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Front Cover: The Willandra Fossil Trackway, southwestern New South Wales. Children from the three traditional tribal groups of the Willandra Lakes walk on the site of what promises to be the world's largest collection of Pleistocene human footprints in the world (photograph courtesy of Michael Amendolia).

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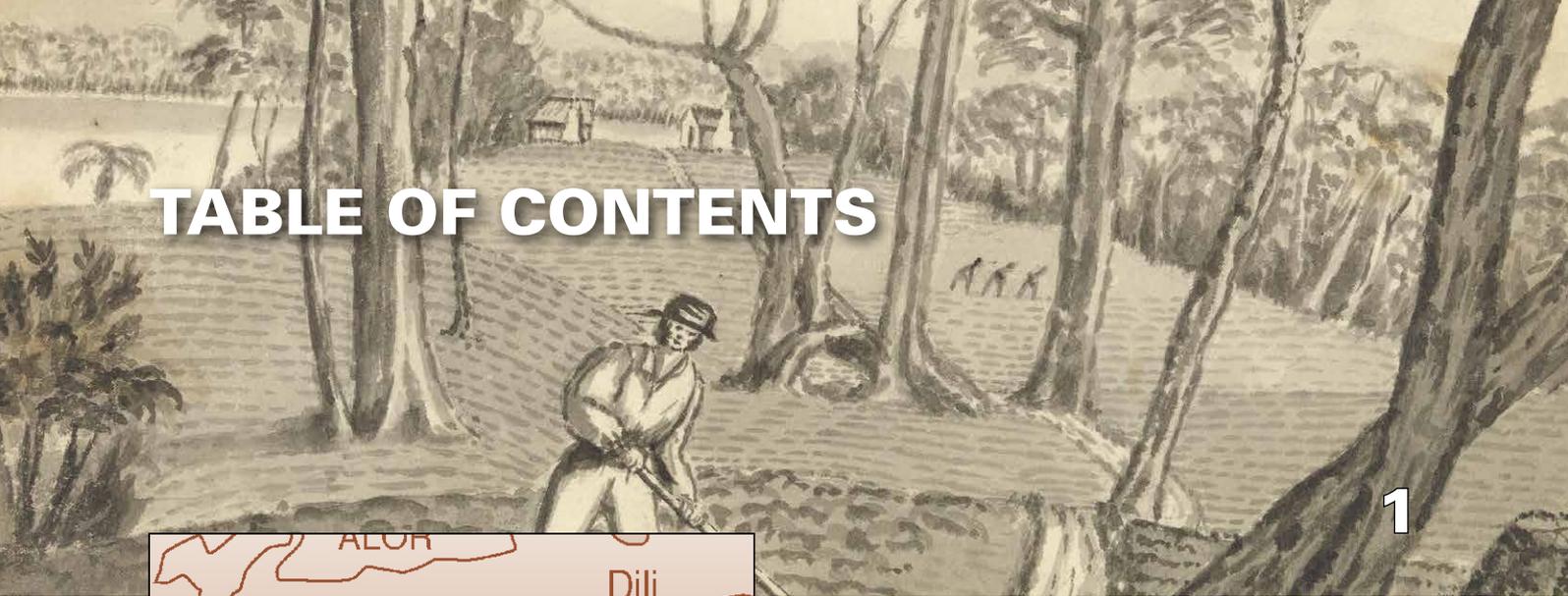
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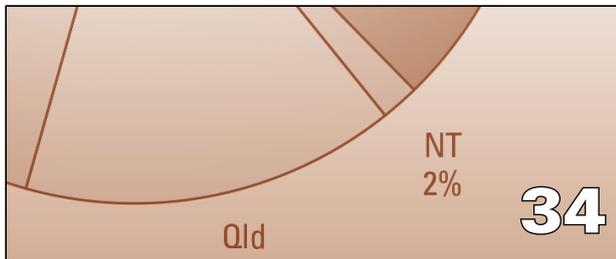
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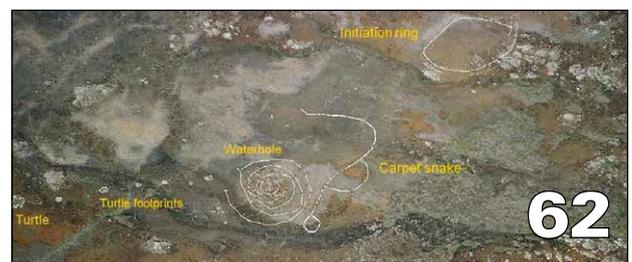
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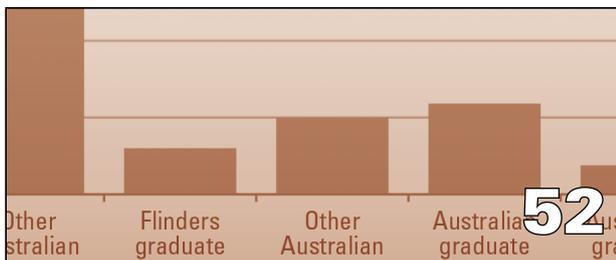
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LATE HOLOCENE CLIMATE CHANGE AND HUMAN BEHAVIOURAL VARIABILITY IN THE COASTAL WET-DRY TROPICS OF NORTHERN AUSTRALIA:

Evidence from a pilot study of oxygen isotopes in marine bivalve shells from archaeological sites

Sally Brockwell¹, Ben Marwick², Patricia Bourke³, Patrick Faulkner⁴ and Richard Willan⁵

Abstract

Previously it has been argued that midden analysis from three geographically distinct coastal regions of tropical northern Australia (Hope Inlet, Blyth River, Blue Mud Bay) demonstrates that changes through time in Aboriginal mollusc exploitation reflect broader coastal environmental transformations associated with late Holocene climatic variability (Bourke et al. 2007). It was suggested that, while a direct link between environmental change and significant cultural change in the archaeological record has yet to be demonstrated unambiguously, midden analysis has the potential to provide the as-yet missing link between changes in climate, environment and human responses over past millennia. We test this hypothesis with a preliminary sclerochronological analysis (i.e. of sequential stable isotopes of oxygen) of archaeological shell samples from all three regions. Our findings suggest the existence of variations in temperature and rainfall indicative of an increasing trend to aridity from 2000 to 500 cal. BP, consistent with previous palaeoenvironmental work across northern Australia.

Introduction

Some archaeologists have argued that climatic change between 800 and 400 years ago had considerable environmental and social consequences in the Indo-Pacific region (e.g. Field 2004; Field and Lape 2010; Haberle and Chepstow Lusty 2000; Haberle and David 2004; Lape 2006; Lape and Chin-Yung 2008; McNiven 2006; Spriggs 1993). Most of these studies have dealt with horticulturalist societies and, until recently, the potential impact of climatic variability on hunter-gatherer societies across the Indo-Pacific, and particularly on the northern Australian coast, has been less frequently considered (cf. Bourke et al. 2007; Haberle and David 2004; Morrison and Addison 2008).

In tropical northern Australia, radiometrically dated sequences from shell middens indicate that substantial changes occurred in the shellfish harvesting practices of hunter-gatherer groups after ca 800 years ago (Bourke 2003, 2004; Bourke et al. 2007; Brockwell et al. 2005; Faulkner 2006, 2009; Faulkner and Clarke 2004; Hiscock 1997, 1999). Archaeological middens act as climate archives (e.g. Sandweiss 2003), containing molluscan remains that potentially provide records of late Holocene climate change in low latitude coastal areas to augment sparse standard pollen and coral core palaeoclimate indicators. In this paper we describe the results of a pilot study of stable oxygen isotope values in marine bivalve shells excavated from middens along the northern Australia coastline. We demonstrate the potential of these data to identify changes in climatic conditions, and explore the link between these processes and human behavioural variability.

Late Holocene Patterns of Climatic and Environmental Change

It is widely acknowledged that climatic variability has increased in the Australasian region in the last few thousand years (Gagan and Chappell 2000:44; Gagan et al. 1994; Kershaw 1983, 1995; Prebble et al. 2005:367–369; Shulmeister 1999:82; Wason 1986). In northern Australia this variability is broadly characterised by a change from low seasonality in the early Holocene to increased seasonality in the late Holocene, within a general trend toward increasing aridity (Shulmeister 1999:86). This is supported by data extracted from scleractinian corals and forams, as well as varve, lake and sea bottom sediments (e.g. Kershaw 1995; Kim et al. 2002; Koutavas et al. 2002; McGlone et al. 1992; McPhail and Hope 1985; Nott et al. 1999:233; Rodbell et al. 1999). Geomorphic data from cheniers, coastal dunefields and fluvial mineral sediment (Lees 1992; Lees and Clements 1987; Lees et al. 1990, 1992; Wason and Bayliss 2010) indicate that some observed changes in these systems are synchronous across northern Australia, and may represent coherent, broad-scale climatic signals (Prebble et al. 2005:367–369; Shulmeister 1999:82; Wason and Bayliss 2010). Oxygen isotope ratios in archaeological shells are another palaeoclimatic archive through which to explore these patterns of late Holocene climatic variability (see Cohen et al. 1992; Culleton et al. 2009; Mannino et al. 2008; Rick et al. 2006; Stephens et al. 2008; Walker and Surge 2006), though they have not yet been used as such in a northern Australian context.

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The geographical focus of this study lies between latitudes 11° and 14° S in the wet-dry monsoonal tropics, an area that receives annual average rainfalls of approximately 1700 mm in the Darwin region, and 1500–1200 mm in central and northeast Arnhem Land. Most of this rain falls during the ‘wet season’ between December and March, flooding the coastal estuaries and plains with freshwater, with much smaller influxes experienced during the dry season. The progradation of the northern coastal plains was initiated following sea-level rise and stabilisation at ca 6000–7000 cal. BP, and is ongoing in the context of this monsoonal climate (Lambeck 2002; Sloss et al. 2007; Woodroffe 2009). A transitional period of rapidly changing estuarine and freshwater mosaic environments followed this initial phase, with widespread establishment of freshwater wetlands on the sub-coastal plains over the last 2000 years (Chappell and Grindrod 1984; Woodroffe and Grime 1999; Woodroffe et al. 1986, 1988, 1993).

Late Holocene Patterns of Change in Cultural Behaviour

Between ca 3000 and 500 cal. BP, shallow marine embayments containing intertidal sand and mudflats gradually prograded, supporting large beds of roughback cockle (*Anadara granosa*) and other molluscs. Shell mounds proliferated in a number of geographically distinct regions across northern Australia, including around the Darwin region, and central and eastern Arnhem Land (Bourke 2000:243–244, 2004; Bourke et al. 2007; Brockwell et al. 2009, 2011; Faulkner 2008, 2009). These mounds are dominated by molluscan species from sheltered beach and mudflat habitats, particularly *A. granosa*. Around 800 to 500 years cal. BP, environmental change in shoreline characteristics and climatic variability associated with ENSO activity led to a gradual decline of sandy/mudflat shell beds, and shell mounding behaviour ceased in these areas (Bourke et al. 2007).

Cultural changes, marked by a reorganisation in foraging relative to available near-shore marine resources, appear to correlate with the period of climatic uncertainty and increased resource patchiness in the transition from estuarine to freshwater conditions, and earth mounds and other open sites containing scatters of shell and stone artefacts proliferated along the floodplain margins. Foraging activities then appear to have again diversified to allow people to utilise the resources of more-closed-in mangrove-lined shores and coastal wetlands more extensively; middens with shell species harvested from varied habitats became more common after 500 years BP. The evidence suggests some people relocated from the coast to the seasonally abundant sub-coastal freshwater wetlands on the mainland during this period (Brockwell et al. 2011; Hiscock 1999, 2008:162, 179–181).

Case Studies

We present data from three geographically distinct areas of northern Australia: Hope Inlet near Darwin (Bourke 2000, 2002, 2004), Blyth River in central Arnhem Land (Brockwell et al. 2005; Meehan 1982) and Blue Mud Bay in northeastern Arnhem Land (Faulkner 2006, 2008, 2009; Faulkner and Clarke 2004) (Figure 1). Within each of these areas, we predicted that seasonal and long-term variation in rainfall should be detectable in the

isotopic composition of bivalve shells that Aboriginal people harvested during the late Holocene.

Hope Inlet

Significant change occurs in the molluscan assemblages of two large shell mounds on the coastline of Hope Inlet (Figure 2), HI80 and HI81, which date to the periods 1000–500 cal. BP and 2000–1400 cal. BP, respectively. There are decreased quantities (ca 20%) of the dominant species *A. granosa*, and a corresponding increase in mangrove-associated gastropod species (mainly *Telescopium telescopium*, *Terebralia semistriata*, *Nerita balteata* and *Cassidula angulifera*) in the more recently formed mound HI80 than in HI81 (Figure 3). The observed trend culminates around 700–500 cal. BP, with a marked change in cultural behaviour: from a shell discard practice that created mounds to one that resulted in low, horizontally dispersed shell middens, such as those observed ethnographically (Bourke 2004; cf. Meehan 1982).

Blyth River

Analysis of shell mounds and middens on the Blyth River coast (Figure 4) indicates that, between ca 1000 and 800 cal. BP, the dominant molluscan species exploited in the area was *Dosinia* cf. *laminata*, a deep burrowing bivalve that inhabits sand and silt areas with good current flow in the mid- and sub-littoral zones. After 800 cal. BP, this species declined and disappeared from these assemblages entirely by 500 cal. BP, with foraging focusing increasingly on other marine and mangrove shellfish species and newly available freshwater resources, such as the freshwater turtle *Chelodina rugosa* (Brockwell et al. 2005; Harte 1998:358; Meehan 1982:99) (Figure 5).

Blue Mud Bay

Prior to ca 2500 cal. BP around Blue Mud Bay on the Point Blane Peninsula (Figure 6) there was a greater focus on molluscan resources from shallow water, and sand and mudflat areas in the near-shore zone. Associated with the period of mound formation in this area, between ca 2500 and 500 cal. BP, there was a decline in the relative abundance of species from the shallow water, hard substrate areas and an increasingly heavy reliance on species from the sand and mudflats, most notably *A. granosa* (Faulkner 2009). The use of mangrove species varied during this time depending on site location. After ca 500 cal. BP, there was an increase in the use of mangrove species, corresponding with a significant decline in exploitation of mudflat bivalves, and a shift to predominantly horizontally spread midden deposits similar to that observed at Hope Inlet (Faulkner 2006:257) (Figure 7).

Synthesis

In all three study areas, the changes in patterns of mollusc exploitation can be correlated with an overall trend towards aridity (cf. Bourke et al. 2007). There is sufficient overlap between the phases of climatic change described above and the timing of behavioural changes within each of the three regions (see Figure 8) to suggest that, with regional variation in the nature and severity of the climatic changes, people responded to the associated shifts in resource structure and availability (Bourke et al. 2007:97).

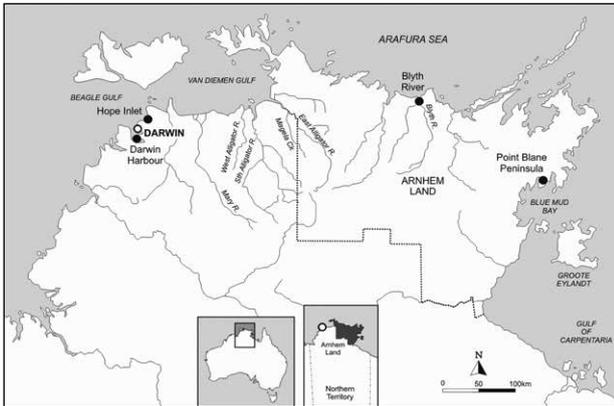


Figure 1 Top End of the Northern Territory, showing the location of the three study areas (courtesy Patrick Faulkner).

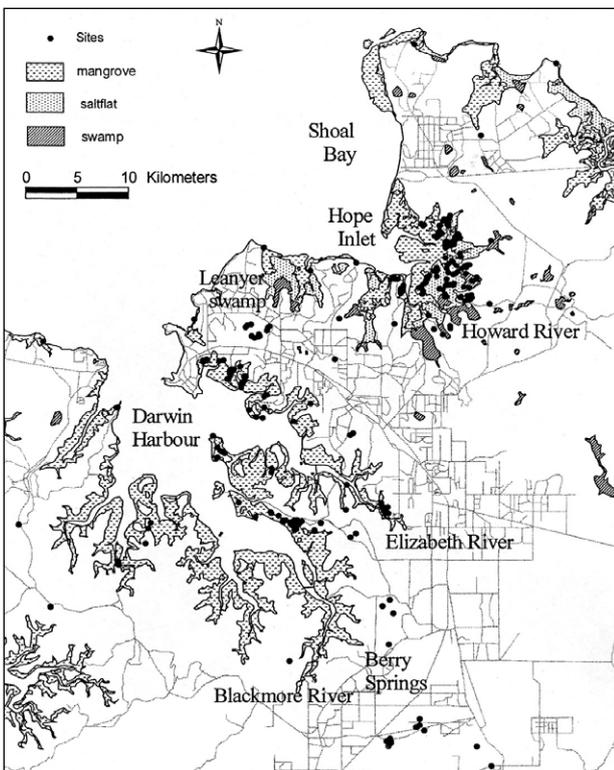


Figure 2 Location of Hope Inlet (courtesy Patricia Bourke).

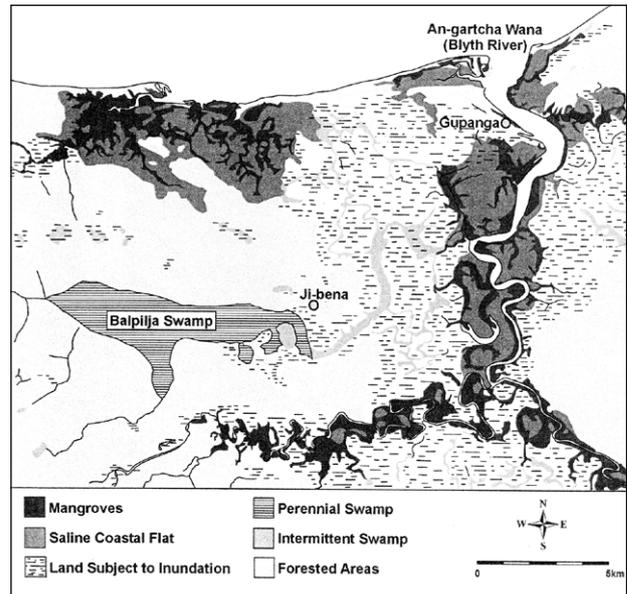


Figure 4 Location of Blyth River (courtesy Multimedia Services, College of Asia and the Pacific, ANU).

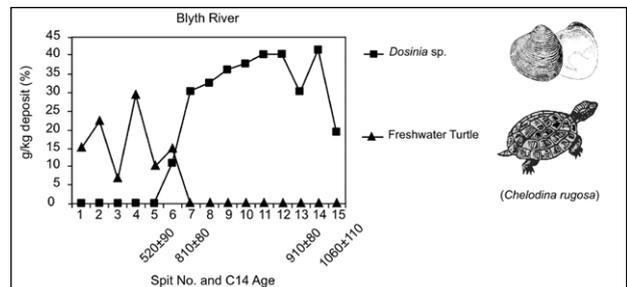


Figure 5 Changes in the relative abundance of the mudflat bivalve *Dosinia cf. laminata* and freshwater turtle, Blyth River (shell images redrawn from Poutiers 1998b:451).

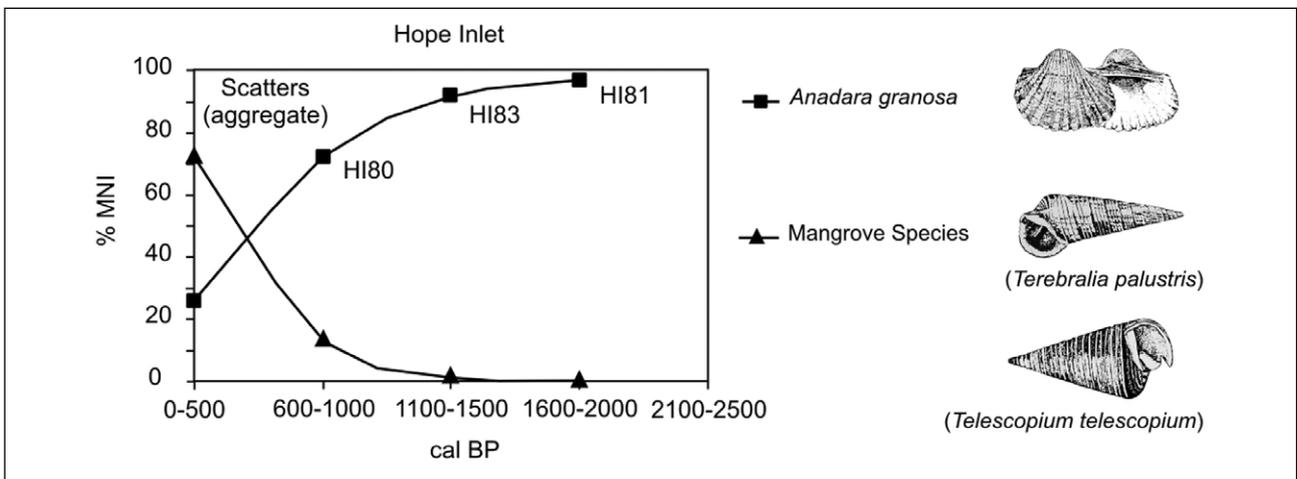


Figure 3 Decrease in *Anadara granosa* and relative increase in mangrove gastropods over time at Hope Inlet (shell images redrawn from Poutiers 1998a:147, 1998b:451).

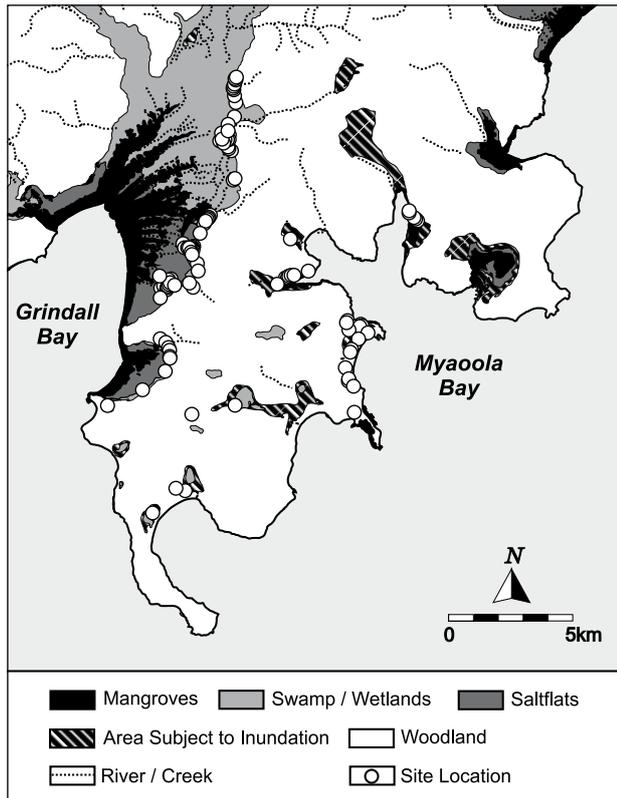


Figure 6 Location of Blue Mud Bay (courtesy Patrick Faulkner).

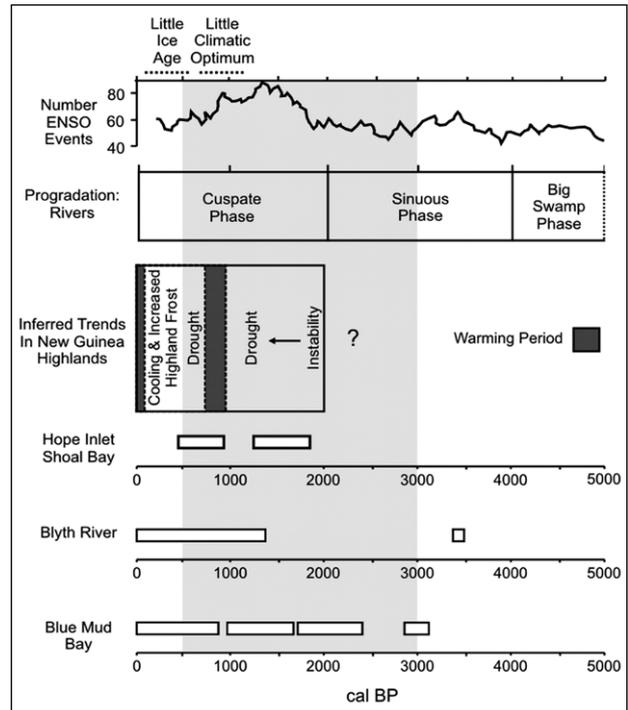


Figure 8 Comparison of radiocarbon dates (2σ combined ranges, unfilled bars) from each study area relative to the Little Climatic Optimum and the Little Ice Age (grey shading indicates main period of mound building in the Northern Territory). Full details of radiocarbon dates can be found in Brockwell et al. (2009).

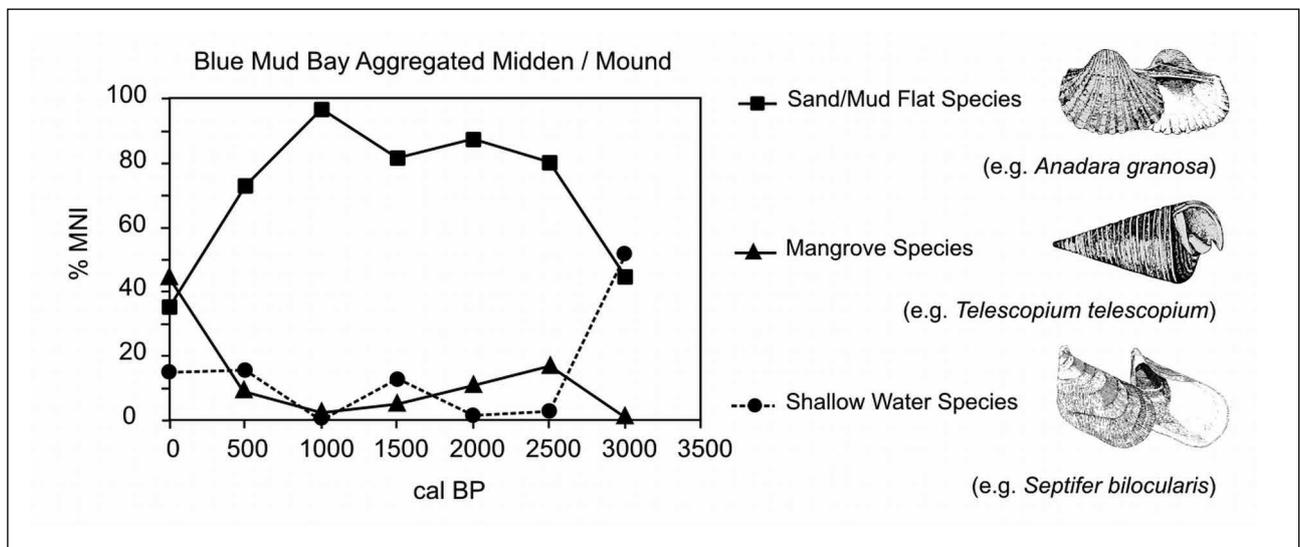


Figure 7 Chronological variation in the exploitation of mudflat, mangrove and shallow water mollusc species on the Point Blane Peninsula, Blue Mud Bay (shell images redrawn from Poutiers 1998a:147, 173, 1998b:451).

In terms of molluscs, there is a clear ecological distinction between those species that live on mudflats and those that live in mangrove forests—indeed some are obligate associates of such forests. Dominant molluscs that live on muddy or sandy shores of northern Australia that have historically been, and presently still are, exploited by coastal Aboriginal people are all bivalves: roughback cockle (*A. granosa*), hiant Venus clam (*Marcia hiantina*) and biscuit clam (*Dosinia* spp.). In contrast, the dominant mangrove-dwellers are longbum (*Telescopium telescopium* and *Terebralia palustris* and *T. semistriata*), nerite or periwinkle (*Nerita balteata*), winding spiral whelk (*Pugilina*

[*Volema*] *cochlidium*), clothed clam (*Gari togata*), mud mussel (*Polymesoda erosa* [*Geloina coaxans*]) and mangrove ‘worms’ (family Teredinidae). The first five of these are gastropods and the latter three are bivalves.

Nomenclature and Physiology of Sampled Molluscan Taxa

The two species of molluscs selected for this sclerochronological analysis, the roughback cockle, *A. granosa* (family Arcidae), and the biscuit clam, *D. cf. laminata* (family Veneridae), are moderately large shelled bivalves, are abundant in northern

Australian coastal waters, were/are consumed by coastal Aboriginal people, and are common archaeologically. These attributes make them the most logical choices to study in this context. However, as with so many northern Australia molluscs, the nomenclature of neither species is entirely settled. The modern trend in malacology, as elsewhere in zoology, is to split large genera into smaller, demonstrably monophyletic units, so the species *granosa* (for which, incidentally, there is a complex of species with nodulose radial ribs, although determining the species requires genetic testing) is most often placed in the genus *Tegillarca* in contemporary taxonomic works (e.g. Huber 2010:573). This change of genus is not settled yet, so in this work we have opted for conservatism and consistency with other archaeological literature and left this species in *Anadara*. The numerically large genus *Dosinia* and its constituent species are poorly understood taxonomically in northern Australia. As with *Anadara*, the genus *Dosinia* will be eventually split into smaller monophyletic units and the unit most likely to encompass this species is *Bonartemis*. The specific name *laminata* is used here because the archaeological specimens best match modern samples identified to this species, though the posterior margin of archaeological examples appears more rounded and the posterior commarginal ribs less lamellate than in modern examples identified as this species from Australia (Lamprell and Whitehead 1992). It has been called *D. cf. laminata* to reflect this taxonomic uncertainty.

No physiological studies have been conducted on *A. granosa* or *D. cf. laminata* in tropical northern Australia (Willan and Dredge 2004), so there are gaps in knowledge for the rate of growth or biomineralisation, or the longevity of these bivalves. There are data on these topics for the former species from Asia (Broom 1985; Davenport and Wong 1986; Richardson 1987), but the environmental conditions there are dissimilar to the 'wet-dry' summer monsoon tropics of northern Australia, so it is unsafe to extrapolate the data to our study. However, for the purposes of this analysis, it is safe to conclude that the lives of both these species span several monsoon seasons (i.e. they have an average life expectancy of greater than five years), they have uniform growth rates, and in nature do not normally move any distance horizontally during their lifetimes (in fact, both can reburrow rapidly if scoured out and translocated by strong currents).

Background to Isotope Geochemistry

A recent review noted that sequential stable isotope analysis was perhaps the most frequently used sclerochronological approach to reconstructing past climate and environments from midden samples (Andrus 2011). The theory behind using shell stable oxygen isotope ratios as a palaeoenvironmental proxy is that the $\delta^{18}\text{O}$ values of a growing shell will reflect those of the water in which the shellfish animal lives during its life. Under conditions of isotopic equilibrium, the $\delta^{18}\text{O}$ values in a shell will be a function of water temperature and the $\delta^{18}\text{O}$ values of the water. Several studies have empirically quantified the contribution of these parameters to shell material (Dettman and Lohmann 1993; Epstein et al. 1953; Grossman and Ku 1986; Wanamaker et al. 2006, 2007). In tropical latitudes, such as our study sites, the relationship between air temperature and $\delta^{18}\text{O}$ values of rainfall is nearly equal to the opposing temperature-dependent water-carbonate relationship; as such, the potential impact

of differing water and air temperature effects on the resulting shell $\delta^{18}\text{O}$ values tends to be cancelled out (Dansgaard 1964; Epstein et al. 1953). This means that, for regions where changes in monsoon intensity and the $\delta^{18}\text{O}$ of rainfall are large, the impact of changing temperature on shell $\delta^{18}\text{O}$ will be relatively small (cf. Araguás-Araguás et al. 1998; Gat 1996; Marwick and Gagan 2011). In tropical settings the $\delta^{18}\text{O}$ values of summer monsoon rainfall are much reduced compared to winter dry-season rainfall (Griffiths et al. 2009, 2010), and so the oxygen isotope values recorded in tropical marine shells can be used as a measure of the relative amount of summer monsoon rainfall. This implies that any variation in $\delta^{18}\text{O}$ in shells from Hope Inlet and Blue Mud Bay, which are relatively sheltered, infilled shallow marine embayments with minor watercourses, will most likely result from changes in monsoon rainfall. A complicating factor at the larger river system of Blyth River is that the influx of freshwater from continental rivers can cause major changes in the oxygen isotopic composition of estuarine water (cf. Kennett and Voorhies 1995, 1996). The influx of river water affects the oxygen isotopic signal of estuarine water because it has lower concentrations of the heavier oxygen isotope (^{18}O) than ocean water (Culleton et al. 2009; Keith et al. 1964). In theory, the peak contribution of continental water to the estuary will coincide with the summer monsoon rain, and because both processes act to lower $\delta^{18}\text{O}$ values in the water, the overall net effect is a reduction in $\delta^{18}\text{O}$ values in the estuarine water as well (Stephens et al. 2008). One of our objectives was to determine if a reliable trend in $\delta^{18}\text{O}$ values can be identified in specimens from Blyth River, which is a typical example of where greater freshwater discharge at marine locations can result in complex interactions.

Methods

Sampling and Dating

As an initial assessment of the viability of this approach for the study area, a small number of bivalves were sampled from archaeological shell middens at Hope Inlet (*A. granosa* n=2), Blyth River (*D. cf. laminata* n=18, as *Anadara* did not occur at this site) and Point Blane Peninsula on Blue Mud Bay (*A. granosa* n=8). All radiocarbon ages available for the sites discussed here were calibrated to two sigma using CALIB 6.1.1. following methods outlined in Brockwell et al. (2009:59–60). As all ages were derived from marine shell samples, the marine 04.14C calibration curve was used (Hughen et al. 2004), with a ΔR correction value of 55 ± 98 used for the Blue Mud Bay samples, and 65 ± 24 for the Blyth River and Hope Inlet samples.

For the Blyth River sites, two valves were taken from nine excavation units of a single earth mound (Table 1; cf. Brockwell et al. 2005). Radiocarbon dates were associated with three of these units and regression techniques were used to assign ages to the other units, indicating that the ages of shell sampled from this site span 550–1000 cal. BP. The method used here to assign ages to those undated units was by linear interpolation (e.g. Bennett 1994:339) and, while not taking into account variations in accumulation rates, is one of the simplest and most frequently used methods for constructing an age-depth model. The median calibrated radiocarbon ages are plotted against the depth of the unit from which they were obtained. The median calibrated ages are used here as they represent a central best-

point estimate of the probability distribution for each calibrated date (after Telford et al. 2004 and Ulm et al. 2010). These points are connected by straight lines, and the age estimates required are calculated from the gradients at the relevant intermediate depths below ground surface for each unit.

For Hope Inlet, eight samples from two valves were used; four from one valve, which came from dated excavation unit (spit) 20 (mound HI80), and another four samples from one valve collected from the wall of mound HI81 at a depth of 65 cm below surface, at the same stratigraphic level as spits 20 and 21 (Table 1). Radiocarbon dates associated with unit 20 in mound HI80, and with dated units bracketing units 20 and 21 in mound HI81, indicate that the ages of shell sampled from these two sites span 650–1500 cal. BP (Bourke 2004; Brockwell et al. 2009). For the Blue Mud Bay sites, eight valves were taken from undated excavation units in three shell mounds. Four samples were

obtained from BMB-29, and two samples each from mounds BMB-71 and BMB-45. In line with the method used for the Blyth River site, radiocarbon dates from each of these three sites enabled ages to be assigned to the sampled excavation units via regression techniques. Based on the available radiocarbon ages and depth/age estimates, the shell valves spanned the period ca 2300–600 cal. BP (Table 1) (Faulkner 2006, 2008). All shells selected for analysis were mature, full-sized specimens to minimise differences in kinetic effects from different growth phases on their isotopic values. In addition, three *A. granosa* specimens live-collected from the mudflats of Darwin Harbour near Hope Inlet (Bourke and Willan 2009) were analysed for comparison of isotopic values in modern shells.

Intra-shell sampling was also undertaken on two similar sized *A. granosa* specimens (one each from two different archaeological middens) for two reasons: first, to identify the range of $\delta^{18}\text{O}$

Archaeological Site Name	¹⁴ C Lab No.	¹⁴ C Age	Radiocarbon Age (2σ cal. BP)	Isotope Sample ID	Sample Species	δ ¹⁸ O V-PDB (‰)
Hope Inlet 80	OZC-958	1090±90	886-530	HI80.B11.1 spit 20	<i>Anadara granosa</i>	-1.4
	OZC-958	1090±90	886-530	HI80.B11.2 spit 20	<i>A. granosa</i>	-2.3
	OZC-958	1090±90	886-530	HI80.B11.3 spit 20	<i>A. granosa</i>	-1.5
	OZC-958	1090±90	886-530	HI80.B11.4 spit 20	<i>A. granosa</i>	-2.2
Hope Inlet 81			*1500	HI81 wall 65 1 spit 20-21	<i>A. granosa</i>	-1.3
			*1500	HI81 wall 65 2 spit 20-21	<i>A. granosa</i>	-3.3
			*1500	HI81 wall 65 3 spit 20-21	<i>A. granosa</i>	-2.8
			*1500	HI81 wall 65 4 spit 20-21	<i>A. granosa</i>	-2.0
Blue Mud Bay 29			*1998	BMB/29 TP1 spit 7	<i>A. granosa</i>	-2.9
			*1998	BMB/29 TP1 spit 7	<i>A. granosa</i>	-2.4
			*2296	BMB/29 TP1 spit 17	<i>A. granosa</i>	-1.4
			*2296	BMB/29 TP1 spit 17	<i>A. granosa</i>	-2.0
Blue Mud Bay 71			*1323	BMB/71TP1 spit 5	<i>A. granosa</i>	-1.3
			*1323	BMB/71TP1 spit 5	<i>A. granosa</i>	-1.7
Blue Mud Bay 45			*585	BMB/45 TP1 spit 9	<i>A. granosa</i>	-0.5
			*585	BMB/45 TP1 spit 9	<i>A. granosa</i>	-0.9
Jibena (Blyth River)			*550	J6 DJ-13	<i>Dosinia cf. laminata</i>	-2.9
			*550	J6 DJ-14	<i>D. cf. laminata</i>	-2.1
			*650	J7 DJ-1	<i>D. cf. laminata</i>	-2.3
			*650	J7 DJ-2	<i>D. cf. laminata</i>	-3.3
	ANU-3416	1260±70	915-625	J8 DJ-3	<i>D. cf. laminata</i>	-2.4
	ANU-3416	1260±70	915-625	J8 DJ-4	<i>D. cf. laminata</i>	-2.6
			*777.5	J9 DJ-15	<i>D. cf. laminata</i>	-2.8
			*777.5	J9 DJ-16	<i>D. cf. laminata</i>	-2.5
			*795	J10 DJ-7	<i>D. cf. laminata</i>	-2.4
			*795	J10 DJ-8	<i>D. cf. laminata</i>	-2.6
			*812.5	J11 DJ-5	<i>D. cf. laminata</i>	-2.2
			*812.5	J11 DJ-6	<i>D. cf. laminata</i>	-2.7
			*835	J12 DJ-17	<i>D. cf. laminata</i>	-2.3
			*835	J12 DJ-18	<i>D. cf. laminata</i>	-2.3
	ANU-3417	1360±70	1003-675	J13 DJ-9	<i>D. cf. laminata</i>	-2.6
	ANU-3417	1360±70	1003-675	J13 DJ-10	<i>D. cf. laminata</i>	-2.3
ANU-2817	1510±100	1236-775	J14 DJ-11	<i>D. cf. laminata</i>	-2.8	
ANU-2817	1510±100	1236-775	J14 DJ-12	<i>D. cf. laminata</i>	-2.7	

Table 1 δ¹⁸O values from bulk samples taken from the umbos of *Anadara granosa* and *Dosinia cf. laminata* shells from dated archaeological deposits on the northern Australian coast. * = Estimates based on age-depth models

values in the bulk measurements indicative of climate change rather than annual seasonal cycles; and second, to evaluate differences in the magnitude of seasonality between ca 2000 and 600 cal. BP through comparison of the spread of isotopic values in the two individual shells. This allows us to explore another dimension of climate change, namely that it may have involved not just a shift in mean temperatures, but also a shift in the range of temperatures. One shell was taken from Hope Inlet mound HI80 (HI80A19, from unit 19 dated to 733 cal. BP) and one from shell mound MA1 (MA1D5, from unit 5 dated to 2056 cal. BP) ca 30 km south of Hope Inlet. Thirty isotope samples were taken from each shell, drilled equidistant along a cross-section from umbo to margin.

Sample Preparation for Stable Isotope Analysis

The shells were mechanically cleaned with an abrasive disk attached to an electric rotary tool to remove adhering organic particles. A cross-sectional cut was made using a 1.75 mm diamond-bladed saw along the axis of maximum growth. Microdrilling was chosen as the most appropriate technique because of the rapid speed of sampling and the relatively low spatial resolution required (Spötl and Matthey 2006). As shell aragonite can transform to calcite under heat and/or stress, resulting in exchange with atmospheric or organic carbon and oxygen (Foster et al. 2008), a slowly rotating 0.35 mm or 0.5 mm twist drill bit was used to obtain a 180–200 µg powder sample from the freshly cut cross-section. Each of the cross-sections was stained with Feigl's solution, which turns black in the presence of aragonite (Friedman 1959) so as to confirm the shell's mineralogy. Diagenesis of aragonitic shells resulting from heating usually involves conversion to the more stable polymorph calcite (Stephens et al. 2008). Since calcite was not detected, we concluded that diagenesis has been minimal and constant across our samples. All shells listed in Table 1 were bulk-sampled from the umbonal region of the cross-section. As noted by Andrus (2011), there are a wide variety of factors that influence seasonal and annual shell growth and, subsequently, how these growth structures are interpreted in archaeological contexts. As noted above, for the species in our sample the fundamental biomineralogical research is yet to appear. To optimise cost

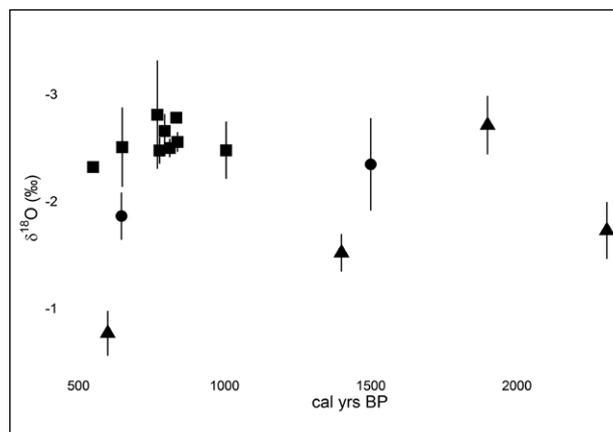


Figure 9 Combined shell isotope plots from all three locations (▲=Blue Mud Bay, ●=Hope Inlet, ■=Blyth River). Error bars are standard error of the mean.

and sampling in this pilot study we chose the umbonal region for bulk sampling for two reasons: first, to minimise the effect of differential diagenetic alteration of the shell, with the best preservation of the original shell mineral hypothesised to be at the thickest area near the umbo; and second, to obtain samples that are time-averaged across the biological age of the specimen (Dick et al. 2007).

Stable Isotope Analysis

The Blyth River and Blue Mud Bay samples were analysed at the ANU Research School of Earth Sciences on a Finnigan MAT 251 using a Kiel microcarbonate preparation device, both computer-controlled with ISODAT software. At the University of Washington, samples from Hope Inlet and the three modern Darwin Harbour specimens were analysed using a Finnigan DeltaPlus with Kiel III Carbonate Device. Carbonate samples were reacted with two drops of 105% phosphoric acid at 90°C over a reaction time of 13 minutes. Water was removed from the H₂O-CO₂ gas evolved from this reaction by freezing and then vaporising CO₂ in a double trap system using liquid nitrogen. The pure CO₂ then entered the inlet system of the mass spectrometer for measurement.

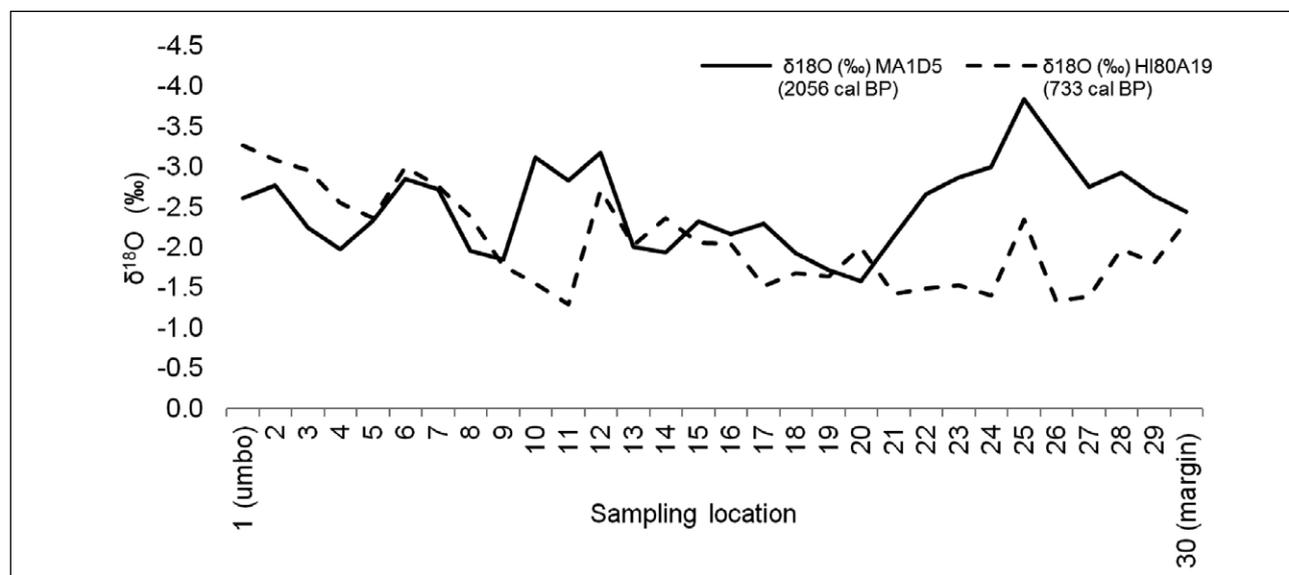


Figure 10 Isotope values from powder samples drilled from cross-sections of single *A. granosa* specimens from sites HI80 and MA1 near Darwin (see text for details of sampling strategy).

Sample Position	$\delta^{18}\text{OVPDB}$ (‰) HI80A19 (733 cal. BP)	$\delta^{18}\text{OVPDB}$ (‰) MA1D5 (2056 cal. BP)
1 (umbo)	-3.2	-2.6
2	-3.1	-2.8
3	-3.0	-2.2
4	-2.5	-1.9
5	-2.3	-2.3
6	-3.0	-2.8
7	-2.7	-2.7
8	-2.4	-1.9
9	-1.7	-1.8
10	-1.5	-3.1
11	-1.3	-2.8
12	-2.7	-3.2
13	-2.0	-2.0
14	-2.3	-1.0
15	-2.0	-2.3
16	-2.0	-2.1
17	-1.0	-2.3
18	-1.7	-1.9
19	-1.6	-1.7
20	-2.0	-1.6
21	-1.4	-2.1
22	-1.5	-2.6
23	-1.5	-2.9
24	-1.4	-3.0
25	-2.3	-3.8
26	-1.3	-3.3
27	-1.4	-2.7
28	-1.9	-2.9
29	-1.8	-2.6
30 (margin)	-2.3	-2.4

Table 2 $\delta^{18}\text{O}$ values of powder samples taken from cross-sections of individual *A. granosa* shells from sites HI80 and MA1 (see text for details of sampling strategy).

	$\delta^{18}\text{OVPDB}$ (‰) HI80A19 (733 cal. BP)	$\delta^{18}\text{OVPDB}$ (‰) MA1D5 (2056 cal. BP)
Mean	-2.0	-2.5
Maximum	-1.3	-1.6
Minimum	-3.2	-3.8
Standard deviation	0.6	0.5
Median absolute deviation	0.7	0.5

Table 3 Descriptive statistics of the $\delta^{18}\text{O}$ values representing the life spans of individual *A. granosa* specimens from sites HI80 and MA1D5.

Following convention, the results are reported as delta (δ) values in units of per mil (‰). The delta value is an expression of the difference between the raw $\delta^{18}\text{O}$ value of the shell and a standard, in this case Vienna Pee Dee Belemnite (VPDB; Criss 1999:35). National Bureau of Standards NBS-19 was used to normalise the data to the VPDB scale. The working gas (KAZZA) was composed of $\delta^{18}\text{OVPDB} = -1.88\text{‰}$ and $\delta^{13}\text{CVPDB} = 2.39\text{‰}$. The data were corrected for ^{17}O interference using the method of Santrock et al. (1985) and normalised so that a sample of solid NBS-19 analysed by this method would yield $\delta^{18}\text{OVPDB} = -2.20\text{‰}$. The working gas values and ion correction methods are reported here to allow comparison with data produced

in different laboratories. Analytical precision for replicate measurements of $\delta^{18}\text{O}$ in NBS-19 was $\pm 0.2\text{‰}$ (2SD).

Results

The $\delta^{18}\text{O}$ values for the three modern Darwin Harbour specimens were -1.8‰ , -1.9‰ and -2.1‰ . Table 1 shows the $\delta^{18}\text{O}$ values for the bulk-sampled shells from the archaeological middens. Comparison of isotopic records from the three locations shows that they have quite different profiles (Figure 9). The isotopic values at Blyth River (mean $\delta^{18}\text{O} = -2.5\text{‰}$) are lower than those from Blue Mud Bay (mean $\delta^{18}\text{O} = -1.5\text{‰}$) and Hope Inlet (mean $\delta^{18}\text{O} = -2.1\text{‰}$).

Figure 9 shows a trend toward isotopically heavier $\delta^{18}\text{O}$ values in shells dated to more recent periods at Hope Inlet. Amongst the Hope Inlet specimens the spread in values is relatively wide. Furthermore, while the trend is suggestive, the difference in the mean values of the two time periods is not statistically significant (Wilcoxon rank sum test, $W = 6$, $p = 0.68$).

The data show a similar overall trend to heavier $\delta^{18}\text{O}$ values of shells from Blue Mud Bay. The samples within each spit at Blue Mud Bay (eight specimens in total, two from each spit) show relatively little variation in their isotopic values, suggesting that they reliably reflect the isotopic conditions of the water in which the shellfish grew. For the Blue Mud Bay specimens the difference between the mean values of each time period is significant (Approximative Kruskal Wallis test, chi-squared = 6.16, $p = 0.03$).

The $\delta^{18}\text{O}$ values from the 18 Blyth River shells show no clear trend, a result which does not fit well with data from the other sites (Figure 9). The long standard error bars for three paired shell specimens at Blyth River show that shells from within the same excavation units vary greatly in their isotopic values relative to the overall trend across the excavation units. There is no significant difference between the mean $\delta^{18}\text{O}$ values for each of the nine time periods (Approximative Kruskal Wallis test, chi-squared = 5.12, $p = 0.82$).

Table 2 and Figure 10 show the variation in isotopic values in the two shells that were sampled from umbo to margin. At sampling location 25, specimen MA1D5 shows a decrease in $\delta^{18}\text{O}$ values, indicating a period of peak precipitation during the life of the shell (Figure 10). A smaller peak is evident at the same location in specimen HI80A19. A Wilcoxon rank sum test indicates that the difference in the central tendency of the distributions of isotopic values in the two specimens is unlikely to be due to chance ($W = 631.5$, $p = 0.007$). Two indicators of the spread of the isotopic values of the two specimens reveal that variation was greater for the ca 700 cal. BP specimen compared to the ca 2000 cal. BP specimen (Table 3). The ca 700 cal. BP specimen has a higher standard deviation of isotopic values during its lifespan and a higher median absolute deviation (a more robust measure of spread than standard deviation; Hoaglin et al. 1983) than the ca 2000 cal. BP sample.

Discussion

With relatively small sample sizes the results must be treated with caution and, at this stage, our interpretations are only preliminary. Whilst acknowledging that there are challenges presented by having two uncontrolled variables (i.e. water temperature and $\delta^{18}\text{O}$) (Andrus 2011), the trends in $\delta^{18}\text{O}$ values observed in the Hope Inlet and Blue Mud Bay specimens are suggestive of a declining summer monsoon rainfall and increasing aridity from 2000 to 500 cal. BP. The $\delta^{18}\text{O}$ values of the live-collected specimens provide a baseline to calibrate these trends, indicating that conditions at 2000 cal. BP were wetter than the present. The trends in isotope values correlate with the decrease in *Anadara granosa* and increase in mangrove-associated gastropod species culminating ca 700–500 cal. BP, and the associated shift from shell mounds to flatter, non-mounded shell middens. The reduced precipitation most convincingly suggested by the Blue Mud Bay data are consistent with a marine rather than fluvial source for estuarine infill and muddy progradation, providing

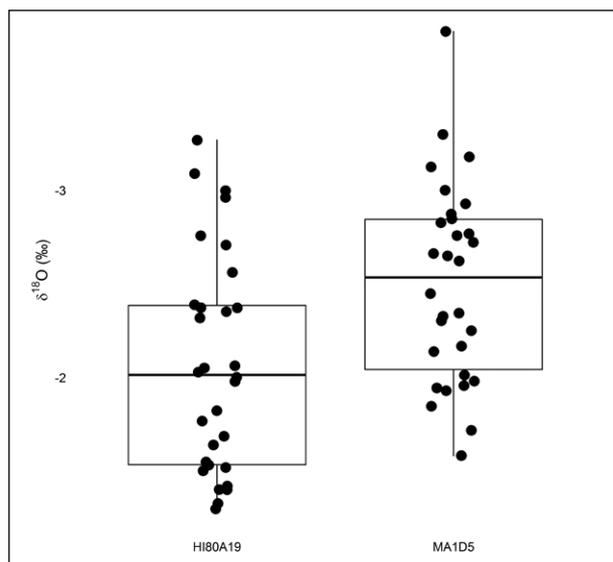


Figure 11 Box and whisker plot overlaid with individual data points for powder samples drilled from cross sections of two *A. granosa* specimens. Note the higher central tendency for the HI80A19 specimen, indicating more arid conditions at ca 700 cal. BP than MA1D5 at ca 2000 cal. BP.

favourable habitats for local mangrove expansion. This marine mud accretion is linked to aridity because rain-fed streams are not contributing substantially to the estuarine sediment supply (Chappell and Grindrod 1984; Kench 1999:375; Woodroffe and Mulrennan 1993:63–65, 98–99). Phytolith analysis undertaken on samples obtained from top, middle and bottom excavation units of sites BMB/029, BMB/071 and BMB/061, spanning the period between ca 2527–929 cal. BP, indicates a wetter phase around 1200 BP (Doreen Bowdery pers. comm.). The overall trend, however, is for climatic instability within a broader pattern of increasing aridity as indicated by other data for the region (e.g. Prebble et al. 2005; Shulmeister 1992). The lack of a significant trend amongst the Hope Inlet and Blyth River specimen values may be due to this climatic instability.

The absence of a statistically significant trend at Hope Inlet may simply be due to the small size of the analysed sample, while the wide range in values per shell may be due to complicated inputs from freshwater and marine sources. Similarly, the absence of a clear trend in the $\delta^{18}\text{O}$ values of shells from Blyth River may be due to the freshwater inputs that have obscured the monsoon signal evident at Blue Mud Bay (cf. Kennett and Voorhies 1995, 1996). However, the isotopically heavier mean value from Blyth River, relative to the other locations sampled, is not consistent with a scenario where continental water contributions reduce ^{18}O concentrations, as this should result in less negative $\delta^{18}\text{O}$ values in the shell carbonate. Therefore, we conclude that different rates in the kinetic fractionation of oxygen isotopes between *A. granosa* at Blue Mud Bay and Hope Inlet, and *D. cf. laminata* at Blyth River, are the likely source of the inconsistencies observed. A further confounding factor may be that *A. granosa* were not available for analysis from this site and the analysed species, *D. cf. laminata*, might not be comparable, perhaps because it does not deposit its biogenic carbonate in isotopic equilibrium with the water adjacent to its habitat (cf. Jones et al. 2002). One reason for this may be that *Dosinia* spp. is known to be a rapid and deep burrowing taxon (Gingras et al.

2008), so the water chemistry might be different in this habitat compared to that of *A. granosa*. Further testing of modern shells is needed to understand these relationships better.

The significant difference in mean values of the two specimens that were intra-sampled suggests that they represent growth under different environmental conditions. These peak precipitation events recorded in the sequence of $\delta^{18}\text{O}$ values for each of the two specimens suggest that they lived through at least one monsoon season. This lifespan is consistent with observations of live specimens (Bourke and Hua 2009:179; Broom 1985). On average, the specimen from ca 700 cal. BP (HI80A19) has higher $\delta^{18}\text{O}$ values, indicating more arid conditions compared to those experienced by the other individual at ca 2000 cal. BP (MA1D5)—this is consistent with the isotopic data from the bulk-sampled shells at the other sites (Table 3, Figure 11).

The greatest divergences between HI80A19 and MA1D5 occur near sampling locations 12 and 25 (Figure 10). The divergence at location 25 suggests there was a difference in the magnitude of summer monsoon precipitation experienced by the two specimens. We cannot dismiss the possibility that the differences between HI80A19 and MA1D5 are due to seasonal fluctuations independent of a broader climate change trajectory, as we currently lack reliable data for distinguishing seasonal fluctuations from millennial scale climate change. We must also consider that the shells belonged to molluscs that grew in different environmental conditions and that the conditions would not have had to vary by much to produce the observed difference. Similarly, the fact that the two curves obtained from 30 consecutive samples across the shells' incremental growth structures do not exactly match might simply be due to differential growth rhythms at the two localities, and/or to slight offsets in their time of recruitment. However, the higher seasonal variation in precipitation in the ca 700 cal. BP specimen compared to the ca 2000 cal. BP specimen is consistent with previous work discussed above that describes an increase in seasonality in the later Holocene. Research underway on a larger number of shells sampled in this way will contribute towards the reliability of these claims and reveal more interesting patterns.

Conclusion

This pilot study has demonstrated that isotopic data from northern Australian archaeological midden shells have the potential to reveal information about climatic change, in this instance a pattern of declining summer monsoon rainfall that is in agreement with other palaeoclimate archives. We have documented a highly localised connection between changes through time in the abundance of species in shell middens, the morphologies the shell middens took in prehistory (mounded vs non-mounded) and independent local environmental conditions measured from shells within the sites themselves. Our isotopic analysis suggests a similar trend in aridity at both Hope Inlet and Blue Mud Bay. This preliminary work indicates that further isotopic analysis is likely to produce a more reliable and detailed reconstruction of climate change and human behavioural variability in coastal northern Australia. Future work should also consider isotopic analysis of larger numbers of archaeological and modern specimens, as well as isotopic profiles of individual shells over a greater number of moments

in time, to examine changes in the magnitude and timing of seasonality at potentially very high chronological resolution.

The case studies described above have established that the archaeological evidence, together with the environmental evidence obtained from archaeological sites, can be used to provide robust support for a model of climate change influencing cultural change in northern Australia during recent prehistoric times. If correct, this model demonstrates the flexibility of Aboriginal people's foraging behaviour in responding to environmental changes. With the increase in evidence for environmental drivers, there would also be a corresponding decrease in support for the alternative hypothesis of *A. granosa* population decline due to human over-harvesting. Analysis of shellfish exploitation in the archaeological record of other sites in the Pacific region (e.g. Morrison and Addison 2008) may reveal similar trends and provide the direct link that is currently missing between changes in climate, environment and human responses over the last millennium.

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