500 cal BP), with a focus on exploiting sandy-mud species. Finally, the most recent phase (0 – 250 cal BP) is typified by decreasing use, likely associated with the arrival of Macassans and later Europeans in the area. Thus, despite highly stable timing and periodicity of site use, Murdumurdu exhibits a multidirectional chronology that shares both similarities and differences with other sites examined in this research. The wider implications of this chronology will be discussed in Chapter 13.

Table 12.5 Three phases of occupation can be identified in Murdumurdu – after Kelly and Evans 1985; Laurie 1866; Macknight 1972, 1986; Moss et al. 2012, 2014; Oertle et al. 2014; Peck 2016 Stubbs 2005; Tindale 1962b.

Occupation Phase (cal BP)	**Assemblage Density**	**Seasonality**	**Landscape and Palynology**	**Shellfish Exploitation**	**Other Factors**
Ephemeral Seasonal 500 – 750	Sparse	Exclusively dry season	NA	Primarily non-economic taxa	Initial occupation
Environmental Shift c.500	NA	NA	Appearance of mangroves at nearby Marralda Swamp	NA	Sharp charcoal spike, increase in grasses and arboreal taxa at Thundiy
Intense Seasonal 250 – 500	Sharp increase, dense	Exclusively dry season	Mangrove swamp	Focus on sandy-mud taxa	NA
Moderate Seasonal 0 – 250	Sharp decrease	Exclusively dry season	Late shift to freshwater swamp	Continued focus on sandy-mud taxa	NA

12.7 Summary

Analysis of archaeological *M. hiantina* from the shell matrix site of Murdumurdu revealed highly seasonal use throughout the archaeological record. Stable oxygen values are indicative of specimens collected exclusively from cool marine conditions during the dry season. Moreover, it is posited that Murdumurdu was not a central-place camp, but was occasionally occupied for short periods of time as a base for exploiting local littoral resources. While the timing of use did not change over the course of the sites use, the intensity of occupation fluctuated through time. This divides use at Murdumurdu into three distinct multidirectional phases that are delineated by environmental change, resource availability, occupation intensity, and contact with European and Macassan parties. This high-resolution chronology provides insight into resource and landscape use beyond central-place camps, suggesting that the Kaiadilt employed a diverse suite of exploitation and occupation strategies.

Chapter 13 Synthesis, Discussion, and Conclusions

13.1 Introduction

A key aim of this research was to demonstrate the importance of local-scale and short-term patterns in constructing broader narratives. This was achieved through the application of a novel methodology that incorporated high-resolution data recovery techniques to characterise relationships between environmental conditions and isotopic records in the shell carbonates of mollusc taxa commonly exploited by the inhabitants of Bentinck Island (Chapters 7 – 9). Applying these methods to archaeological assemblages allowed the generation of some of the highest resolution occupation chronologies produced for Australia's tropical north coast to date (Chapters 10 – 12). By demonstrating the efficacy of these techniques in tropical Australian settings this research has opened new avenues for researchers to approach nuanced interpretations of fundamental Aboriginal decision-making processes, while highlighting the diversity and complexity of human-environment relationships and how these change through time.

This chapter synthesises isotopic seasonality and archaeological data from Thundiy, Dangkankuruwuru, and Murdumurdu to construct a high-resolution chronology of site-use for Bentinck Island over the last c.1500 years. Stable isotope analysis of archaeological shell carbonates reveal variable links between seasonal cycles and patterns of occupation at these sites, highlighting the presence of changing human-environment interactions. Decision-making processes that govern these relationships shift through time in accordance with environmental, cultural, and economic conditions and contexts. These changes suggest that Kaiadilt occupation of Bentinck Island, and by extension the South Wellesley's as a whole, was highly complex, exhibiting a number of multidirectional, localised patterns of use that fluctuated at varying temporal and geographic scales.

Occupation patterns on Bentinck Island can be contextualised against broader regional and inter-regional models of offshore island use during the mid-to-late Holocene. Findings refute notions of static or unidirectional use of island environments, instead highlighting the importance of temporally and geographically localised human-environment interaction. These patterns can be used to generate nuanced narratives that explore how shifting relationships are reflected in behavioural and cultural changes. Moreover, larger questions relating to changes in social structuring during the mid-to-late Holocene, which numerous authors argue are key in characterising behavioural decision-making processes (Attenbrow 2006; Hiscock 1994, 2008; Smith 2013; Williams et al. 2010, 2015a), can also be approached. This discussion is then couched within the context of key findings and contributions to the discipline. Finally, potential future directions and extensions of this research are outlined before final conclusions are presented.

13.2 Late Holocene Kaiadilt Occupation of Bentinck Island

The South Wellesley Archipelago is an environmentally dynamic area that is rich with archaeological material, with surveys revealing myriad cultural features deposited over the last c.3500 years (Figure 13.1). It is therefore unsurprising that the archaeological narrative associated with such an active landscape is complex, displaying highly localised multidirectional patterns of site-use formed in conjunction with changing behavioural responses to variably scaled environmental and cultural influences (see Chapters 10 – 12). While these findings represent a substantial step towards better understanding Aboriginal use of offshore islands using local-scale data, the diversity and changeability of ways in which sites were used throughout the occupation of the region also presents a hurdle as a single overarching model of occupation constructed from the three target sites may not accurately represent use patterns. To overcome this, site chronologies are couched within the broader regional sequence proposed by complementary studies (Memmott et al. 2016; Peck 2016; Ulm et al. 2010) as well as other well documented behavioural influences, including region-wide environmental shifts and periods of contact with external parties, allowing highly localised patterns to assist in the construction of narratives on broader scales.

The radiocarbon chronology proposed for the South Wellesley Islands utilises 128 dates from 96 sites to characterise three overarching phases of occupation (Memmott et al. 2016; Peck 2016). The earliest phase (2000 – c.3500 cal BP) appears to be a period of exploratory occupation within a landscape that displayed substantial differences from today owing to heightened sea levels of +2m (Moss et al. 2015; O'Connor 2016; Sloss et al. 2015). None of the sites explored in this research correspond to this time period, and thus it is not discussed in any detail. The second phase (800 – 2000 cal BP) is characterised by discontinuous low-intensity occupation of the island group by wide-ranging foragers, with increasing use from c.1000 cal BP (Memmott et al. 2016; Peck 2016; Ulm et al. 2010). Dangkankuruwuru is brought into use during this phase (Figure 13.2). The most recent phase (0 – 800 cal BP) saw intensive occupation, site establishment, and material deposition, with a majority of dates from across the South Wellesley Islands falling within this period. All three sites analysed for this thesis show evidence of occupation during this phase (Figure 13.2). Amalgamating site-specific chronologies with this broader regional sequence highlights complex patterns of occupation and site-use across the landscape. Moreover, it refutes the assumption of static or unidirectional use, with all sites displaying multidirectional patterns that are continuously modified through time in response to a variety of environmental and cultural influences.

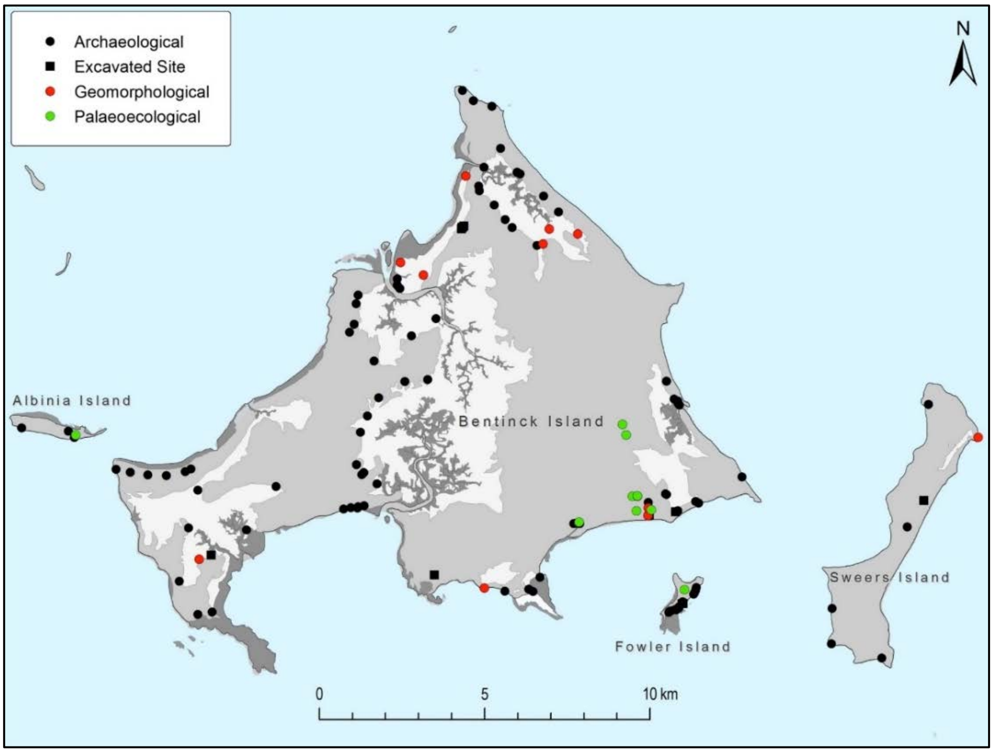

Figure 13.1 Extensive archaeological, geomorphological, and palaeoecological research in the South Wellesley Islands has produced an increasingly nuanced view of the formation and use of the region (Map: Lincoln Steinberger and Sean Ulm, 2015).

Within this broader chronology are a number of unique patterns manifesting at localised and short-term scales. These patterns suggest a variety of factors impacted Kaiadilt decision-making processes, fundamentally shaping behavioural responses to environmental and cultural changes. Of particular interest to this research is the impact of seasonal climatic and environmental change on behavioural choices. While seasonal cycles appear to have been key drivers behind short-term behavioural change, their importance fluctuates through time. Early periods of occupation tend to be highly seasonal, with a majority of use scheduled to coincide with dry season conditions. This is particularly salient at Dangkankuruwuru where the timing and periodicity of occupation, coinciding with the broader discontinuous phase, was potentially driven by seasonally timed climatic shifts, including wind direction and storminess. Thus, providing conditions suitable for groups of wide-ranging foragers to undertake open water voyages from the mainland (see Chapter 11). It is therefore possible that use of Bentinck Island prior to 800 cal BP was directly linked with dry season conditions, however additional analyses of sites containing similarly timed depositions are required. Early occupation at Thundiy (300 –

c.800 cal BP) displays similarly strong links with seasonal climatic shifts, where occupants engaged in a cyclical pattern of dry season use and wet season abandonment (see Chapter 10). This patterned behavioural change was linked with short-term climatic shifts associated with the Australian monsoonal cycle, as suggested by a number ethnographic sources (Davies 1985; Meehan 1977, 1982; Memmott 2010; Sutton 2010; Thomson 1939). Unlike Dangkankuruwuru this period of highly seasonal use coincides with the broader intensive occupation phase, suggesting a shift away from seasonal abandonments of Bentinck Island to the scheduled movement of groups across the local landscape.

The importance of seasonal climatic cycles to Kaiadilt decision-making processes does not remain static throughout time, with evidence from Dangkankuruwuru and Thundiy suggesting a move away from highly scheduled dry season use after c.300 cal BP (Figure 13.3). This may be representative of a number of changes occurring within Kaiadilt culture. Rising deposition rates of archaeological material, increasing evidence of site establishment, and broadening diets suggest increases in population density (Memmott et al. 2016; Peck 2016). Ethnographic accounts indicate that during the mid-twentieth century Kaiadilt populations were among the densest in Australia (0.7 people per 1km^2), with Tindale (1977:249) suggesting that in 1940 the South Wellesley Islands population was 'one of the highest known for a living stone tool-using people depending on foraging for their existence'. Provisioning such a large population likely required intensive exploitation, encouraging longer residency times at sites with access to plentiful or reliable resources. Increasing populations may also be associated with the emergence of the clearly documented territoriality documented in the archaeological record.

Reductions in the seasonality of site occupation may also point to increasing reliance on resource procurement facilities, in particular the expansive stone-walled fish trap complexes found along the South Wellesley Islands coastline (Memmott 1982b; Memmott et al. 2008; Memmott and Trigger 1998; Tindale 1962a, 1962b). While establishing the antiquity of fish trap construction and use is difficult owing to a paucity of directly associated datable material, the late timing of sea-level stabilisation (c.800 cal BP) provides a timeframe in which fish trap use likely commenced (Sloss et al. 2015). Moreover, increases in archaeological fish bone density from 500 – 750 cal BP are indicative of increasing exploitation of trap systems (Peck 2016), suggesting construction and use began within this timeframe and peaked between 250 – 500 cal BP. This coincides with shifts towards pan-seasonal use of sites. Establishment, maintenance, and management of these complex features would have required an on-site population, tethering groups to specific tracts of land and further encouraging more permanent occupation. Moreover, authors have suggested that the Kaiadilt reliance on fish traps may have led to technological specialisation (Memmott et al. 2006, 2008), further strengthening associations between groups and nearby trap complexes.

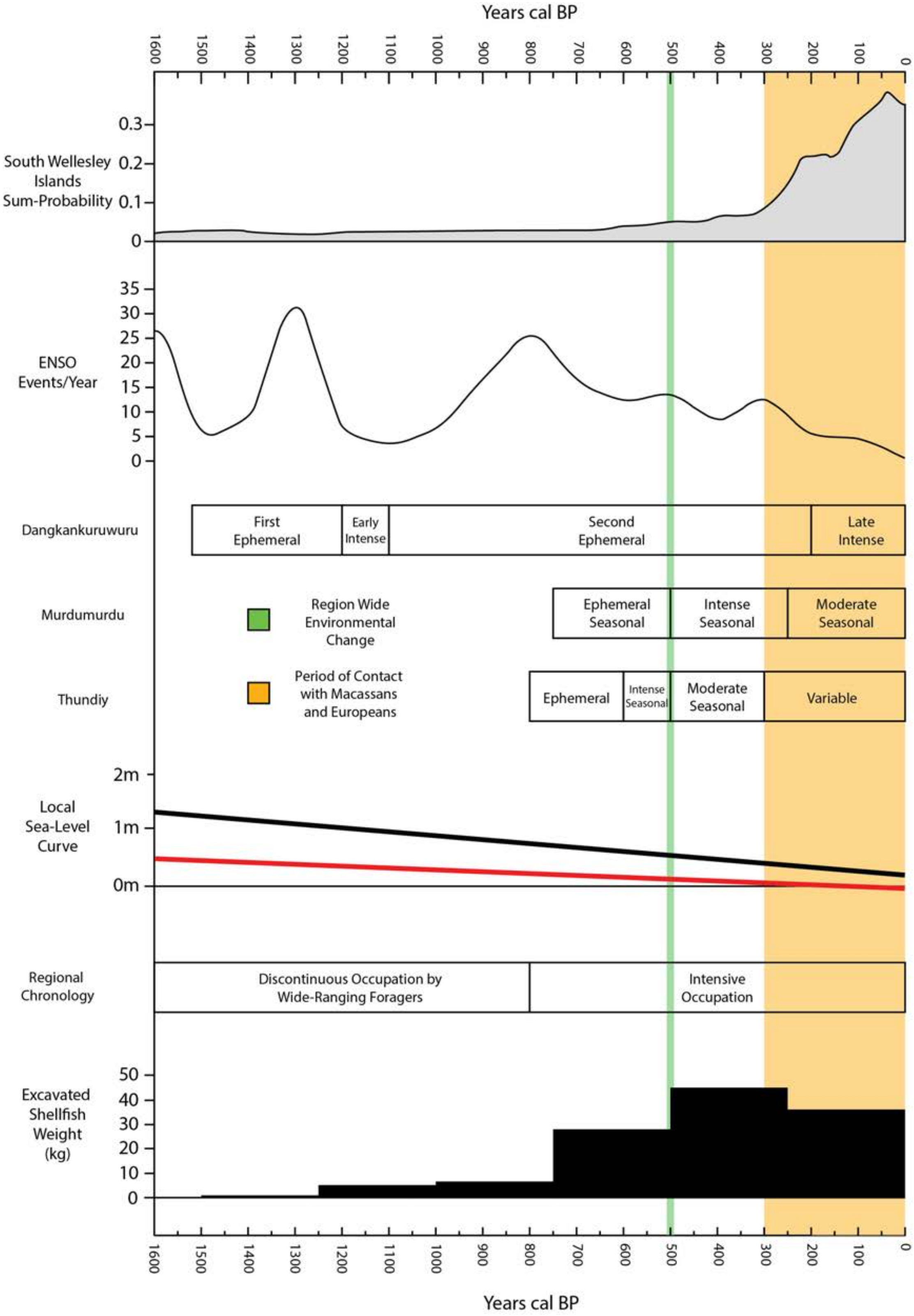

Figure 13.2 A comparison of both site-specific and regional occupation phases with broader environmental and cultural trends that impacted the South Wellesley Islands in the last c.1600 years (after Memmott et al. 2016; Moy et al. 2002; Peck 2016; Sloss et al. 2015).

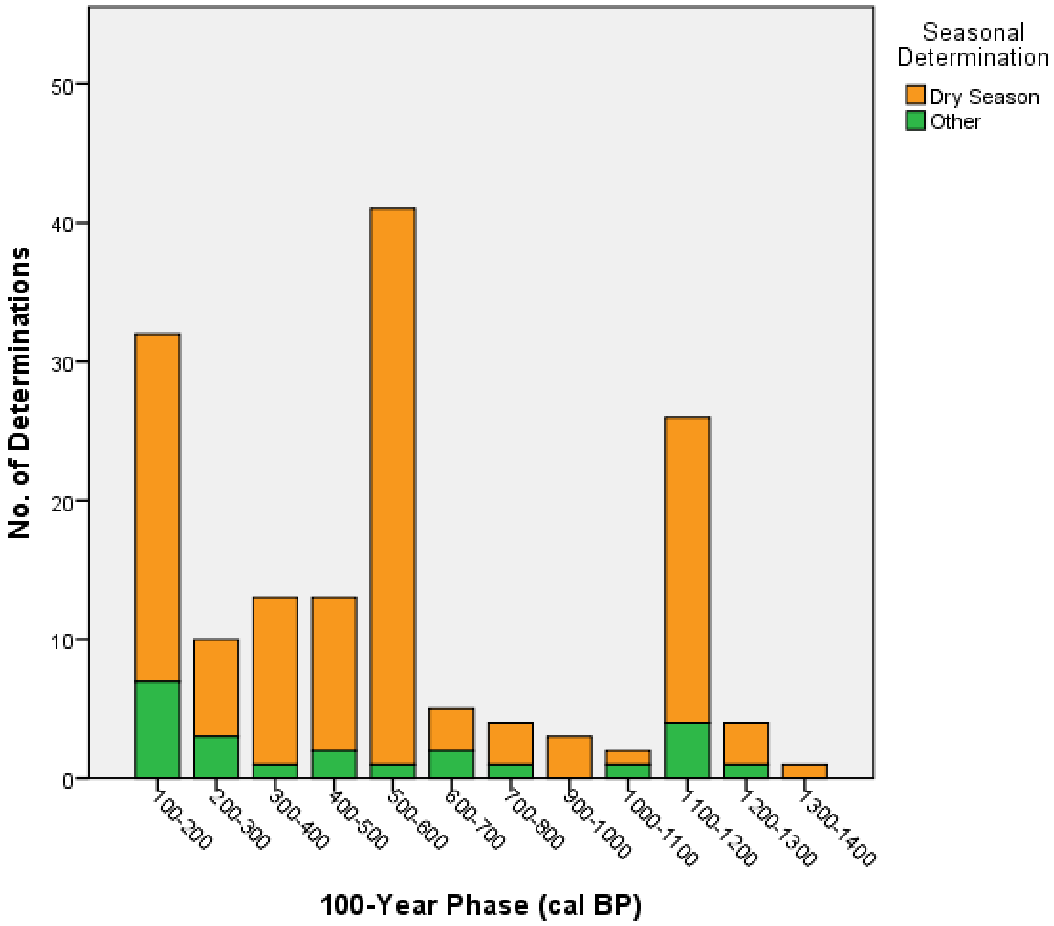

Figure 13.3 Combined seasonal determinations from Dangkankuruwuru and Thundiy suggest increasingly frequent site-use outside of dry season conditions after 300 cal BP.

Region-wide environmental changes were also instrumental in shaping Kaiadilt decision-making processes. The most salient example of this is apparent c.500 cal BP where concurrent shifts are evidenced at both Thundiy and Marralda Swamp (Moss et al. 2014, 2015). For Thundiy this signalled a decrease in occupation intensity and a move away from mangrove exploitation (Peck 2016), while the establishment of mangrove communities at Marralda Swamp suggests the presence of a sheltered, prograding coastal system (Moss et al. 2015). This allowed habitat and range expansion of littoral resources, such as *M. hiantina* and *G. pectinatum* populations, which were exploited by people at Murdumurdu from c.500 cal BP (see Chapter 12). On a broader scale, the frequency of ENSO events began to diminish significantly from c.800 cal BP (Moy et al. 2002; Figure 13.2), coinciding with increases in deposition and site establishment rates across the South Wellesley Islands (Peck 2016). Some authors have posited that ENSO played a significant role in dictating the commencement of permanent occupation in offshore island contexts (see Sim and Wallis 2008), suggesting similar forces may have impacted occupation patterns on Bentinck Island. However, differences in scale make such comparisons problematic (see Section 13.3 for further discussion of this).

Dominating later influences on Kaiadilt behaviour and decision-making processes is the arrival of Macassan and European parties, which extended over a period beginning c.300 cal BP until present. However, until now there had been relatively little evidence of how this era of contact may have impacted the Kaiadilt beyond the temporary loss of access to Sweers and Fowler Island and incorporation of European materials into the local toolkit (Kelly and Evans 1985; Oertle et al. 2014; Stubbs 2005; Tindale 1962a; Ulm et al. 2010). Findings presented in previous chapters indicate that Thundiy and Murdumurdu display changes in occupation strategies coinciding broadly with periods of contact with external groups (see Chapters 10 and 12). In particular, Thundiy saw increasing use outside of the dry season subsequent to the establishment of a nearby Macassan site, while Murdumurdu saw a reduction in use during Macassan and European occupation of Fowler and later Sweers Island. Connections can therefore be drawn for the first time directly between contact with external parties and shifts in Kaiadilt mobility as well as the timing and periodicity of site-use.

When considered together, many of the changes discussed above are indicative of shifts in the permanency of site-use with movement towards longer or even year-round occupation and use. While early occupation of the region appears to have been highly seasonal, suggesting links to broad climatic cycles that dictated the ease of access to the South Wellesley Islands from the mainland, later more permanent occupation does not require such stringent scheduling. Increases in population through time presented the need for more intensive use of available resources, with broad environmental changes providing the conditions for the development of littoral resource bases. The widespread construction of technology capable of reliably exploiting these bases, such as fish traps, led to stronger ties with the local landscape, potentially encouraging the development of land tenure systems such as the ethnographically described territorial *Dolnoro* system (Tindale 1962a, 1962b, 1963, 1977). Thus, it can be seen that decisions associated with the occupation of Bentinck Island, and by extension the South Wellesley Islands, are made in response to numerous temporally and geographically localised cultural and environmental influences, interweaving into a complex multidirectional narrative that required high-resolution data to meaningfully approach. This demonstrates the efficacy of employing local-scale interpretations to construct broader narratives that do not normalise diverse responses to change into simplified overarching patterns, thus alleviating concerns related to temporal and spatial homogenisation that are echoed throughout archaeological literature.

13.3 Approaching Nuanced Understandings of Aboriginal Offshore Island Use

Findings from the South Wellesley Islands refute notions of island occupation following a continuous unidirectional trajectory, instead confirming the presence of complex settlement patterns in offshore island contexts. This stresses the diversity of responses present within even a contiguous landscape occupied by a single cultural group, highlighting the need to approach understandings of Aboriginal offshore island use at resolutions that allow the full breadth of behaviours to be characterised and discussed. Therefore, interpretative frameworks based upon the broad continental or regional models often used to explain Aboriginal behaviour are incapable of generating nuanced narratives that adequately account for the variability inherent to hunter-gatherer life. Findings from the South Wellesley Islands provide a salient case study in which inconsistencies between local-scale patterns and broad models can be characterised.

When considered against broad-scale patterns the timing of Aboriginal occupation in the South Wellesley Islands largely conforms to the continental model of expansion into island environments after c.3000 cal BP (Barker 1996; Bowdler 1995; Williams et al. 2010). However, this model assumes continuous occupation commenced at initial colonisation and continued through until the ethnographic present (Bowdler 1995), a pattern which is not seen in the South Wellesley Islands (see Chapter 11 and Section 13.2). Similarities with the common notion of unidirectional increases in occupation intensity are also evident, with movements from low-level or ephemeral use towards more permanent occupation (see Chapters 10 – 13). However, this is not the smooth gradient of intensification that is often alluded to, with the intensity of occupation on Bentinck Island fluctuating through time (see Chapter 11 and Section 13.2). It is also difficult to assume that the rationale and timing for changes in occupation patterns remains similar between island contexts given fundamental cultural and chronological differences (e.g. Barker 1989; McNiven et al. 2014; O'Connor 1994; Rowland et al. 2015; Sim and Wallis 2008).

The South Wellesley Islands were utilised in an ephemeral or seasonal manner for a majority of their occupation history, over a period of c.2700 years from the earliest evidence of use (c.3500 cal BP) to the permanent colonisation of the island chain after c.800 cal BP. This deviates from the ideas presented by O’Connor (1992), who suggested islands along Australia’s north coast required a permanent human presence owing to unpredictably available resource bases requiring constant monitoring to ensure successful exploitation. However, O’Connor’s argument does not account for seasonal restrictions beyond those presented by the presence or absence of food. Access to offshore islands is often dictated by ocean conditions, particularly for groups utilising raft technologies such as the local *walbu* or *walba* (Evans 1992; Memmott and Trigger

1998; Figure 13.4). Movement between the mainland and the South Wellesley Islands was therefore largely reliant on calm waters and favourably orientated winds (see McNiven et al. 2014; McNiven 2015 for additional examples of seasonal island use in Australia's north). Moreover, later periods of permanent occupation were unlikely to be directly linked with the monitoring of resources owing to the year-round abundance of numerous marine and terrestrial foods, with broader cultural or environmental changes likely acting as the catalyst for more permanent expansion into the South Wellesley Islands (Memmott et al. 2016; Peck 2016).

Figure 13.4 The traditional watercraft of the Wellesley Island region (Lardil: *Walba*, Kayardild: *Walbu*) was constructed by lashing mangrove logs together using grass string (Evans 1992; Memmott 2010; Memmott et al. 2016; Photograph: Bleakley, 1917).

Broad environmental mechanisms are frequently employed by archaeologists in explanations of changing patterns of island use during the mid-to-late Holocene. The most widely applied among these is the shifting frequency and amplitude of ENSO. One of the oft-cited examples of this is Sim and Wallis (2008), who link a hiatus in occupation on Vanderlin Island, Sir Edward Pellew Island Group, to declining marine resource availability and inclement weather conditions brought about by increasing ENSO intensity. However, as suggested in Section 13.2, vast differences in scale make comparisons between regional ENSO records and local patterns of human occupation problematic. This is particularly salient in cases where changes in ENSO are used to explain apparent cessations in human use of offshore islands. Humans, particularly hunter-gatherers, react to change in real-time, taking advantage of contemporary conditions rather than waiting for long-term trends to develop. Groups are therefore likely to have opportunistically utilised offshore islands, even during periods that display an overall trend of unsuitable conditions. This is demonstrated by early occupation at Dangkankuruwuru, which coincides with a period of peak ENSO frequency (see Gagan et al. 2004; Moy et al. 2002; Figure

13.2), suggesting island visitation continued despite fluctuations in ENSO cycles. Thus, it is difficult to accurately map temporally broad ENSO patterning to short-term decision-making processes.

By comparing high-resolution findings reached for the South Wellesley Islands to broad regional and/or continental models previously proposed for offshore island use a number of discrepancies between differently scaled data are highlighted. This is largely due to a disconnection between how archaeologists view the past and how people experiencing those trends responded to change at the time (Thomson 1939). By studying datasets that encompass multiple regions and stretch across centuries or millennia, archaeologists are able to discern broad patterns and trends in environment, culture, or behaviour. However, for hunter-gatherers living hundreds if not thousands of years ago, these long-term trajectories are of no consequence as it is their immediate environmental and cultural situation that structures behavioural choices. This posits the question of why archaeologists continue to construct interpretations of localised datasets, such as those derived from offshore islands, from broader regional or even continental models? Instead, high-resolution data should be used to assist in constructing larger narratives, allowing diversity associated with different cultural groups and environments to be accounted for. The interpretations of occupation presented as part of this research make a salient case for this, bringing the complex and diverse ways in which Aboriginal groups utilised offshore island environments to the fore while still contributing to the broader narrative.

13.4 Changing Settlement Patterns at Regional Scales

Approaching questions related to the impact of mid-to-late Holocene change on behavioural patterns and how this manifests within the archaeological record is an important step towards better characterising human-environment interactions and associated decision-making processes. In particular hunter-gatherer responses to increased risk during the Holocene have become the focus of many such discussions (Attenbrow 2006; Hiscock 1994, 2008; Smith 2013; Williams et al. 2010, 2015a, 2015b). The notion of risk refers to the 'probability of being unsuccessful in procuring resources' (Hiscock 1994:275), which in-turn may incur larger energy costs or even endanger individuals or groups. The current discourse surrounding human responses to mid-to-late Holocene risk is interested in associated modifications to occupation patterns, in particular change in patterns of mobility. As has been highlighted throughout this thesis, higher-order concepts of social organisation are underpinned by understandings of occupation timing, periodicity, and permanency. Thus, approaching questions related to mobility requires characterisations of localised short-term patterns, like those attained here via stable isotopic analysis.

Despite being part of an ongoing discussion that has continued for more than a decade, ideas associated with Aboriginal responses to increasingly risky Holocene conditions have rarely been tested within the context of island environments (cf. Hiscock 1994:274, 281). The occupation of island environments is inherently risky, with often dense populations occupying a constrained geographic area containing limited resources. This is particularly true of the South Wellesley Islands, which was calculated to host an exceptionally dense ethnographic hunter-gatherer population (Tindale 1962b, 1977). Moreover, interpretations of risk management are often undertaken at broad geographic scales (e.g. Attenbrow 2006; Hiscock 1994, 2008; Smith 2013; Williams et al. 2010, 2015a, 2015b), prompting the application of regional or inter-regional models to localised datasets. Exploring behavioural strategies employed by inhabitants of offshore islands, particularly during the mid-to-late Holocene, can therefore provide a salient example of how Aboriginal groups negotiated risky environments at localised scales.

Commonly cited arguments presented by Attenbrow (2006) and Hiscock (1994, 2008) suggest that a key component of risk mitigation is the ability for groups to be highly mobile, with versatile toolkits allowing the exploitation of a diverse range of resources. However, findings from the South Wellesley Islands display patterns more indicative of the opposing view suggested by Williams et al. (2015a), with shifts towards more sedentary (less seasonal) occupation of both Dangkankuruwuru and Thundiy from c.300 cal BP (see Chapters 10 and 11). It was also posited that reductions in use at Murdumurdu in the last 250 years were also indicative of more permanent occupation at larger central-place sites, with ephemeral dinner-time camps seeing less frequent use (see Chapter 12). Moreover, the late Holocene Kaiadilt toolkit is highly specialised towards marine exploitation, particularly with the advent of fish trap technology (Memmott et al. 2006). Further evidence of a move towards sedentary behaviour includes increased ties to certain areas owing to the use of static or highly managed resource bases (particularly fish trap complexes), rises in site establishment rates (Memmott et al. 2016), and more of the landscape being brought into regular (re)use – as evidenced by increased use of Dangkankuruwuru from c.200 cal BP following an extended 800 year period of low-level occupation (see Chapter 11).

Notions of mobility in island environments should not be restricted to movement across the immediate landscape, with variable connections to the mainland, other island groups, and intervening seascapes encouraging voyaging between geographically distant landforms. Early use of the South Wellesley Islands during the exploratory and discontinuous use phases was dependent on repeated return voyages from the mainland. While the frequency of these visitations is currently unclear, evidence of low-level dry season occupation of Dangkankuruwuru throughout much of the discontinuous use phase suggests wide-ranging foragers regularly journeyed to the South Wellesley Islands. Subsequent to the more permanent occupation of the region it was long suspected that the Kaiadilt lived in more or less total isolation from other Aboriginal groups (Tindale 1962a, 1962b, 1977), suggesting a significant decrease on inter-island mobility. However, ethnographic accounts indicate that people undertook open-water voyages to other islands beyond their territory 5 – 6 times during their lifetime (Memmott 1982b). Thus, while there was a decrease in inter-island travel when compared to the frequency of early seasonally scheduled visitations, Kaiadilt populations appear to have remained mobile throughout the greater Wellesley region during the late Holocene.

Despite indications that patterns of late Holocene mobility are incongruous with those suggested by Hiscock (1994, 2008), a number of other suggested risk mitigation indicators are present in the South Wellesley Islands. Firstly, economic diversification is evident with the broadening of diets as evidenced by increases in the amount and variety of mollusc and fish taxa through time (Peck 2016). These resources were likely extremely reliable owing to their local abundance, an attribute that is thought to be highly advantageous for risk reduction (Torrence 1983). Political boundaries and alliances are also demonstrated by the ethnographically reported *dolnoro* system (Tindale 1962a), with agreements allowing resource sharing based on kinship through marriage (Evans 1995; Memmott 1982b). Finally, increased technological investment in techniques that allow more efficient resource procurement techniques are evidenced by the high frequency and diverse nature of fish trap complexes around the South Wellesley Islands (see Memmott et al. 2008).

While numerous risk minimisation strategies are evidenced across the South Wellesley Islands, increased mobility as suggested by Attenbrow (2006) and Hiscock (1994, 2008) is not among them. Instead, there is an overall trend towards increased residency times and more sedentary behaviours designed to take advantage of developing resource bases and new technologies, a pattern more congruous with the continental model suggested by Williams et al. (2015a, 2015b). These behavioural modifications also impacted cultural mechanisms, facilitating the development of place-based tenure and political systems. The absence of increased mobility in island contexts is not particularly surprising when its advantages and aims are considered. Increased mobility is often seen when entering unknown environments, allowing foragers to monitor and take advantage of diverse resources over wide often sparsely populated areas

(Hiscock 1994). These attributes are rarely seen in late Holocene island contexts, which often exhibit dense populations inhabiting constrained geographic spaces with limited resources. Risk is therefore mitigated in other ways, such as those discussed above, and has likely been deeply engrained within island cultures owing to the inherently risky marginal environments they occupy. This also highlights key differences between mainland and island cultural and environmental attributes, reiterating the need for localised analyses.

13.5 Key Findings

13.5.1 Sclerochronology in a Tropical Australian Setting

Over the past decade sclerochronology has become an increasingly powerful and important tool utilised by archaeologists working in coastal contexts, allowing detailed analyses of behavioural and palaeoenvironmental patterns. However, a majority of this work has been undertaken using temperate mollusc taxa (e.g. Andrus and Crowe 2000; Burchell et al. 2013a, 2013b; Culleton et al. 2009; Hallmann et al. 2013), whose exposure and responses to environmental conditions can vary from tropical species. Those researchers that have applied sclerochronology to tropical shellfish taxa rarely acknowledge these differences (e.g. Brockwell et al. 2013; Hinton 2012; Stephens et al. 2008), with a handful of notable exceptions (e.g. Kennett and Voorhies 1995, 1996). Moreover, very few studies have applied sclerochronological methods to Australian contexts (see Godfrey 1988; Hinton 2012). It was therefore imperative that the efficacy of utilising sclerochronology in a tropical Australian setting was explored as part of this research.

Habitat conditions and shell geochemistry of three molluscan taxa (*Gafrarium pectinatum*, *Marcia hiantina*, and *Polymesoda coaxans*) common throughout the archaeological record in the South Wellesley Islands and across Australia's tropical north were explored through the collection and analysis of 34,248 instrumental readings, 257 water samples, and 289 carbonate samples extracted from 64 live-collected shellfish specimens (see Chapters 6 – 8). Results were mixed with *G. pectinatum* and *P. coaxans* deemed unsuitable for use within the context of this research owing to environmental, ecological, and physiological complexities (see Chapters 7 and 8). These results also highlighted a number of methodological hurdles specific to tropical species. Despite this, *M. hiantina* was found to act as a highly reliable recorder of ambient environmental conditions, proving useful in palaeoenvironmental and seasonality determinations (see Chapter 9). While further research is recommended to reinforce knowledge bases associated with *M. hiantina* biology and ecology (see Chapter 9 and Section 13.8), this study successfully incorporated data derived from this species into nuanced interpretations of both past and modern behavioural and environmental patterns. Thus, these findings have laid the foundation for deploying sclerochronological techniques in Australian contexts, opening and refining a novel avenue for researchers to explore human-environment interactions and responses along coastlines.

13.5.2 Seasonal Climatic Change and Human Decision-Making Processes

Numerous ethnographic sources have linked seasonal climatic change to fundamental aspects of Aboriginal lifeways, including occupation and subsistence patterns, mobility and demography, and landscape use (e.g. Davies 1985; Meehan 1977, 1982; Memmott 2010; Sutton 2010; Thomson 1939). Despite this, Australian archaeologists have historically found it difficult to directly demonstrate seasonal behavioural patterns using archaeological material owing to a lack of suitably scaled techniques. Ideas of seasonality are therefore often relegated to brief discussions or abstractions within broader interpretations, leaving a considerable gap in our understandings of Aboriginal decision-making processes at the most fundamental levels. However, recent interest in generating increasingly nuanced narratives has demanded that notions such as seasonality, as well as the broader concepts it underpins including the timing, periodicity, and permanency of occupation, are meaningfully addressed. The findings of this research demonstrate links between Kaiadilt behaviour and seasonal climatic change, highlighting shifting impacts on occupation, subsistence, mobility, and demography. Moreover, it demonstrates the importance of characterising repeated, short-term changes in behaviour to approaching holistic interpretations of Aboriginal decision-making processes.

This thesis employed 184 seasonality determinations from three archaeological sites across Bentinck Island to generate high-resolution site-use histories capable of characterising links between human behaviour and seasonality (Chapters 10 – 12). Evidence of seasonal occupation was displayed across all target sites, suggesting a cyclical pattern of periodic use and abandonment. This is particularly obvious for Thundiy (Chapter 10) and Murdumurdu (Chapter 12) where occupation was principally linked with dry season conditions. However, the rationale for seasonally patterned occupation likely differs between sites. Use at Thundiy appears to be linked with localised responses to seasonal climatic cycles and resource access (Chapter 10), while decisions associated with Murdumurdu were more likely the product of short-term changes to mobility or subsistence strategies (Chapter 12). Meanwhile, Dangkankuruwuru exhibits a more complex use history that stretches over multiple phases of regional occupation, where responses to seasonal climatic change are modified over time. Movement from highly seasonal occupation early in the sites history towards more permanent use in its later phases suggest changing priorities for those utilising the area, which are likely linked to shifting patterns of mobility, demography, and subsistence (see Chapter 11 and Section 13.2). Similar shifts are also found in later phases of occupation at Thundiy (see Chapter 10). Findings from these three sites not only directly demonstrate links between Aboriginal decision-making processes and seasonal climatic change through archaeological material, but also highlight that these patterns do not remain static through time with shifts in culture, environment, and resources mediating responses. These results contribute to the broader discipline as they make a salient argument as to why short-term patterns are integral to approaching nuanced interpretations of Aboriginal decision-making processes.

13.5.3 Complex Patterns of Offshore Island Use

Historically interpretations of offshore island use in Australia have been grounded in notions of static or unidirectional patterns of occupation with questions related to the antiquity and nature of use at the forefront of research. Thus, discussion surrounding Aboriginal use of offshore island contexts have remained largely generalised, with broad regional or inter-regional models used to interpret archaeological findings. The ability of researchers to approach nuanced narratives is therefore limited, with the overall diversity of responses and behaviours muted by homogenised understandings. Moreover, recent evidence indicates that complex hunter-gatherer cultures and behavioural patterns are present within island environments (e.g. O'Connor 1999a; Peck 2016; Rosendahl 2012; Rowland 2008; Sim and Wallis 2008; Ulm et al. 2010), with numerous authors calling for a re-evaluation of how associated assemblages are characterised and interpreted (e.g. Frankel 1995; Rosendahl 2012; Rosendahl et al. 2014a; Ulm 2013).

Findings from the South Wellesley Islands confirm that offshore island environments exhibit unique patterns of behaviour, which do not necessarily conform to the continental models previously applied to them. These inconsistencies are primarily a matter of scale, with researchers often unable to convincingly reconcile geographically or temporally broad models constructed from regional or inter-regional patterns with short-term localised patterns. For instance, evidence from Bentinck Island suggest continued visitation by wide-ranging marine foragers throughout periods of high ENSO intensity, which had previously been emphasised as a key driver behind the cessation of open water crossings in nearby island groups (see Sim and Wallis 2008). This reinforces the notion that interpretations constructed from broad inter-regional trends are not necessarily accurate representations of behaviours occurring at local-levels. Moreover, it highlights a disconnection between how archaeologists often view the past and how those living at the time responded to numerous cultural and environmental stimuli.

The results of this research therefore argue that in order to reach holistic interpretations of how Aboriginal groups were utilising and interacting with island contexts, archaeologists must begin to rethink how broad narratives are constructed by better incorporating local-level datasets.

13.5.4 Changing Mid-to-Late Holocene Human-Environment Interactions

As posited in Chapter 1, one of the most fundamental questions currently facing Australian archaeologists is: *How are shifting human-environment interactions reflected in changes in behaviour and culture?* This is particularly salient to the mid-to-late Holocene when shifts in social organisation, occupation, subsistence, technology, and culture are evident across the continent. For the South Wellesley Islands there exists evidence of multiple changes in behaviour and culture that can be directly linked with shifts in relationships shared by humans and the environments they occupy. Most notable for current discussions are responses to increasing risk during later periods of occupation. Elevated population density would have placed pressure on cultural and economic systems, forcing the Kaiadilt to adapt behaviours accordingly. Evidence of moves towards the exploitation of reliable resources using specialised technology in the form of complex stone-walled fish trap systems are a particularly prevalent marker of this. People became increasingly tied to specific areas owing to the need to maintain and operate fish trap complexes, lowering mobility and increasing residency. This sedentary behaviour allowed the development of complex cultural systems including land and resource tenure. These results contribute to broader discussions through a direct, locally scaled archaeological demonstration of suggestions that the late Holocene was host to a widespread pattern of decreased mobility coinciding with growing populations and emerging social complexity.

13.6 Future Research Directions

While this research was successful in achieving its research goals, a number of issues emanating from this study demand further research. Below are examples of future research aimed at addressing questions that were beyond the scope of this study:

Further Analyse Gafrarium pectinatum *and its Intertidal Environment*

Inconclusive results regarding the viability of *G. pectinatum* as proxy for palaeoenvironmental and seasonality data may be linked with a variety of methodological and environmental factors. To overcome the issues associated with time-averaging highlighted in Chapter 8, future research should explore alternative carbonate extraction methods that either produce larger samples or require smaller weights for analysis (e.g. spot sampling, laser ablation, sensitive high-resolution

ion microprobe, or secondary ion mass spectrometry). This should be coupled with techniques designed to better delineate internal shell growth structures, such as staining or scanning electron microscope analysis. Uncertainties stemming from *G. pectinatum* ecology and physiology may be more challenging to meaningfully approach, however gaining firmer knowledge regarding how environmental conditions change and develop within this taxa's complex intertidal habitat would establish a solid foundation. Moreover, characterising the frequency and periodicity of movement between open marine environments and rock pool systems would assist in elucidating the impact of divergent conditions on *G. pectinatum* shell geochemistry. Once these fundamental data have been obtained it should be possible for future researchers to determine the cause of seasonally ambiguous stable isotope values characterised in catch cohorts from this study and provide a definitive interpretation of the usefulness of *G. pectinatum* as a proxy for seasonality and palaeoenvironmental data.

Extend Analysis of Marcia hiantina *during Typical Wet Season Conditions*

Low rainfall during the 2014/2015 and 2015/2016 wet seasons introduced a level of uncertainty to the accuracy of this species as an indicator for occupation seasonality. It should be noted that such variability undoubtedly occurs during other periods in accordance with ENSO cycling. While other avenues of evidence, including the ontogenetic isotope profile of a dry season collected specimen and archaeological material, were employed to demonstrate its efficacy, direct evidence of links between environmental conditions and *M. hiantina* shell geochemistry would negate any remaining doubt. Thus, it is suggested that future research aims to undertake live-collection of *M. hiantina* specimens during typical wet season conditions. Moreover, a larger assemblage of both wet and dry season live-collected specimens should be sought to further strengthen the findings of this research. This should be accompanied by a water sampling regime designed to provide environmental context for each catch cohort.

Characterise Seasonality for More Archaeological Sites across the South Wellesley Islands

Varied Kaiadilt responses to seasonal climatic cycles evidenced with the archaeological sites targeted in this research suggest that similarly diverse patterns may be evidenced within other archaeological depositions. Future studies should aim to incorporate more archaeological sites, particularly those from the earlier exploratory and discontinuous phases of occupation. While early shellfish assemblages are sparse, characterising patterns of seasonality for sites such as Jirrkamirndiyarrb, Nalkurdallayarrb, and Wirrngaji would provide more comprehensive understandings of early Aboriginal occupation across the South Wellesley Islands (Figure 13.5). Moreover, incorporating Wardilmiru and Banbanbarukeind would strengthen interpretations of use subsequent to occupation intensifying (Figure 13.5), while also providing an example of use for Fowler Island (Wardilmiru). Expanding analysis of Thundiy and Dangkankuruwuru to encapsulate all excavations would also serve to bolster current interpretations. While other sites have been dated (e.g. Camp 2, Wirrikiwirriki, and Melbamelbari; see Figure 13.5), they have not yet undergone detailed analysis and thus should be seen as a longer-term goal for future research.

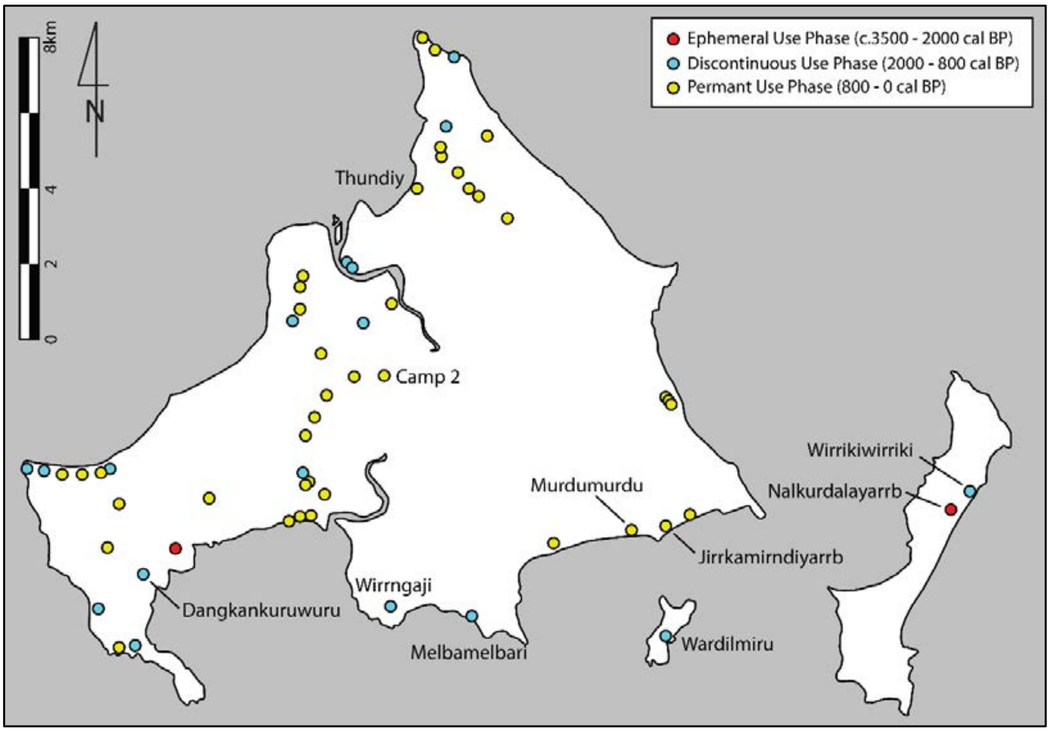

Figure 13.5 Incorporating seasonality determinations from other sites around the South Wellesley Islands would provide further information regarding Kaiadilt occupation patterns throughout all phases of occupation.

Undertake Research Focused on the Adjacent Mainland and Stepping-Stone Islands

Given the potential importance of wide-ranging mainland foragers to the early periods of occupation in the South Wellesley Islands, undertaking archaeological research on the adjacent mainland and intermediary islands (e.g. Horseshoe and Allen Island) would provide an important regionally scaled contextual framework. Moreover, despite the archaeological record frequently containing stone artefacts (Peck 2016), there is little understanding as to the origin of associated raw materials. Bentinck Island exhibits very few sources of stone useful in the production of artefacts, the largest being a silcrete deposit located just off the northern tip of the island (Tindale 1963) (Figure 13.6). Other artefacts produced using stone types not present in the immediate region, including quartz, have been found across the island chain (Daniel Rosendahl, pers. comm., 2013). When these factors are combined with the early visitation by mainland peoples and ethnographic accounts of regular voyages to Allen Island, it can be suggested that artefacts or raw materials may have been sourced from outside the immediate South Wellesley region. Thus, stone raw material studies focused on comparisons between mainland sources and South Wellesley Island artefacts may assist in characterising connections with the mainland and other nearby island groups.

Figure 13.6 The largest silcrete source on Bentinck Island is located just off the north coast of Rukathi.

13.7 Conclusions

Problems associated with interpreting local-scale responses to late Holocene change through a broad inter-regional lens have long been discussed (e.g. Claassen 1991; Frankel 1993, 1995), with White (1994:225) making the astute observation that when ‘taken together … [the] evidence does indeed seem to suggest that “something happened” in Australia about 2000 BP. But when each piece of evidence is examined individually, the apparent pattern becomes blurred’ over two decades ago. Since then numerous authors have echoed this sentiment, the most recent being Ulm (2013) and Rosendahl (2012) who emphasise that in order to approach more meaningful interpretations broader narratives must be constructed from localised cultural and environmental datasets. Moreover, these ideas have become increasingly important as more researchers characterise complex patterns within constrained temporal and geographic contexts. Despite this, the core problem remains prevalent within the Australian archaeological tradition, where local-scale data continue to be forced into interpretative frameworks constructed from pan-regional patterns.

This study demonstrates that a solution to this problem can be reached. A high-resolution model incorporating localised, short-term human-environment interactions was developed for late Holocene occupation of the South Wellesley Islands. The model was then used to demonstrate that assumptions made by broad inter-regional interpretations frequently do not accurately represent locally-scaled patterns. Thus, this research represents a move towards constructing increasingly high-resolution interpretations of human-environment interactions that will provide the foundation for nuanced archaeological narratives while facilitating better understandings of responses to environmental and cultural change and how these manifest within the archaeological record.

This research is among the first to accurately characterise direct links between seasonal climatic cycles and short-term changes in Australian Aboriginal behaviour through archaeological material. Deploying sclerochronology in an island environment along Australia's tropical north coast allowed for the successful evaluation of the timing and periodicity of site-use, identifying changing patterns in the frequency and permanency of occupation across the landscape and through time (Chapters 10 – 12). This demonstrates the efficacy of applying sclerochronology in tropical Australian contexts, provided a suitable mollusc species is available for analysis (Chapters 7 – 9). Moreover, findings highlight the importance of patterns occurring at small scales, as they represent some of the most fundamental components of past lifeways.

The evidence presented within this thesis demonstrates that Aboriginal decision-making processes were extremely complex during the mid-to-late Holocene, with groups responding to cultural, social, and environmental contexts on a variety of different scales. This is particularly true for those people occupying dynamic coastal and island environments, which continued to develop until only very recently. Responses to change are highly variable, even within a constrained cultural group or landscape, displaying highly localised differences. Thus, delivering a convincing holistic interpretation of Aboriginal life during the Holocene requires our interpretations to be constructed from the local-level up, rather than forcing broader inter-regional patterns upon highly diverse patterns of human behaviour.

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Appendix A – Details for modern live-collected *Polymesoda coaxans* used in isotopic analysis

FS#	**Year**	**Season**	**Collection Date**	**Location**	**Length (mm)**	**Height (mm)**	**Breadth (mm)**
1R	2012	Dry	01/07/2012	Mosquito Story	92.05	76.65	29.05
2R	2012	Dry	01/07/2012	Mosquito Story	80.89	69.73	26.15
3R	2012	Dry	01/07/2012	Mosquito Story	73.00	63.93	23.16
4R	2012	Dry	01/07/2012	Mosquito Story	73.60	60.52	22.32
5R	2012	Dry	01/07/2012	Mosquito Story	63.23	57.80	19.73
6R	2012	Dry	01/07/2012	Mosquito Story	53.62	47.39	16.00
1/1	2014	Wet	05/03/2014	Mulla Island	88.5	77.2	26.5
1/2	2014	Wet	05/03/2014	Mulla Island	86.1	75.8	25.6
1/3	2014	Wet	05/03/2014	Mulla Island	83.2	74.0	54.5
1/4	2014	Wet	05/03/2014	Mulla Island	78.6	69.8	25.0
1/5	2014	Wet	05/03/2014	Mulla Island	75.2	66.3	26.1
1/6	2014	Wet	05/03/2014	Mulla Island	68.8	63.0	24.9
1/7	2014	Dry	20/07/2014	Mulla Island	83.47	75.05	26.12
2/7	2014	Dry	20/07/2014	Mulla Island	82.88	69.60	28.38
3/7	2014	Dry	20/07/2014	Mulla Island	88.89	75.09	28.38
4/7	2014	Dry	20/07/2014	Mulla Island	86.40	71.01	26.63
5/7	2014	Dry	20/07/2014	Mulla Island	80.02	69.22	26.33
6/7	2014	Dry	20/07/2014	Mulla Island	72.64	63.63	24.26
7/7	2014	Dry	20/07/2014	Mulla Island	88.95	74.64	28.15
1/1	2015	Dry-Wet	17/09/2015	Mulla Island	85.02	73.03	27.74
1/2	2015	Dry-Wet	17/09/2015	Mulla Island	78.96	69.22	26.23
1/3	2015	Dry-Wet	17/09/2015	Mulla Island	92.05	77.73	28.20

Appendix B – Details for modern live-collected *Gafrarium pectinatum* used in isotopic analysis

FS#	Year	Season	Collection Date	Location	Context	Length (mm)	Height (mm)	Breadth (mm)
2/2	2014	Wet	02/03/2014	Raft Point	Intertidal	41.9	36.6	15.1
2/3	2014	Wet	02/03/2014	Raft Point	Intertidal	42.2	35.5	13.5
2/4	2014	Wet	02/03/2014	Raft Point	Intertidal	39.4	34.9	12.4
2/5	2014	Wet	02/03/2014	Raft Point	Intertidal	38.1	33.6	12.8
2/6	2014	Wet	02/03/2014	Raft Point	Intertidal	37.1	32.9	12.2
2/8	2014	Wet	02/03/2014	Raft Point	Intertidal	35.4	31.4	12.4
2/9	2014	Wet	02/03/2014	Raft Point	Intertidal	34.1	28.8	11.5
2/10	2014	Wet	02/03/2014	Raft Point	Intertidal	37.1	32.2	11.8
17	2014	Dry	20/07/2014	Raft Point	Intertidal	40.42	36.42	14.57
18	2014	Dry	20/07/2014	Raft Point	Intertidal	35.93	33.08	12.09
19	2014	Dry	20/07/2014	Raft Point	Intertidal	35.30	30.74	9.73
21	2014	Dry	20/07/2014	Raft Point	Intertidal	28.43	25.25	8.72
2/1	2015	Dry-Wet	18/09/2015	Ngathald	Exposed	34.68	30.33	11.61
2/2	2015	Dry-Wet	18/09/2015	Ngathald	Exposed	29.74	27.95	11.39
3/1	2015	Dry-Wet	18/09/2015	Ngathald	Pool	37.43	30.73	12.22
7/1	2015	Dry-Wet	18/09/2015	Ngathald	Pool	37.45	33.11	12.61
7/2	2015	Dry-Wet	18/09/2015	Ngathald	Pool	35.81	31.71	11.95
7/3	2015	Dry-Wet	18/09/2015	Ngathald	Pool	33.68	28.93	10.86
7/4	2015	Dry-Wet	18/09/2015	Ngathald	Pool	33.99	29.04	9.79
7/5	2015	Dry-Wet	18/09/2015	Ngathald	Pool	34.24	29.68	11.13
11/1	2015	Dry-Wet	18/09/2015	Ngathald	Pool	34.11	29.33	11.86
11/2	2015	Dry-Wet	18/09/2015	Ngathald	Pool	35.91	29.84	11.45
11/3	2015	Dry-Wet	18/09/2015	Ngathald	Pool	36.32	32.17	11.24
15/1	2015	Dry-Wet	18/09/2015	Ngathald	Pool	35.96	31.07	12.80
15/2	2015	Dry-Wet	18/09/2015	Ngathald	Pool	31.25	26.77	10.34
19/1	2015	Dry-Wet	18/09/2015	Ngathald	Intertidal	39.67	33.07	12.53
19/2	2015	Dry-Wet	18/09/2015	Ngathald	Intertidal	38.84	32.77	12.70
30/1	2016	Wet	21/02/2016	Fowler Island	Intertidal	42.2	35.0	13.7
30/2	2016	Wet	21/02/2016	Fowler Island	Intertidal	41.0	36.5	14.7
30/3	2016	Wet	21/02/2016	Fowler Island	Intertidal	41.1	34.3	12.9
30/4	2016	Wet	21/02/2016	Fowler Island	Intertidal	39.9	35.1	11.8
30/5	2016	Wet	21/02/2016	Fowler Island	Intertidal	38.7	34.3	12.6
30/6	2016	Wet	21/02/2016	Fowler Island	Intertidal	34.3	29.1	9.2
30/7	2016	Wet	21/02/2016	Fowler Island	Intertidal	40.3	34.4	13.3

Appendix C – Details for modern live-collected *Marcia hiantina* used in isotopic analysis

FS#	Year	Season	Collection Date	Location	Length (mm)	Height (mm)	Breadth (mm)
1/4	2014	Dry	23/07/2014	Mirdidingki	34.10	25.92	9.32
2/4	2014	Dry	23/07/2014	Mirdidingki	29.42	23.04	7.66
3/4	2014	Dry	23/07/2014	Mirdidingki	25.53	19.95	6.79
4/4	2014	Dry	23/07/2014	Mirdidingki	25.62	19.60	6.88
1	2016	Wet	25/02/2016	Raft Point	26.09	18.61	6.15
31/1	2016	Wet	25/02/2016	Fowler Island	34.02	26.01	9.34
31/2	2016	Wet	25/02/2016	Fowler Island	28.70	22.30	8.04
35/1	2016	Wet	25/02/2016	Fowler Island	31.30	24.25	8.74

Appendix D – Micro-Milled Isotope Values from Modern Shellfish Specimens

Specimen 1/4 – *Marcia hiantina* (Dry Season)			
Sample No.	**$\delta^{18}O_{shell}$ (VPDB ‰)**	**$\delta^{13}C_{shell}$ (VPDB ‰)**	**Position (µm)**
1/4-1	-1.8	-1.9	322
1/4-3	-2.3	-1.8	1001
1/4-4	-2.2	-2.1	1324
1/4-5	-2.4	-2.0	1741
1/4-6	-2.5	-2.2	2049
1/4-7	-3.5	-3.0	2411
1/4-8	-3.3	-2.8	2719
1/4-9	-3.1	-2.3	3028
1/4-10	-3.8	-2.8	3328
1/4-11	-4.1	-2.7	3694
1/4-12	-4.3	-3.0	4061
1/4-13	-4.5	-3.1	4384
1/4-14	-4.4	-3.0	4757
1/4-15	-4.8	-3.1	5144
1/4-16	-4.4	-3.2	5388
1/4-17	-5.3	-3.5	5826
1/4-18	-5.7	-3.4	6154
1/4-19	-5.3	-3.2	6358
1/4-20	-5.9	-1.9	6890

Specimen 31/1 – *Marcia hiantina* (Wet Season)			
Sample No.	**$\delta^{18}O_{shell}$ (VPDB ‰)**	**$\delta^{13}C_{shell}$ (VPDB ‰)**	**Position (µm)**
31/1-1	-2.5	-3.0	288
31/1-2	-1.9	-2.3	629
31/1-3	-2.0	-2.0	1103
31/1-4	-1.8	-1.6	1522
31/1-5	-1.9	-1.2	2111
31/1-6	-1.3	-1.2	2514
31/1-7	-1.9	-1.3	3064
31/1-8	-1.8	-1.6	3395
31/1-9	-0.9	-1.2	3750
31/1-10	-1.4	-1.3	4205
31/1-11	-1.4	-2.2	4806
31/1-12	-2.3	-3.0	5372
31/1-13	-2.2	-2.9	5900
31/1-14	-1.6	-2.1	6426
31/1-15	-2.1	-1.4	7004

Specimen 5/7 – *Polymesoda coaxans* (Dry Season)			
Sample No.	**$\delta^{18}O_{shell}$ (VPDB ‰)**	**$\delta^{13}C_{shell}$ (VPDB ‰)**	**Position (µm)**
5/7-1	-5.4	-11.9	128
5/7-2	-3.9	-9.4	229
5/7-3	-1.8	-9.0	430
5/7-4	-2.0	-10.8	616
5/7-5	-3.1	-9.6	695
5/7-6	-2.4	-10.3	1001
5/7-7	-5.7	-10.3	1214
5/7-8	-3.4	-10.7	1466
5/7-9.2	-2.9	-10.2	1925
5/7-10	-2.9	-10.6	2034
5/7-11	-3.2	-12.1	2204
5/7-12	-5.0	-11.2	2377
5/7-13	-7.9	-11.0	2588
5/7-14	-8.8	-10.9	2730
5/7-15	-7.0	-9.8	2938
5/7-16	-5.6	-9.5	3117
5/7-17.2	-3.9	-9.3	3488
5/7-18	-4.9	-9.8	3650
5/7-19	-2.5	-10.3	3725
5/7-20	-2.3	-11.4	3833
5/7-21	-5.7	-11.4	4083
5/7-22	-5.0	-11.1	4271
5/7-23	-5.8	-11.0	4392
5/7-24	-7.9	-10.6	4554
5/7-25	-6.5	-10.8	4751
5/7-26	-6.7	-10.6	5017
5/7-27	-6.1	-10.1	5127
5/7-28	-3.1	-10.1	5360
5/7-29	-2.4	-11.4	5567
5/7-30	-6.2	-11.1	5730
5/7-31	-8.2	-9.8	5930
5/7-32	-8.4	-9.7	6126
5/7-33.1	-8.5	-10.0	6315
5/7-33.2	-6.4	-10.3	6505
5/7-34	-5.0	-9.7	6747
5/7-35	-1.9	-9.0	6964
5/7-36	-2.4	-9.6	7171
5/7-37	-1.6	-9.4	7386
5/7-38	-2.7	-10.2	7584
5/7-39	-3.3	-10.5	7785
5/7-39.2	-3.6	-10.2	7881
5/7-40	-5.6	-10.2	8063
5/7-41	-5.2	-10.0	8359
5/7-42	-5.0	-9.5	8595
5/7-43	-3.5	-10.0	8768
5/7-44	-2.1	-10.0	9029
5/7-45	-2.4	-9.3	9304
5/7-46	-2.5	-9.4	9500
5/7-47	-1.7	-10.4	9668

Specimen 5/7 – *Polymesoda coaxans* (Dry Season) cont.			
Sample No.	**$\delta^{18}O_{shell}$ (VPDB ‰)**	**$\delta^{13}C_{shell}$ (VPDB ‰)**	**Position (µm)**
5/7-48	-2.6	-11.4	9814
5/7-49.1	-4.7	-11.1	9940
5/7-49.2	-6.2	-10.4	10129
5/7-50	-4.7	-9.0	10288
5/7-51	-4.1	-8.4	10566
5/7-52	-4.9	-8.9	10731
5/7-53	-2.6	-7.4	10862
5/7-56	-2.9	-7.9	11060
5/7-55	-3.6	-8.2	11236

Specimen 1/2 – *Polymesoda coaxans* (Wet Season)			
Sample No.	**$\delta^{18}O_{shell}$ (VPDB ‰)**	**$\delta^{13}C_{shell}$ (VPDB ‰)**	**Position (µm)**
1/2-1	-4.3	-8.1	130
1/2-2	-3.9	-9.5	324
1/2-3	-4.6	-9.1	512
1/2-4	-4.7	-9.6	707
1/2-5	-5.3	-8.6	882
1/2-6	-3.0	-8.6	1010
1/2-7	-4.9	-9.5	1252
1/2-8	-6.1	-9.4	1441
1/2-9	-4.9	-9.8	1730
1/2-10	-4.5	-8.8	1984
1/2-11	-4.7	-7.6	2237
1/2-12	-4.4	-9.0	2755
1/2-13	-4.6	-8.1	3033
1/2-14	-3.7	-9.4	3216
1/2-16	-5.9	-8.2	3717
1/2-17	-3.0	-8.4	3892
1/2-18	-5.1	-9.4	4102
1/2-19.1	-4.4	-8.5	4292
1/2-19.3	-6.0	-8.9	4609
1/2-20	-7.7	-9.8	4772
1/2-21	-8.2	-9.7	4931
1/2-23	-3.6	-8.5	5390
1/2-24	-5.3	-8.3	5624
1/2-25	-3.8	-8.2	5939
1/2-26	-3.5	-8.9	6179
1/2-27	-3.0	-8.8	6353
1/2-28.1	-5.7	-9.2	6480
1/2-28.2	-3.5	-8.5	6723
1/2-29	-4.0	-8.7	6939
1/2-30	-5.0	-9.1	7075
1/2-31	-6.2	-9.2	7277
1/2-32	-5.8	-9.3	7448
1/2-33	-5.6	-9.2	7660
1/2-34	-5.5	-9.2	7898
1/2-35	-3.5	-9.2	8045

Specimen 1/2 – *Polymesoda coaxans* (Wet Season) cont.

Sample No.	$\delta^{18}O_{shell}$ (VPDB ‰)	$\delta^{13}C_{shell}$ (VPDB ‰)	Position (µm)
1/2-36	-3.2	-9.3	8201
1/2-37	-3.4	-9.0	8380
1/2-38	-4.0	-9.3	8567
1/2-39.1	-3.5	-9.4	8765
1/2-39.2	-4.2	-8.7	9011
1/2-39.3	-5.4	-8.9	9303
1/2-40	-5.1	-9.0	9430
1/2-41	-4.3	-9.0	9563
1/2-42	-3.9	-9.0	9726
1/2-43	-3.6	-9.1	9914
1/2-44	-4.4	-9.6	10111
1/2-45	-3.8	-9.6	10299
1/2-46	-3.9	-9.5	10424
1/2-47	-4.4	-9.5	10565
1/2-48	-3.7	-10.0	10696
1/2-49	-3.2	-10.3	10878
1/2-50	-3.9	-10.6	11160

Specimen 18 – *Gafrarium pectinatum* (Dry Season)

Sample No.	$\delta^{18}O_{shell}$ (VPDB ‰)	$\delta^{13}C_{shell}$ (VPDB ‰)	Position (µm)
18-2	-3.3	-1.6	468
18-4	-4.4	-1.3	819
18-6	-2.7	-0.9	1199
18-8	-3.3	-0.5	1639
18-10	-2.9	-0.3	2102
18-12	-1.9	-0.2	2581
18-13	-1.6	-0.3	2797
18-14	-2.4	-0.4	2994
18-15	-2.2	-0.3	3179
18-16	-2.6	-0.4	3476
18-17	-2.0	-0.3	3563
18-18	-2.3	-0.3	3738
18-19	-1.8	-0.3	3928
18-20	-2.1	-0.2	4141
18-21	-2.2	-0.5	4364
18-23	-2.1	-0.2	4784
18-24	-1.9	-0.4	5015
18-25	-2.8	-0.4	5217
18-26	-2.3	-0.5	5403
18-27	-2.4	-0.3	5622
18-28	-2.6	-0.5	5873
18-29	-2.5	-0.2	6168
18-30	-2.4	-0.4	6325
18-31	-2.6	-0.1	6489
18-32	-2.4	-0.2	6668
18-33	-2.3	-0.3	6879
18-34	-2.7	-0.1	7063

Specimen 18 – *Gafrarium pectinatum* (Dry Season) cont.

Sample No.	$\delta^{18}O_{shell}$ (VPDB ‰)	$\delta^{13}C_{shell}$ (VPDB ‰)	Position (µm)
18-35	-2.4	-0.4	7301
18-36	-2.4	-0.2	7576
18-37	-2.5	-0.2	7790
18-38	-2.4	-0.3	8008
18-39	-2.2	-0.2	8213
18-40	-2.4	-0.2	8388
18-41	-2.0	-0.2	8556
18-42	-2.0	-0.3	8723
18-43	-2.3	-0.4	8999
18-44	-2.9	-0.3	9380
18-45	-3.4	-0.7	9633

Specimen 2/10 – *Gafrarium pectinatum* (Wet Season)

Sample No.	$\delta^{18}O_{shell}$ (VPDB ‰)	$\delta^{13}C_{shell}$ (VPDB ‰)	Position (µm)
2/10-5	-2.1	+0.6	576
2/10-8	-2.0	+0.4	913
2/10-10	-2.4	+0.3	1114
2/10-11	-2.9	+0.0	1231
2/10-12	-2.7	+0.4	1367
2/10-13	-2.8	+0.5	1485
2/10-14	-2.6	+0.8	1589
2/10-16	-2.9	+0.5	1835
2/10-17	-3.1	+0.0	1932
2/10-18.2	-3.1	-0.4	2141
2/10-19	-3.2	-0.4	2274
2/10-20.2	-3.1	-0.5	2532
2/10-21	-3.1	-0.4	2660
2/10-22	-2.9	-0.2	2793
2/10-23	-3.0	+0.0	3038
2/10-24	-2.5	+0.0	3305
2/10-25	-2.7	+0.0	3562
2/10-26	-2.4	+0.1	3790
2/10-27	-2.6	-0.7	3959
2/10-28	-3.5	-0.8	4103
2/10-30	-3.3	-0.6	4690
2/10-31	-4.4	-1.3	4913
2/10-32	-3.1	-0.3	5109
2/10-33.2	-2.6	-0.4	5380
2/10-34	-2.2	+0.1	5753
2/10-35	-2.3	+0.2	5900
2/10-36	-2.6	-0.34	6023
2/10-37	-2.0	+0.3	6230
2/10-38	-2.1	+0.5	6433
2/10-39.1	-1.1	+0.2	6611
2/10-40	-0.2	-0.2	7214
2/10-41	-1.2	-0.5	7378
2/10-42	-1.2	-0.5	7604

Specimen 2/10 – *Gafrarium pectinatum* (Wet Season) cont.			
Sample No.	**$\delta^{18}O_{shell}$ (VPDB ‰)**	**$\delta^{13}C_{shell}$ (VPDB ‰)**	**Position (µm)**
2/10-43	-1.3	-0.31	7838
2/10-44	-1.9	-0.87	8071
2/10-45	-1.6	-0.80	8272
2/10-47	-3.0	-1.33	8653
2/10-48	-3.1	-0.94	8855
2/10-49	-3.7	-1.37	9069
2/10-51	-2.3	-0.90	9517

Appendix E – Targeted Ventral Margin Values from Modern Shellfish Specimens

Ventral Margin Values from Modern Shellfish Specimens

Specimen	Species	Season	Site	$\delta^{18}O_{shell}$ (VPDB ‰)	$\delta^{13}C_{shell}$ (VPDB ‰)
2/2	*G. tumidum*	Wet	Raft Point	-2.8	-1.5
2/3	*G. tumidum*	Wet	Raft Point	-2.0	-1.3
2/4	*G. tumidum*	Wet	Raft Point	-2.4	-0.6
2/5	*G. tumidum*	Wet	Raft Point	-2.9	-1.9
2/6	*G. tumidum*	Wet	Raft Point	-2.4	-1.0
2/7	*G. tumidum*	Wet	Raft Point	-2.4	-1.3
2/8	*G. tumidum*	Wet	Raft Point	-3.3	-2.2
2/9	*G. tumidum*	Wet	Raft Point	-2.9	-1.1
2/10	*G. tumidum*	Wet	Raft Point	-2.8	-1.5
17	*G. tumidum*	Dry	Raft Point	-2.5	-1.1
18	*G. tumidum*	Dry	Raft Point	-3.6	-2.0
19	*G. tumidum*	Dry	Raft Point	-3.5	-1.5
21	*G. tumidum*	Dry	Raft Point	-2.5	-1.2
2/1	*G. tumidum*	Dry-Wet	Sweers Is.	-1.8	-0.4
2/2	*G. tumidum*	Dry-Wet	Sweers Is.	-2.4	-2.5
3/1	*G. tumidum*	Dry-Wet	Sweers Is.	-3.5	-2.4
7/1	*G. tumidum*	Dry-Wet	Sweers Is.	-2.2	-2.4
7/2	*G. tumidum*	Dry-Wet	Sweers Is.	-2.4	-2.3
7/3	*G. tumidum*	Dry-Wet	Sweers Is.	-2.3	-2.9
7/4	*G. tumidum*	Dry-Wet	Sweers Is.	-1.1	-1.2
7/5	*G. tumidum*	Dry-Wet	Sweers Is.	-1.0	-1.0
11/1	*G. tumidum*	Dry-Wet	Sweers Is.	-2.7	-2.5
11/2	*G. tumidum*	Dry-Wet	Sweers Is.	-1.9	-1.4
11/3	*G. tumidum*	Dry-Wet	Sweers Is.	-0.3	-1.1
15/1	*G. tumidum*	Dry-Wet	Sweers Is.	-2.8	-2.7
15/2	*G. tumidum*	Dry-Wet	Sweers Is.	-1.0	-1.2
19/1	*G. tumidum*	Dry-Wet	Sweers Is.	-2.5	-2.1
19/2	*G. tumidum*	Dry-Wet	Sweers Is.	-1.8	-1.2
1/1	*M. hiantina*	Wet	Raft Point	-2.3	-1.5
31/1	*M. hiantina*	Wet	Fowler Is.	-3.7	-5.5
31/2	*M. hiantina*	Wet	Fowler Is.	-2.6	-2.7
35/1	*M. hiantina*	Wet	Fowler Is.	-1.9	-1.4
1/4	*M. hiantina*	Dry	STN6	-2.0	-2.1
2/4	*M. hiantina*	Dry	STN6	-1.0	-1.6
3/4	*M. hiantina*	Dry	STN6	-0.5	-1.4
4/4	*M. hiantina*	Dry	STN6	-1.4	-2.0
1/2	*P. coaxans*	Wet	Mulla Is.	-4.4	-10.1
1/4	*P. coaxans*	Wet	Mulla Is.	-4.6	-9.6
1/5	*P. coaxans*	Wet	Mulla Is.	-4.0	-11.6
1/6	*P. coaxans*	Wet	Mulla Is.	-4.3	-8.1
1R	*P. coaxans*	Dry	Mosquito Story	-8.5	-10.0
2R	*P. coaxans*	Dry	Mosquito Story	-8.9	-9.5
3R	*P. coaxans*	Dry	Mosquito Story	-8.5	-10.4
4R	*P. coaxans*	Dry	Mosquito Story	-5.5	-8.6

Ventral Margin Values from Modern Shellfish Specimens cont.					
Specimen	**Species**	**Season**	**Site**	**$\delta^{18}O_{shell}$ (VPDB ‰)**	**$\delta^{13}C_{shell}$ (VPDB ‰)**
5R	*P. coaxans*	Dry	Mosquito Story	-6.3	-9.7
6R	*P. coaxans*	Dry	Mosquito Story	-3.5	-10.7
1/7	*P. coaxans*	Dry	Mulla Is.	-6.1	-9.9
2/7	*P. coaxans*	Dry	Mulla Is.	-3.7	-9.3
3/7	*P. coaxans*	Dry	Mulla Is.	-4.7	-8.3
4/7	*P. coaxans*	Dry	Mulla Is.	-5.0	-9.0
6/7	*P. coaxans*	Dry	Mulla Is.	-4.3	-8.7
7/7	*P. coaxans*	Dry	Mulla Is.	-5.6	-10.0
1/1	*P. coaxans*	Dry-Wet	Mulla Is.	-3.9	-10.9
1/2	*P. coaxans*	Dry-Wet	Mulla Is.	-5.1	-10.2
1/3	*P. coaxans*	Dry-Wet	Mulla Is.	-3.8	-10.6

Appendix F – Water Isotope and Salinity Values from Mirdidingki Creek, Bentinck Island

Dry Season 2013							
Date	Time	Sample Set	Tidal Mode	Location	$\delta^{18}O_{water}$ (‰)	$\delta^{13}C_{DIC}$ (‰)	Salinity (PSU)
16/07/2013	1135	1	Neap	Intertidal	+0.2	-0.6	35.6
16/07/2013	1122	1	Neap	Mouth	+0.1	-5.5	34.4
16/07/2013	1435	2	Neap	Intertidal	+0.6	-0.2	35.5
16/07/2013	1422	2	Neap	Mouth	+0.1	-4.7	34.8
16/07/2013	1755	3	Neap	Intertidal	+0.4	0.2	35.6
16/07/2013	1740	3	Neap	Mouth	+0.1	-5.1	35.0
16/07/2013	2045	4	Neap	Intertidal	+0.1	-0.1	35.6
16/07/2013	2100	4	Neap	Mouth	+0.2	-5.1	34.8
22/07/2013	0815	1	Spring	Intertidal	+0.4	-0.5	37.0
22/07/2013	0800	1	Spring	Mouth	+0.5	0.1	35.9
22/07/2013	1115	2	Spring	Intertidal	+0.5	-0.3	37.0
22/07/2013	1100	2	Spring	Mouth	+0.2	-1.2	36.2
22/07/2013	1415	3	Spring	Intertidal	+0.3	-1.8	36.5
22/07/2013	1400	3	Spring	Mouth	+0.2	-4.4	36.0
22/07/2013	1715	4	Spring	Intertidal	+0.6	-4.4	37.1
22/07/2013	1700	4	Spring	Mouth	+0.0	-4.9	36.1
22/07/2013	2115	5	Spring	Intertidal	+0.9	-5.8	38.8
22/07/2013	2100	5	Spring	Mouth	+0.1	NA	35.9

Wet Season 2014							
Date	Time	Sample Set	Tidal Mode	Location	$\delta^{18}O_{water}$ (‰)	$\delta^{13}C_{DIC}$ (‰)	Salinity (PSU)
28/02/2014	0955	1	Spring	Intertidal	-4.2	-5.0	17.0
28/02/2014	1035	1	Spring	Mouth	-5.8	-12.8	2.6
28/02/2014	1020	1	Spring	End	-5.6	-13.0	0.1
28/02/2014	1150	2	Spring	Intertidal	-3.5	-3.1	7.5
28/02/2014	1240	2	Spring	Mouth	-5.6	-11.7	0.9
28/02/2014	1225	2	Spring	End	-5.2	-12.3	0.7
28/02/2014	1440	3	Spring	Intertidal	-5.5	-8.0	4.4
28/02/2014	1445	3	Spring	Mouth	-5.9	-11.3	0.6
28/02/2014	1455	3	Spring	End	-5.6	-10.2	1.3
28/02/2014	1750	4	Spring	Intertidal	-4.8	-5.6	21.0
28/02/2014	1745	4	Spring	Mouth	-5.8	-10.2	1.0
28/02/2014	NA	4	Spring	End	NA	NA	NA
28/02/2014	2005	5	Spring	Intertidal	-4.3	-2.8	17.1
28/02/2014	2015	5	Spring	Mouth	-5.6	-9.0	5.3
28/02/2014	NA	5	Spring	End	NA	NA	NA
05/03/2014	0555	1	Neap	Intertidal	-3.1	-5.5	24.5
05/03/2014	0635	1	Neap	Mouth	-4.1	-10.0	16.3
05/03/2014	0620	1	Neap	End	-5.7	-12.7	7.5
05/03/2014	0900	2	Neap	Intertidal	-3.2	NA	23.3
05/03/2014	0920	2	Neap	Mouth	-4.4	-9.7	17.8

Wet Season 2014 cont.							
Date	Time	Sample Set	Tidal Mode	Location	$\delta^{18}O_{water}$ (‰)	$\delta^{13}C_{DIC}$ (‰)	Salinity (PSU)
05/03/2014	0905	2	Neap	End	-5.7	-12.5	7.7
05/03/2014	1115	3	Neap	Intertidal	-3.1	-0.8	23.5
05/03/2014	1125	3	Neap	Mouth	-3.9	-9.0	19.3
05/03/2014	1112	3	Neap	End	-5.6	-11.6	6.1

Dry Season 2014							
Date	Time	Sample Set	Tide Amplitude	Location	$\delta^{18}O_{water}$ (‰)	$\delta^{13}C_{DIC}$ (‰)	Salinity
13-07-14	920	1	Spring	Intertidal	-1.0	-0.4	33.5
13-07-14	917	1	Spring	Mouth	-1.1	-0.1	33.2
13-07-14	907	1	Spring	End	-0.8	-2.1	33.2
13-07-14	1220	2	Spring	Intertidal	-0.9	-0.9	33.9
13-07-14	1235	2	Spring	Mouth	-0.8	-1.3	33.2
13-07-14	1220	2	Spring	End	-1.3	-7.1	31.9
13-07-14	1545	3	Spring	Intertidal	-1.1	NA	33.3
13-07-14	1535	3	Spring	Mouth	-1.0	-5.6	33.0
13-07-14	1515	3	Spring	End	-1.4	-7.2	32.3
13-07-14	1815	4	Spring	Intertidal	-1.3	NA	33.4
13-07-14	1830	4	Spring	Mouth	-1.9	NA	32.7
13-07-14	1800	4	Spring	End	-1.4	NA	32.6
13-07-14	2210	5	Spring	Intertidal	-0.5	-0.5	33.4
13-07-14	2235	5	Spring	Mouth	-1.8	NA	32.3
20-07-14	1217	1	Neap	Intertidal	-0.4	+0.0	33.8
20-07-14	1213	1	Neap	Mouth	-1.6	-5.6	32.7
20-07-14	1200	1	Neap	End	-1.7	NA	30.6
20-07-14	1527	2	Neap	Intertidal	-0.8	+0.2	33.9
20-07-14	1520	2	Neap	Mouth	-1.6	-6	32.7
20-07-14	1505	2	Neap	End	-1.6	-7.5	29.8
20-07-14	1803	3	Neap	Intertidal	-1.2	NA	34.1
20-07-14	1830	3	Neap	Mouth	-1.2	NA	32.6
20-07-14	1805	3	Neap	End	-1.1	NA	31.9
20-07-14	2020	4	Neap	Intertidal	-0.7	+0.0	33.9
20-07-14	2027	4	Neap	Mouth	-1.2	-6.5	32.3
20-07-14	2005	4	Neap	End	-1.2	-7.0	31.6

Appendix G – Additional information for archaeological material from Thundiy used for isotopic analysis

FS#	SQ	XU	Species	Valve	Length (mm)	Height (mm)	Breadth (mm)	Weight (mg)
49/2	B	1	*M. hiantina*	Left	40.34	31.16	11.40	5.81
49/3	B	1	*M. hiantina*	Left	42.04	31.99	11.93	7.49
49/4	B	1	*M. hiantina*	Left	39.03	30.81	11.32	4.96
49/8	B	1	*M. hiantina*	Right	-	28.44	11.74	5.17
49/10	B	1	*M. hiantina*	Right	-	29.04	10.19	3.66
51/1	B	2	*M. hiantina*	Left	-	26.09	9.65	2.79
51/2	B	2	*M. hiantina*	Left	32.10	26.10	10.43	3.74
51/3	B	2	*M. hiantina*	Left	37.44	29.01	10.49	4.29
51/8	B	2	*M. hiantina*	Left	-	33.20	11.23	6.28
51/9	B	2	*M. hiantina*	Left	37.72	29.48	10.45	4.09
51/13	B	2	*M. hiantina*	Right	38.43	30.89	11.74	4.99
51/15	B	2	*M. hiantina*	Right	39.63	30.88	11.22	4.64
53/2	B	3	*M. hiantina*	Left	37.57	27.97	9.83	3.63
53/3	B	3	*M. hiantina*	Left	42.38	32.48	12.33	6.10
53/4	B	3	*M. hiantina*	Left	41.30	31.14	11.40	5.24
53/8	B	3	*M. hiantina*	Left	35.29	29.24	10.64	3.70
53/10	B	3	*M. hiantina*	Left	35.87	26.24	9.82	3.54
53/11	B	3	*M. hiantina*	Left	30.37	23.12	8.42	1.84
53/14	B	3	*M. hiantina*	Right	35.28	26.49	9.89	3.45
53/15	B	3	*M. hiantina*	Right	37.13	27.64	10.72	3.74
53/16	B	3	*M. hiantina*	Right	37.00	27.34	10.45	3.40
53/17	B	3	*M. hiantina*	Right	33.01	25.51	10.14	3.23
55/3	B	4	*M. hiantina*	Left	-	33.66	12.47	7.09
55/4	B	4	*M. hiantina*	Left	41.22	30.70	12.14	5.39
55/6	B	4	*M. hiantina*	Left	36.84	27.50	10.96	4.42
55/7	B	4	*M. hiantina*	Left	-	29.99	11.63	5.50
55/10	B	4	*M. hiantina*	Right	39.62	30.62	10.98	4.88
55/12	B	4	*M. hiantina*	Right	-	29.46	10.87	4.47
55/13	B	4	*M. hiantina*	Right	34.05	26.71	10.03	3.61
55/16	B	4	*M. hiantina*	Right	-	32.42	10.74	4.69
55/17	B	4	*M. hiantina*	Right	-	30.40	12.34	6.20
57/1	B	5	*M. hiantina*	Left	39.16	30.55	11.36	5.34
57/2	B	5	*M. hiantina*	Left	41.39	32.35	12.13	5.57
57/3	B	5	*M. hiantina*	Left	42.13	33.44	12.45	6.78
57/8	B	5	*M. hiantina*	Left	-	29.20	10.91	4.93
57/11	B	5	*M. hiantina*	Right	-	34.41	12.87	6.89
57/13	B	5	*M. hiantina*	Right	40.36	31.38	11.14	4.93
57/15	B	5	*M. hiantina*	Right	-	29.37	11.61	4.91
57/18	B	5	*M. hiantina*	Right	38.38	28.69	10.75	3.80
57/19	B	5	*M. hiantina*	Right	-	27.81	10.96	4.66
57/21	B	5	*M. hiantina*	Right	-	29.23	12.02	5.10
57/22	B	5	*M. hiantina*	Right	36.84	27.75	9.62	3.62

Appendix H – Additional information for archaeological material from Dangkankuruwuru used for isotopic analysis

FS#	SQ	XU	Species	Valve	Length (mm)	Height (mm)	Breadth (mm)	Weight (mg)
1	A	1	*M. hiantina*	Right	34.15	27.78	9.75	3.01
6	A	2	*M. hiantina*	Right	32.47	25.48	8.99	2.87
11	A	3	*M. hiantina*	Right	38.50	32.89	11.68	5.81
19	A	4	*M. hiantina*	Right	41.41	32.81	11.93	6.06
25	A	5	*M. hiantina*	Left	37.99	30.61	11.00	5.27
26	A	6	*M. hiantina*	Right	35.99	27.82	9.58	3.42
32	A	7	*M. hiantina*	Left	37.84	28.89	11.67	4.26
36	A	8	*M. hiantina*	Right	35.95	28.46	9.79	3.72
38	A	9	*M. hiantina*	Right	38.47	28.97	9.90	3.58
41	A	10	*M. hiantina*	Left	35.80	27.12	10.46	3.99
43	A	11	*M. hiantina*	Left	33.17	26.42	9.92	2.98
45	A	12	*M. hiantina*	Right	34.56	26.05	9.35	3.24
47	A	13	*M. hiantina*	Right	-	28.30	-	2.65
49	A	14	*M. hiantina*	Left	35.12	27.66	10.47	3.90
51	A	15	*M. hiantina*	Left	36.60	28.26	10.55	4.61
53	A	16	*M. hiantina*	Right	35.15	29.18	9.90	4.11
55	A	17	*M. hiantina*	Left	29.89	23.78	8.66	2.52
95	B	1	*M. hiantina*	Right	36.12	29.54	10.54	4.42
99	B	2	*M. hiantina*	Left	37.76	29.40	10.89	4.10
106	B	3	*M. hiantina*	Right	35.98	30.46	12.04	4.61
112	B	4	*M. hiantina*	Left	36.66	29.72	10.94	4.41
131	B	5	*M. hiantina*	Left	34.33	26.37	10.33	3.42
140	B	6	*M. hiantina*	Left	-	24.42	9.14	2.14
151	B	7	*M. hiantina*	Right	-	26.69	9.59	2.43
156	B	8	*M. hiantina*	Left	34.30	26.53	9.67	3.40
167	B	10	*M. hiantina*	Right	34.12	28.40	9.67	4.00
176	B	12	*M. hiantina*	Right	37.72	-	-	4.33
180	B	13	*M. hiantina*	Right	32.31	25.95	9.16	3.20
182	B	14	*M. hiantina*	Left	28.95	-	-	2.28
188	B	15	*M. hiantina*	Left	35.74	27.58	11.08	4.24
190	B	16	*M. hiantina*	Left	31.59	25.30	9.02	2.10
196	B	17	*M. hiantina*	Left	38.11	28.70	10.51	4.62
208	B	19	*M. hiantina*	Right	26.71	2036	7.27	1.47
209	B	20	*M. hiantina*	Right	35.29	30.34	11.10	4.95
213	B	21	*M. hiantina*	Right	35.23	27.75	9.75	3.53
227	B	23	*M. hiantina*	Right	-	23.39	-	1.47
231	B	24	*M. hiantina*	Left	37.30	29.46	11.58	5.94
76	C	1	*M. hiantina*	Right	38.91	31.42	11.42	5.79
78	C	2	*M. hiantina*	Right	35.82	27.68	10.09	3.80
82	C	3	*M. hiantina*	Left	38.64	29.99	10.75	3.99
89	C	4	*M. hiantina*	Left	35.34	28.28	10.35	3.75
93	C	5	*M. hiantina*	Right	35.04	26.22	9.33	3.39
101	C	6	*M. hiantina*	Right	39.27	32.54	11.52	5.24
126	C	8	*M. hiantina*	Left	31.66	24.98	8.48	2.52
129	C	9	*M. hiantina*	Left	35.02	26.47	9.59	2.82

FS#	SQ	XU	Species	Valve	Length (mm)	Height (mm)	Breadth (mm)	Weight (mg)
138	C	10	*M. hiantina*	Left	32.51	24.75	9.25	2.50
153	C	11	*M. hiantina*	Left	-	-	-	1.86
158	C	12	*M. hiantina*	Left	35.11	27.29	9.91	3.57
164	C	13	*M. hiantina*	NA	-	-	-	0.74
169	C	14	*M. hiantina*	Left	42.08	32.53	11.60	6.74
174	C	15	*M. hiantina*	Right	-	29.31	11.01	4.70
178	C	16	*M. hiantina*	Right	35.84	29.31	9.78	3.47
184	C	17	*M. hiantina*	Right	39.85	27.91	8.19	1.83
192	C	19	*M. hiantina*	Right	38.42	23.76	10.47	3.88
206	C	22	*M. hiantina*	Right	33.35	25.63	9.62	2.76
204	D	1	*M. hiantina*	Left	29.55	24.89	9.85	3.08
211	D	2	*M. hiantina*	Right	34.34	27.56	10.12	3.45
220	D	3	*M. hiantina*	Left	35.94	28.84	10.81	4.87
235	D	4	*M. hiantina*	Right	38.05	29.79	11.62	4.96
241	D	5	*M. hiantina*	Left	35.54	28.01	11.00	4.66
245	D	6	*M. hiantina*	Right	40.08	32.04	11.20	5.35
255	D	8	*M. hiantina*	Left	-	25.08	8.53	1.76
257	D	9	*M. hiantina*	Right	37.69	30.39	10.83	4.75
259	D	10	*M. hiantina*	Right	-	29.84	-	3.09
263	D	12	*M. hiantina*	Left	36.75	28.55	10.13	3.33
266	D	13	*M. hiantina*	Right	37.38	29.02	10.79	4.87
268	D	14	*M. hiantina*	Left	37.69	-	9.80	3.51
270	D	15	*M. hiantina*	Right	34.44	28.34	10.39	4.33
272	D	16	*M. hiantina*	Right	-	28.03	10.03	3.61
274	D	17	*M. hiantina*	Right	36.45	28.63	10.07	3.56
283	D	21	*M. hiantina*	Left	35.66	29.38	10.75	4.48
287	D	23	*M. hiantina*	Right	-	25.23	9.19	2.20
289	D	24	*M. hiantina*	Left	38.27	27.18	10.25	3.91

Appendix I – Additional information for archaeological material from Murdumurdu used for isotopic analysis

FS#	SQ	XU	Species	Valve	Length (mm)	Height (mm)	Breadth (mm)	Weight (mg)
9-1	A	3	*M. hiantina*	Left	35.11	27.12	9.95	3.81
13-1	A	4	*M. hiantina*	Left	34.36	26.91	9.94	3.22
13-2	A	4	*M. hiantina*	Right	36.24	26.46	9.84	3.53
13-3	A	4	*M. hiantina*	Right	37.4	27.39	9.87	3.37
13-4	A	4	*M. hiantina*	Right	35.69	26.91	9.78	2.68
17-1	A	5	*M. hiantina*	Right	36.88	27.79	10.31	3.65
17-2	A	5	*M. hiantina*	Right	32.54	23.74	7.96	2.64
17-3	A	5	*M. hiantina*	Right	36.57	27.73	9.79	3.01
17-4	A	5	*M. hiantina*	Left	33.4	26.38	9.23	3.23
17-5	A	5	*M. hiantina*	Right	36.37	26.92	10.08	3.79
21-1	A	6	*M. hiantina*	Right	35.56	26.62	9.41	3.4
21-2	A	6	*M. hiantina*	Right	-	30.7	11.06	5.4
21-3	A	6	*M. hiantina*	Right	37.27	27.99	10.71	4.52
26-1	A	7	*M. hiantina*	Left	32.37	26.51	9.82	3.2
27-1	A	8	*M. hiantina*	Left	-	24.02	7.88	1.85
33-1	A	9	*M. hiantina*	Left	31.89	23.84	8.22	2.06
37-1	A	10	*M. hiantina*	Left	-	28.74	10.05	2.92
7-1	B	2	*M. hiantina*	Right	33.34	25.35	8.9	2.7
11-1	B	3	*M. hiantina*	Left	36.42	27.21	8.85	3.12
15-1	B	4	*M. hiantina*	Left	33.24	24.98	8.02	2.37
15-2	B	4	*M. hiantina*	Left	35.87	26.78	9.57	3.37
19-1	B	5	*M. hiantina*	Right	32.37	24.01	8.22	2.17
19-2	B	5	*M. hiantina*	Left	36.22	28.02	9.88	3.19
19-3	B	5	*M. hiantina*	Left	33	26.21	9.36	3.02
19-4	B	5	*M. hiantina*	Right	38.3	29.64	10.08	4.49
23-1	B	6	*M. hiantina*	Right	32.16	25.3	8.77	2.58
23-2	B	6	*M. hiantina*	Right	34.97	28.42	9.6	3.44
27-1	B	7	*M. hiantina*	Right	33.28	25.3	8.79	2.57
27-2	B	7	*M. hiantina*	Right	35.04	26.33	9.32	2.99
27-3	B	7	*M. hiantina*	Right	37.78	28.98	9.64	4.05
31-1	B	8	*M. hiantina*	Right	36.34	29.14	9.59	3.35
31-2	B	8	*M. hiantina*	Right	35.96	27.48	10.04	3.69
35-1	B	9	*M. hiantina*	Right	-	30.2	-	3.15