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Complexities in the Palaeoenvironmental and Archaeological Interpretation of Isotopic Analyses of the Mud Shell *Geloina erosa* (Lightfoot, 1786)

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Abstract

Isotope signals derived from molluscan shell carbonates allow researchers to investigate palaeoenvironments and the timing and periodicity of depositional events. However, it cannot be assumed that all molluscan taxa provide equally useful data owing to species-specific biological and ecological traits. The Mud Shell, *Geloina erosa* (Lightfoot, 1786) (syn. *Polymesoda coaxans*, syn. *Polymesoda erosa*), an infaunal mangrove bivalve, is a common component of archaeological deposits along Australia's tropical north coast and throughout the Indo-West Pacific. The ubiquity of *G. erosa* has led to numerous researchers incorporating this taxon into interpretations of associated deposits, particularly in the generation of radiocarbon chronologies and as a palaeoenvironmental proxy. Despite this, concerns have been expressed regarding the impact of *G. erosa* physiology and ecology on associated geochemical signals. Adaptations allowing the survival of this species within its highly changeable mangrove environment may introduce complexities into radiocarbon and environmental data archived within its shell. This study combines local environmental and hydrological data with isotopic analysis ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and ^{14}C) of live-collected specimens to explore the interpretability of geochemical proxies derived from *G. erosa*. Results suggest a number of factors may impact geochemical markers in unpredictable ways, eroding the usefulness of associated interpretations.

Keywords

Palaeoenvironmental proxy, Palaeoenvironmental reconstruction, Sclerochronology, Stable Isotope Analysis, Radiocarbon dating, *Geloina erosa*, syn. *Polymesoda coaxans*, syn. *Polymesoda erosa*

Highlights

- Isotopic analysis of *Geloina erosa* for radiocarbon and palaeoenvironmental data.
- Complex interactions between environments and geochemistry of shell carbonates.
- Stable isotopes from *G. erosa* difficult to interpret owing to complex environments.
- Environmental and physiological factors negatively impact radiocarbon dating.

1. Introduction

Reconstructing past environments assists archaeologists in approaching interpretations of human-environment relationships, which underpin fundamental cultural and behavioural decision-making processes. Geochemical archives derived from the calcium carbonates of molluscan shell represent sources of geochronological and palaeoenvironmental data, often providing the foundation for archaeological investigations in coastal contexts. While it is considered best practice to preferentially select filter-feeding bivalves for geochemical analyses (Forman and Polyak 1997; Hogg et al. 1998; Petchey et al. 2008), owing to a diet dominated by suspended phytoplankton and dissolved inorganic carbon (DIC) (Tanaka et al. 1986), recent studies have suggested that this is an overly-simplistic view that does not account for species-specific physiological and ecological factors (Petchey et al. 2013). Therefore, assessing whether a particular taxon can provide meaningful information is central to ensuring the validity of associated interpretations.

The common mangrove bivalve *Geloina erosa* (syn. *Polymesoda coaxans*, syn. *Polymesoda erosa*) is an important component of past and present economic systems throughout the Indo-West Pacific region (e.g. Carter 2014; Coleman et al. 2003; Davies 1985; Gimin et al. 2005; Meehan 1982; Morton 1976; Willan and Dredge 2004). As *G. erosa* is frequently found in archaeological shell midden deposits along Australia's north coast, the species has been utilised as part of approximately 30 radiocarbon chronologies since the late 1980s (see Ulm and Reid 2000; Williams et al. 2014). Additionally, stable isotope studies from Australia (Hinton 2012; Twaddle et al. 2016) and Borneo (Stephens et al. 2008) have sought to characterise *G. erosa* as an accurate palaeoenvironmental proxy. Despite geochemical data from *G. erosa* shell being employed to support numerous facets of archaeological interpretation, few studies have examined the reliability of information derived from the species in any detail.

Several biological and physiological attributes developed by adult *G. erosa* to survive the harsh conditions of their landward mangrove habitats have the potential to negatively impact the usefulness of geochemical data from shell carbonates. Complexities associated with variable respiration and feeding behaviours, periods of aerial exposure, brackish water conditions, and irregular environmental fluctuations may complicate isotopic fractionation, pathways, and profiles (Petchey et al. 2012; Schöne 2008). Characterising the magnitude of any such effects using modern live-collected specimens can assist in determining the efficacy of employing geochemical data from archaeological *G. erosa* shell to characterise seasonality of site-use, palaeoenvironmental reconstruction, and radiocarbon dating. This study combines modern local environmental observations with sclerochronological analyses of *G. erosa* specimens live-collected from Bentinck Island, southern Gulf of Carpentaria in order to determine whether isotopic analysis of shell carbonate from this species can support reliable interpretation.

2. Background

2.1 Study Area

The South Wellesley Islands are located along Australia's tropical north coast in the southern Gulf of Carpentaria (Fig. 1). This region exhibits a wet tropical climate primarily controlled by interactions between the Australian monsoon and south-easterly trade winds, producing a stark dichotomy between one wet (November – March) and one dry (May – August) season annually. Wet and dry seasons are primarily delineated by rainfall intensity and frequency with 92 – 95% of the average 1200mm of precipitation occurring during the wet season (BOM 2016). Heavy rain during the wet season causes extensive flooding

across much of the island chain with low-lying areas and estuarine systems inundated annually. Combined runoff from this local flooding and input from mainland catchment systems cause significant shifts in productivity and hydrology in the southern Gulf of Carpentaria (Burford et al. 2009; Oliver and Thompson 2011; Twidale 1966). Conversely, the dry season exhibits very little rainfall, a stable marine environment, and strong south-easterly winds. These main seasons are punctuated by two short transitional periods, April (Wet-Dry transition) and September/October (Dry-Wet transition), which exhibit a combination of both wet and dry season characteristics.

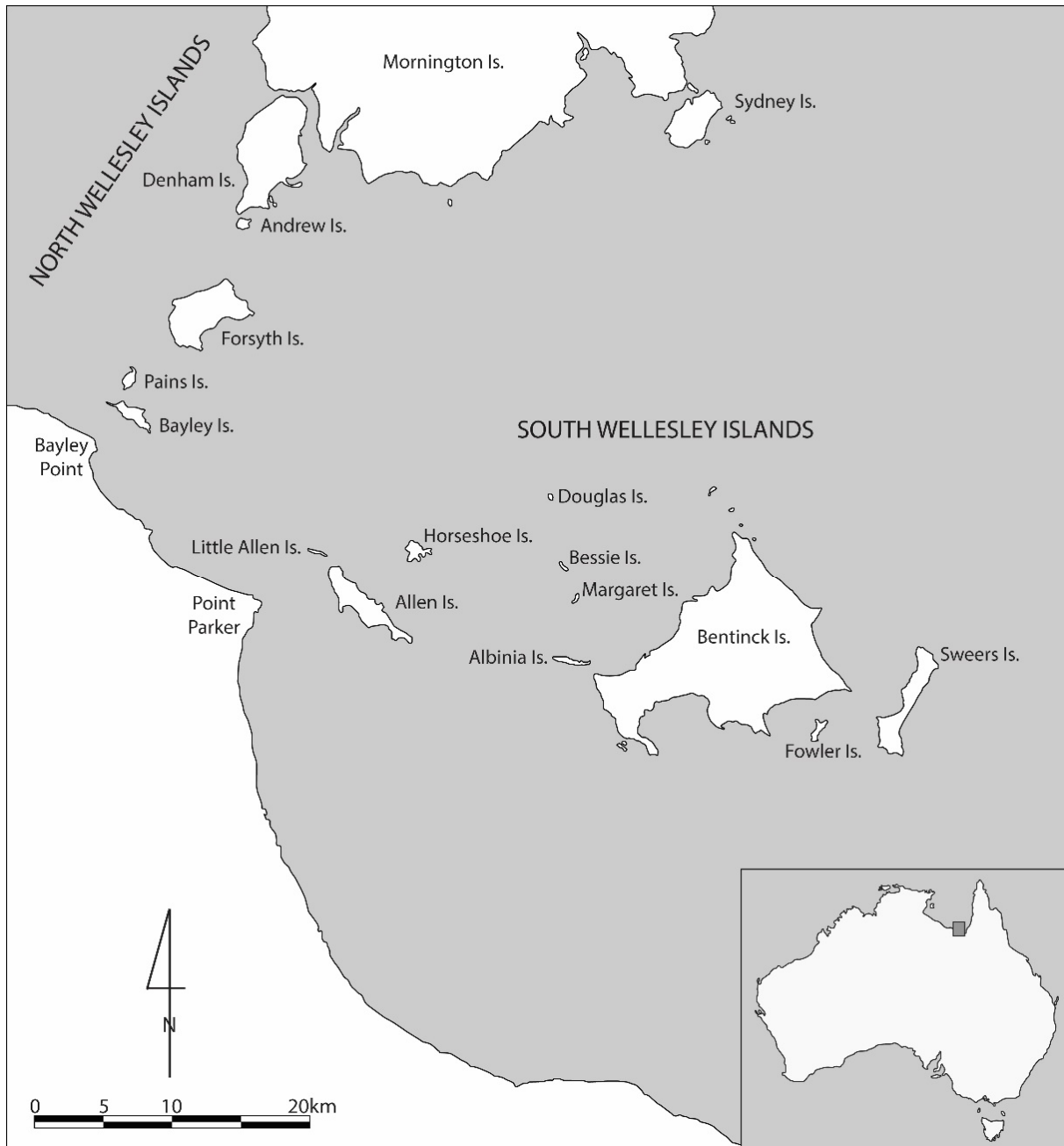


Fig. 1. The South Wellesley Islands are located in the southern Gulf of Carpentaria, Australia. This region is the traditional country of the Kaiadilt people.

Relatively narrow temperature ranges evident in the South Wellesley Islands are typical of tropical climates, with average temperature maxima of 34.6°C during December and minima of 23.1°C occurring during June (BOM 2016). Accompanying these temperature shifts are changes to humidity, which peak during the wet season, although high humidity quickly dissipates with the onset of dry season conditions (Memmott 1979:48). Records from the nearest sea surface temperature (SST) recording station (Karumba (1999 – 2006), c.150km southeast of Bentinck Island) indicate that for much of the dry season SSTs are relatively low, averaging 23.8°C, with transitional periods seeing significant $\pm 4 - 5^\circ\text{C}$ shifts (AIMS 2015). Wet season SSTs are approximately 7°C higher, averaging 30.7°C (AIMS 2015).

Local tidal variations primarily follow a daily diurnal pattern (one high and low tide a day), however for one to three days every fortnight tides shift to a semi-diurnal ‘double tide’ during which relatively little water movement occurs (BOM 2014). Tidal cycles display minor seasonal variability with fluctuations most prominent during the wet season owing to tidal banking from strong north-westerly winds (BOM 2014; Memmott 1982).

2.2 The Mud Shell, *Geloina erosa*

G. erosa (Lightfoot, 1786) is an infaunal bivalve species found in mangrove forests across tropical and sub-tropical zones throughout the Indo-West Pacific (Fig. 2). This species is common in the archaeological record along Australia’s tropical north coast with evidence of it being collected as part of subsistence practices (Barker 2004; Faulkner 2009, 2013; Peck 2016; Rosendahl 2012; Rosendahl et al. 2014a, 2014b, 2015) and used in Aboriginal toolkits (Beaton 1985; Harris et al. in press; Schall 1985). The wide availability of this species in the archaeological record has encouraged radiocarbon dates and palaeoenvironmental reconstructions to be obtained from *G. erosa* shell, often in the absence of other datable materials (Brockwell 2006a, 2006b; Brockwell and Ackerman 2007; Brockwell et al. 2009; Hinton 2012; Rosendahl 2012; Stephens et al. 2008), however the reliability of this practice has recently been called into question (see Petchey et al. 2013).

Regular shifts in salinity, temperature, and periods of aerial exposure inherent to tidally fed mangrove environments suggest that *G. erosa* is a hardy species that possesses several specialised adaptations. However, these adaptations may also limit the applicability of *G. erosa* shell geochemistry to robust radiocarbon and palaeoenvironmental determinations. Petchey et al. (2013) posited that the tolerance of *G. erosa* to brackish waters (also see Clemente 2007 for laboratory experiments demonstrating the same) facilitates significant terrestrial ^{14}C input into shell structures (Petchey et al. 2013). Terrestrial carbon sources can introduce ^{14}C of variable age, thereby significantly offsetting radiocarbon dates (Higham and Hogg 1995; Hogg et al. 1998).



Fig. 2. *G. erosa* is found in its preferred mangrove habitat across much of the Indo-Pacific region. This specimen in the Australian Museum collection (C58503) was collected by H.F. Bernhard from Ross Creek, near Yeppoon on the central Queensland coast, on 26 January 1933.

Other biological and ecological factors must also be considered, including the ability of *G. erosa* to shift between deposit and filter-feeding modes during periods of exposure (Clemente 2007; Morton 1976). These characteristics combined with the highly variable nature of this taxon's preferred landward mangrove habitat (Clemente 2007; Clemente and Ingole 2011; Gimin et al. 2004), potentially complicate relationships between shell geochemistry and broader environmental trends as has been identified for other shellfish (e.g. Anderson et al. 2001; Dye 1994). There is also the potential for truncated environmental records owing to cessations in shell growth as conditions move outside the taxon's tolerances (Clemente 2007; Clemente and Ingole 2009; Morton 1976, 1988), and for disequilibrium isotope fractionation between the shell carbonate and ambient environmental conditions (Latal et al. 2006; McConnaughey 1989; McConnaughey and Gillikin 2008).

Thus, further research is required to better understand the potential utility of the geochemical archives imprinted in *G. erosa* shell. Without robust analysis the validity of previous radiocarbon chronologies and palaeoenvironmental reconstructions will go untested, potentially introducing avoidable inaccuracies to interpretations. To achieve this analysis, local environmental and hydrological cycles must be characterised before being combined with geochemical data from contemporary live-collected specimens.

3 Methods

3.1 Sensor Deployment

Modern environmental and hydrological data was gathered over the course of a full annual cycle (June 2013 – July 2014) from Mirdidingki Creek located on the south coast of Bentinck Island (Fig. 3). This area was targeted as it encompasses a number of environments commonly associated with *G. erosa* across the South Wellesley Islands and the greater Gulf region. These include dense landward mangrove forests, low-lying clay pan, tidally fed estuaries, broad intertidal flats, and shallow subtidal zones (Fig. 3). Sclerophyll systems are also present across all islands.

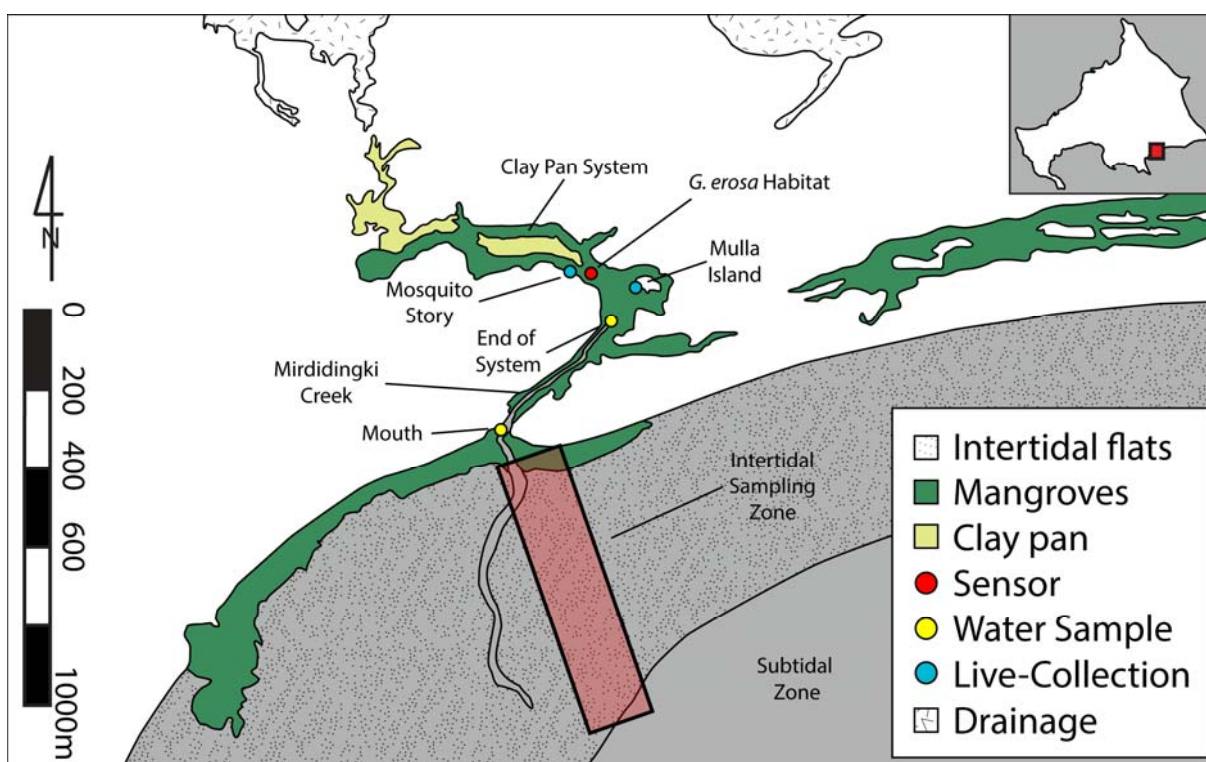


Fig. 3. The area surrounding Mirdidingki Creek consists of mangrove forests, intertidal flats, low-lying drainage channels, and a numerous clay pans.

In June 2013 a temperature sensor (HOBO Pendant) was deployed in the mangrove environment home to *G. erosa* north of Mirdidingki Creek to track water temperature fluctuations (Fig. 3). The sensor was programmed to log readings every 90 minutes and inspected for fouling during two subsequent field seasons in 2014. Instrument recovery occurred July 2014, providing datasets covering 395 days.

Third-party environmental data was sourced from Bureau of Meteorology (BOM) and Australian Institute of Marine Science (AIMS) stations located at Sweers Island (ID: 029139) and Karumba (ID: KURFL1), respectively. These stations provide long-term regional temperature (atmospheric and sea surface), tide, and rainfall records for the southern Gulf of Carpentaria. 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 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.

3.2 Water Sampling and Analysis

Sets of water samples were collected from Mirdidingki Creek, its fringing mangrove system, and adjacent intertidal and subtidal zones throughout discrete neap and spring tides during both wet (February 2014; $n = 27$) and dry (July 2013 ; $n = 23$ and July 2014; $n = 30$) seasons to establish seasonal ranges for $\delta^{18}\text{O}_{\text{water}}$, $\delta^{13}\text{C}_{\text{DIC}}$, and salinity (Fig. 3). The positioning of each intertidal zone sample was dictated by tidal height. Samples were collected every three hours over discrete tidal cycles (high tide to low tide). $\delta^{18}\text{O}_{\text{water}}$ and salinity samples were collected in 12mL and 50mL centrifuge vials, respectively. Water for $\delta^{13}\text{C}_{\text{DIC}}$ was injected via syringe into septa capped extainer vials that had been acidified with 2mL of 85% phosphoric acid (H_3PO_4) and flush filled with helium (He) prior to fieldwork.

All isotopic analyses of water samples were conducted at the Advanced Analytical Centre, James Cook University, Cairns. A ThermoFisher thermal conversion elemental analysis mass spectrometer (TC/EA IRMS) was used to determine the oxygen isotope composition in water samples. Isotopic values were calibrated using VSMOW and GISP standards, with a precision error of $<0.1\text{‰}$. Cycles of three to five injections per sample were employed to negate memory effects.

Stable carbon isotope ratios for water samples (dissolved inorganic carbon – DIC) were determined using an online ThermoFisher Gas Bench III coupled to a ThermoFisher DeltaV^{PLUS} isotope ratio mass spectrometer (IRMS) via a ThermoFisher ConFlo IV. Laboratory standards were prepared to calibrate isotopic values using three carbonates (NaHCO_3 , Na_2CO_3 , and CaCO_3) with known isotopic values. Precisions for internal standards were better than 0.1‰ .

Analysis of salinity samples was undertaken 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).

3.3 Live-Collection and Analysis of Modern *G. erosa*

Modern *G. erosa* specimens were collected during both wet and dry seasons in the thick mangrove forest surrounding Mirdidingki Creek (Fig. 3). A total of 19 individuals, collected over the course of four field seasons (May 2012 (dry season, $n = 6$), 2014 (February (wet season, $n = 4$), 2014 (July dry season, $n = 6$), and 2015 (September transitional period, $n = 3$)), were analysed. Each field season collection constitutes a single cohort of temporal and geographic contemporaneity. Live-collections occurred in the mangroves fringing Mulla Island (2014 and 2015 cohorts) and at Mosquito Story c.150m to the west (2012 cohort). Specimens were euthanized by freezing as soon as possible after collection to ensure edge margin carbonates reflect environments at the time of collection.

All specimens were abraded with a wire brush to remove loosely adhering particulates and periostracum. Each valve was then immersed in an ultrasonic bath of deionised water for a minimum of 10 minutes to remove any remaining matter before being left to air dry for 24 hours.

The ventral margin of right valves was targeted for carbonate collection in all specimens. Collection at the maximum growth axis was designed to represent the most recent period of growth. As precise timing of collection is known for modern specimens, targeted ventral margin collection allows comparisons between specimens collected during different seasons with relative ease. Sampling was undertaken 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 gently abraded to remove a small carbonate sample (c.100µg). Between samples drill bits were cleaned in an ultrasonic bath of deionised water to avoid cross contamination.

Micro-mill carbonate extraction was undertaken on thick sections of the left valves of one dry season and one wet season specimen. This sampling was designed to investigate isotopic variability in the growth period immediately preceding death. After encasing specimens in E180 epoxy, two c.3mm thick sections per encased specimen were prepared at the Centre for Archaeological Science, University of Wollongong. 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 until sections were approximately 4mm to 5mm thick. A series of 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 particulates.

Thick sections were mounted on the milling stage of a NewWave Micromill™ system fitted with a 50µm conical drill bit. Under magnification (x45 – x75) scan lines were digitised at an average resolution of 198µm, corresponding with individual growth features where possible (Fig. 4). Each transect measured approximately 80µm deep and 100µm wide, traversing the width of the upper shell layer. An average of 60µg of powder was produced per transect, dependent on transect length. Between samples the stage, drill bit, section, and associated tools were cleaned with compressed argon.

All carbonate samples were processed for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ at the Advanced Analytical Centre, James Cook University, Cairns. Exetainer vials containing 40µg to 80µg of carbonate were flush filled with helium before being acidified with 100% phosphoric acid and left to acidify for 18 hours at 25°C. A Thermo GasBench III connected to a DeltaV^{PLUS} (ThermoFisher) gas source mass spectrometer via a ThermoFisher ConFloIV was used to analyse stable oxygen and carbon isotope composition. Isotope values ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) were calibrated against NBS-18 using NBS-19 as control samples. Results are reported with reference to the international standard Vienna Pee Dee Belemnite (VPDB) with precision better than 0.1‰.

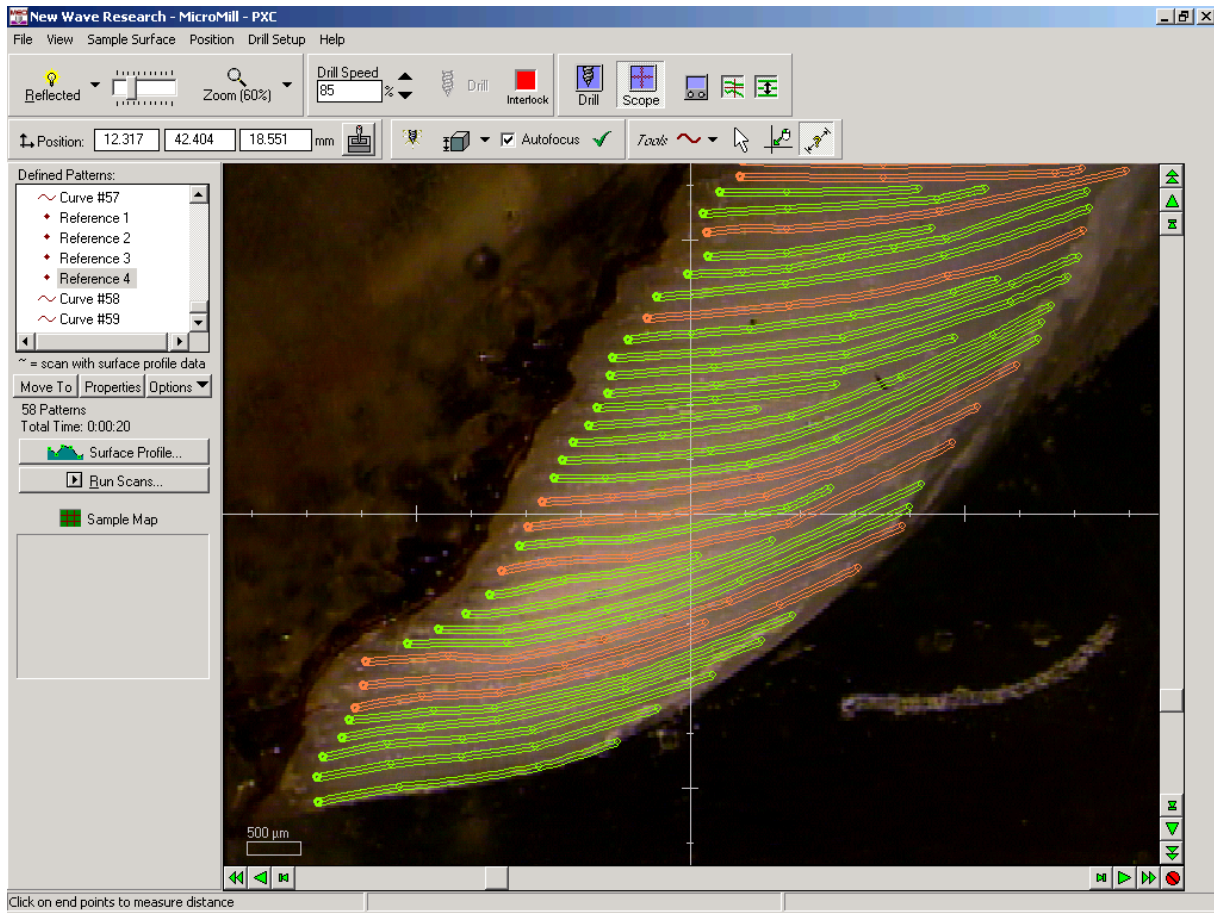


Fig. 4. NewWave Micromill™ interface showing the process of transect digitisation. Green transects represent periods of regular growth (translucent lightly coloured shell), while orange transects represent growth stoppages (dark, opaque shell).

3.4 Modelling and Predictions

Seasonal $\delta^{18}\text{O}_{\text{shell-predicted}}$ values for mangrove environments were modelled using Equation 1, a rearrangement of the 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), to solve for $\delta^{18}\text{O}_{\text{shell}}$ (following Prendergast et al. 2013). This allows expected ranges for wet and dry season $\delta^{18}\text{O}_{\text{shell}}$ values to be predicted and compared to those observed in the shells of live-collected *G. erosa* specimens.

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

Measured seasonal $\delta^{18}\text{O}_{\text{water}}$ ($\delta^{18}\text{O}_{\text{water(VSMOW)}}$) values from the Mirdidingki Creek region are used in these calculations. Temperature (T) data originates from the sensor station deployed in the Mirdidingki Creek mangrove forest. Seasonal maxima, minima, and averages are calculated to act as estimated ranges for comparison with isotopic values derived from live-collected specimens.

Extreme temperature maxima/minima have the potential to inflate $\delta^{18}\text{O}_{\text{shell-predicted}}$ seasonal ranges beyond those likely recorded in *G. erosa* shell owing to environmental tolerances that impact growth regimes (Clemente 2007; Clemente and Ingole 2011; Gimin et al. 2004; Morton 1976, 1984). In order to provide a more accurate representation of $\delta^{18}\text{O}_{\text{shell-predicted}}$ values, end quartiles and interquartile ranges (IQR) were calculated to remove the more extreme values from the dataset. To account for the potentially aggressive nature of data removal using raw IQR, upper and lower fences were generated by multiplying IQR by 1.5 (following Hodge and Austin 2004). Data outside of these fences are then removed. The remaining data is used exclusively for $\delta^{18}\text{O}_{\text{shell-predicted}}$ calculations.

4 Results

4.1 Environmental and Hydrological Cycles

Readings from the mangrove sensor station indicate a temperature range of 11.6°C to 56.8°C (wet season range = 20.8°C – 53.0°C, mean = 29.7°C; dry season range = 11.6°C – 47.5°C, mean = 22.8°C) with numerous months registering maximum temperatures of between 45°C and 56.8°C (2013: July – December) (Table 1). This equates to a mean season shift of 6.9°C, occurring primarily during transitional months April (range = 24.2°C – 38.0°C; mean = 28.1°C) and September/October (range = 17.9°C – 56.8°C; mean = 28.7°C). Extreme maximum temperatures are due to a combination of shallow water depth, dark sediments, and exposure to extended periods of direct sunlight.

Table 1 Temperature minimum, maximum, and mean derived from the mangrove sensor station.

	Wet Season	Dry Season	April	September/ October
	(°C)	(°C)	(°C)	(°C)
Minimum	20.8	11.6	24.2	17.9
Maximum	53.0	47.5	38.0	56.8
Mean	29.7	22.8	28.1	28.7

Tidal data from the Sweers Island BOM station and the Karumba AIMS station indicate that when tidal cycles are in a daily diurnal mode, heights range between -0.33 and +5.33m. Slight seasonal variations are evident with the dry season displaying a mean of +1.91m (range = -0.38m – +4.58m), while the wet season exhibits a higher average tidal height of +2.41m (range = +0.33m – +5.33m). Upon switching to semi-diurnal tidal cycles water movement diminishes significantly. Seasonal amplitudes are relatively consistent, displaying a 0.44m shift (wet season: range = 3.07m – 4.36m, mean = 3.64m; dry season: range = 2.48m – 4.08m, mean = 3.39m).

Water sampling revealed changes in $\delta^{18}\text{O}_{\text{water}}$, $\delta^{13}\text{C}_{\text{DIC}}$, and salinity coinciding with seasonal cycles (Table 2). Oxygen isotopes of water from the open marine zone adjacent to Mirdidingki Creek range between -5.5‰ and -3.1‰ during the wet season and -1.3‰ to +0.9‰ in the dry season. Estuarine waters from the creek system exhibit similar isotopic values, with the wet season ranging between -5.9‰ and -3.9‰ and the dry season displaying a range of -1.9‰ to +0.5‰. These ranges indicate that wet season conditions are typified by significant hydrological variability owing to inconsistent amounts of freshwater input from monsoonal rainfall and flood runoff. This is further demonstrated by salinity values which are significantly depressed during the wet season across all environments (Table 2). Moreover, more negative wet season $\delta^{13}\text{C}_{\text{DIC}}$ values across all environments (with the exception of mangroves) are indicative of an increase in terrestrial carbon input caused by interaction with runoff from flooding (Table 2).

Table 2 Ranges and means for salinity, $\delta^{18}\text{O}_{\text{water}}$, and $\delta^{13}\text{C}_{\text{DIC}}$ water sampling in environments across the Mirdidingki region.

Salinity (PSU)				
	Wet		Dry	
Environment	Range	Mean	Range	Mean
Marine	4.4 – 24.5	17.3	33.3 – 38.8	35.0
Estuarine	0.1 – 19.3	6.2	27.8 – 36.2	33.5
Mangroves		15.2		20.1
$\delta^{18}\text{O}_{\text{water}}$ (VSMOW ‰)				
	Wet		Dry	
Environment	Range	Mean	Range	Mean
Marine	-5.5 – -3.1	-4.0	-1.3 – +0.9	-0.3
Estuarine	-5.9 – -3.9	-5.3	-1.9 – +0.5	-0.8
Mangroves		-4.1		-2.9
$\delta^{13}\text{C}_{\text{DIC}}$ (VSMOW ‰)				
	Wet		Dry	
Environment	Range	Mean	Range	Mean
Marine	-8.0 – -0.8	-4.4	-5.2 – +0.2	-1.0
Estuarine	-13.0 – -9.0	-11.2	-7.5 – +0.1	-4.7
Mangroves		-11.5		-15.0

Variability between environments is also evident. During the dry season, conditions in the mangrove environments display significant deviations from broad environmental trends evident in marine and estuarine systems (Table 2). Lower salinity and $\delta^{18}\text{O}_{\text{water}}$ values indicate that the mangrove system is influenced by freshwater input, decoupling it from adjacent estuarine environments. Moreover, low $\delta^{13}\text{C}_{\text{DIC}}$ values suggest that mangrove systems are heavily influenced by terrestrial carbon.

4.2 Shell Stable Isotopes

Ventral margin carbonates extracted from 19 live-collected *G. erosa* specimens revealed complex relationships between shell geochemistry and ambient environmental conditions. Results show a broad range of $\delta^{18}\text{O}_{\text{shell}}$ values (range = -8.9‰ – -3.5‰ ; mean = -5.3‰) (Fig. 5). A majority of this variability is contributed by dry season data, which encompass the entire range of values with a mean of -5.6‰ . Conversely, wet season results are tightly grouped (range = -4.5‰ – -4.0‰ ; mean = -4.3‰). Specimens collected during the 2015 dry-wet transitional period (September/October) returned results resembling wet season values (Fig. 5) with relatively tightly grouped $\delta^{18}\text{O}_{\text{shell}}$ values (range = -5.1‰ – -3.8‰ ; $1\sigma = \pm 0.7\text{‰}$; mean = -4.3‰). These results are consistent with observed seasonal differences in water temperature and composition as well as the timing and periodicity of inundation. Only minor variability is evident in overall $\delta^{13}\text{C}_{\text{shell}}$ values, exhibiting a muted amplitude (3.5‰) and range (-11.6‰ – -8.1‰) when compared to $\delta^{18}\text{O}_{\text{shell}}$ (Fig. 5). Consequently, $\delta^{13}\text{C}_{\text{shell}}$ values display minimal shifts between wet and dry seasons, returning means of -9.8‰ (range = -11.6‰ – -8.1‰) and -9.7‰ (range = -10.9‰ – -8.3‰), respectively. $\delta^{13}\text{C}_{\text{shell}}$ values from the 2015 transitional period catch cohort exhibit particularly low $\delta^{13}\text{C}_{\text{shell}}$ values, with a mean of -10.5‰ (range = -10.9‰ – -10.2‰). Consistently low $\delta^{13}\text{C}_{\text{shell}}$ values mirror the results of Petchey et al. (2013), suggesting a tolerance to brackish conditions and input from terrestrial carbon sources.

Results from micro-milled specimens revealed distinct isotopic patterning through ontogeny. Specimen 1/2 was collected during the 2014 wet season (March) from the mangrove forest fringing Mulla Island. Carbonate sampling transects were digitised to align with growth features at a resolution ranging from $125\mu\text{m}$ to $532\mu\text{m}$. Each transect produced between $26\mu\text{g}$ and $88\mu\text{g}$ (mean = $60.3\mu\text{g}$) of carbonate powder. A total distance of $11160\mu\text{m}$ was sampled along the section, equating to between 3.4 and 4 months of growth (see Clemente 2007; Dolorosa and Dangan-Galon 2014). In two instances samples were combined to reach the minimum weight requirements of the mass spectrometer (1/2_11.1 and 1/2_11.2; 1/2_19.1 and 1/2_19.2). A further two samples were discarded owing to material loss during sampling (1/2_22) and an error during analysis (1/2_15). Stable isotope analysis reveals highly variable $\delta^{18}\text{O}_{\text{shell}}$ values ranging between -8.2‰ and -3.0‰ (mean = -4.5‰). Stable carbon values display less variability with a range spanning -10.6‰ to -7.6‰ (mean = -9.1‰) (Fig. 6).

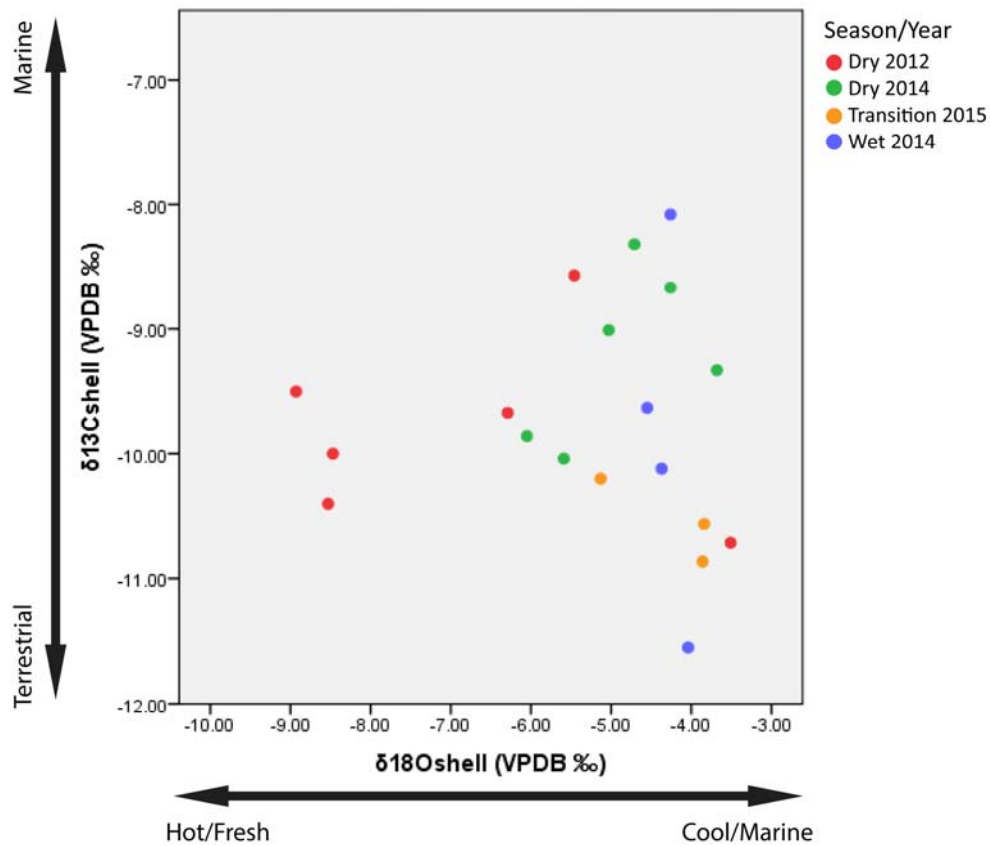


Fig. 5 Stable oxygen and carbon isotope values from the edge margins of unique catch cohorts of *G. erosa* indicate the presence of habitat-specific variability as well as the influences of terrestrial carbon sources. Note the extremely negative $\delta^{13}\text{C}_{\text{shell}}$ values across the dataset that, when compared to typical marine values of greater than -4‰ (Keith et al. 1964; Petchey et al. 2013), suggest brackish water conditions.

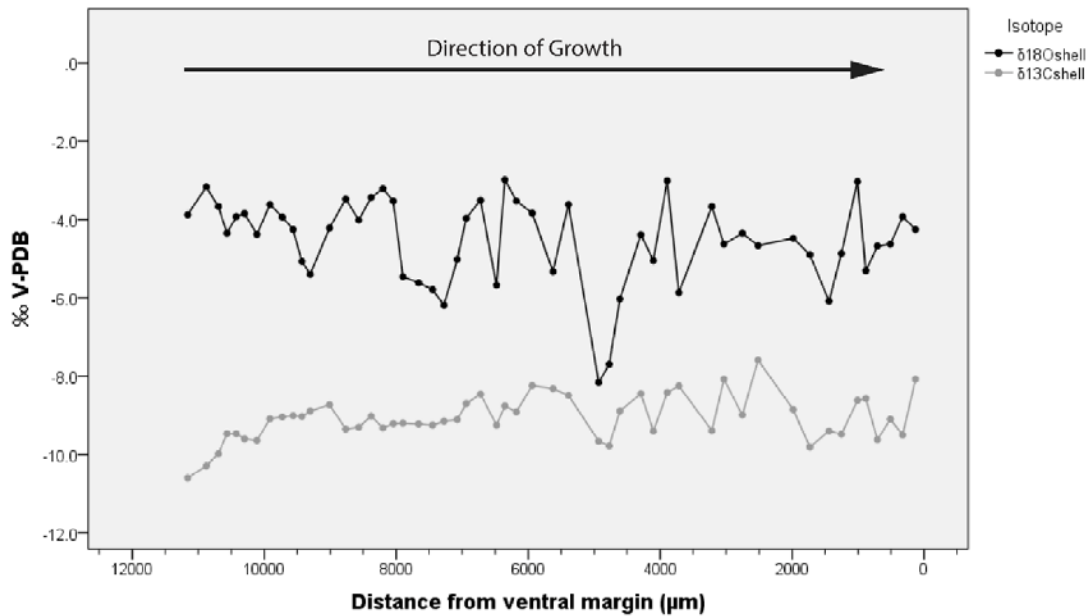


Fig. 6 The isotope profile of *G. erosa* specimen 1/2 extends across 11.16mm of the 86.10mm shell. While $\delta^{18}\text{O}_{\text{shell}}$ fluctuations are evident, they do not appear to correlate with seasonal climatic shifts.

Specimen 5/7 was gathered from the dense mangrove forest to the north of Mirdidingki Creek during the 2014 dry season (July). Micro-mill transects were digitised corresponding to growth features at a resolution of 75µm to 306µm (mean = 188µm), producing carbonate samples of 14µg to 84µg (mean = 59.3 µg). 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). Two sample 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). Much like Specimen 1/2, stable isotope values derived from Specimen 5/7 reveal high variability in $\delta^{18}\text{O}_{\text{shell}}$ (range = -8.8‰ – -1.6‰; mean = -4.4‰) (Fig. 7). Stable carbon isotope values again display significantly less variability when compared to oxygen (range = -12.1‰ – -7.4‰; mean = -10.1‰) (Fig. 7).

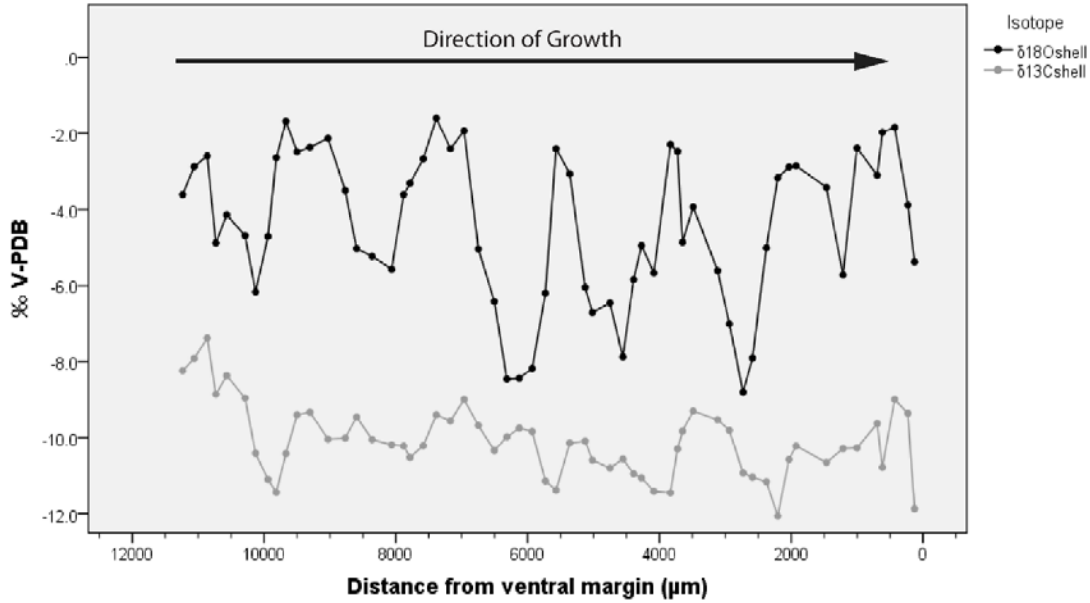


Fig. 7 The isotope profile of *G. erosa* specimen 5/7 extends across 11.24mm of the 80.02mm shell. While $\delta^{18}\text{O}_{\text{shell}}$ fluctuations are evident, they are too numerous to represent seasonal variation.

4.3 Modelled $\delta^{18}\text{O}_{\text{shell-predicted}}$ Seasonal Ranges

Modelled averages of dry season $\delta^{18}\text{O}_{\text{shell-predicted}}$ for mangrove species live-collected during wet and dry season conditions returned a complex dataset. While wet and dry season values see some variability (dry season: range = -1.3‰ – -7.6‰, mean = -3.4‰; wet season: range = -4.4‰ – -8.9‰, mean = -6.4‰), considerable overlap between seasons owing to seasonal extremes (dry season: temperature highs and $\delta^{18}\text{O}_{\text{water}}$ minimums; wet season: temperature lows and $\delta^{18}\text{O}_{\text{water}}$ maximums) is evident (Fig. 8). Thus, attempting to delineate season of collection for *G. erosa* via stable isotopic analysis is likely to produce ambiguous results.

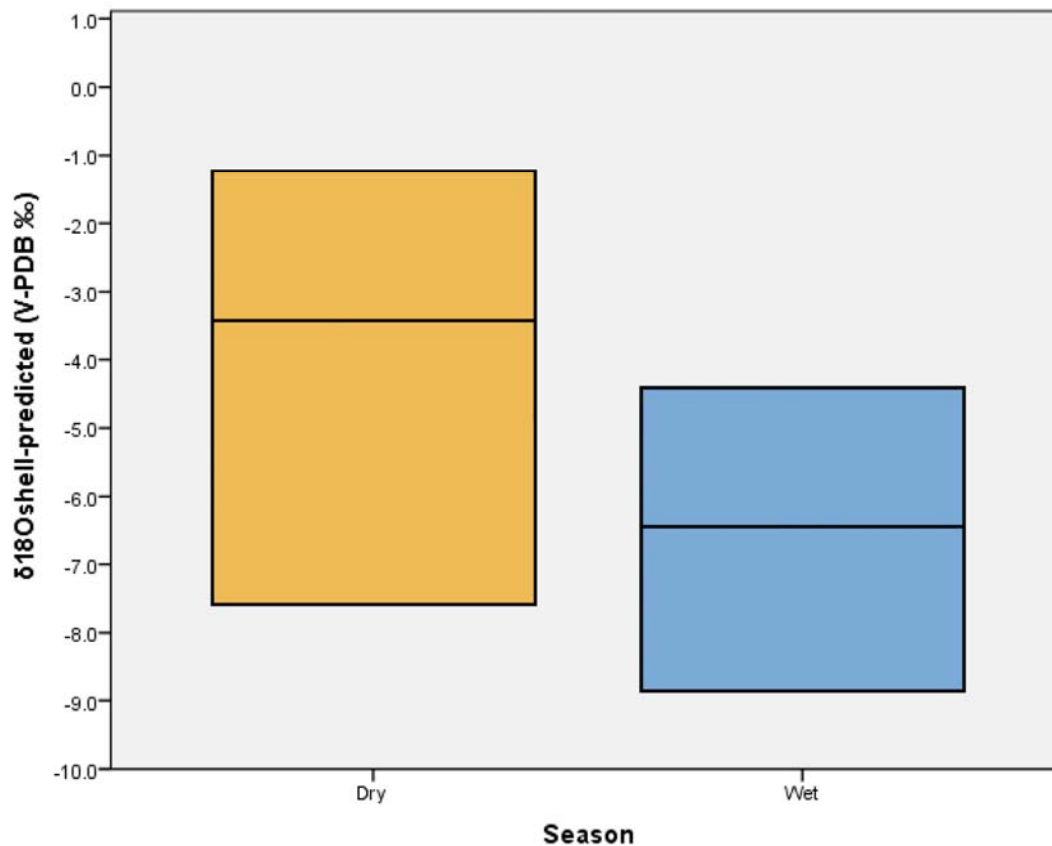


Fig. 8 Seasonal ranges of $\delta^{18}\text{O}_{\text{shell-predicted}}$ were calculated using maximum, minimum, and mean temperature and $\delta^{18}\text{O}_{\text{water}}$ data from mangrove environments.

5 Discussion

5.1 Palaeoenvironmental Reconstruction and Seasonality Determinations

When assessing the efficacy of *G. erosa* as a proxy for palaeoenvironmental and seasonality reconstruction a number of complications must be addressed. Underpinning many considerations are complex environmental characteristics that typify landward mangrove forests. Results from water sampling indicate that environmental conditions within mangroves fringing Mirdidingki Creek can become decoupled from broader trends evident in marine and estuarine systems. This process is linked with irregular patterns of tidal flushing. Observations of Mirdidingki Creek undertaken in September 2015 indicate a minimum tidal height of 3.64m is required to inundate *G. erosa* habitats. Data from Sweers Island suggests that of the 383 tidal highs in 2014, only 147 (38%) rose above this height (BOM 2014). This low rate of inundation is likely the primary cause of the inter-environmental variability exhibited between dry season marine/estuarine and mangrove water samples. More consistent inundation during the wet season from flood runoff may facilitate increased connectedness between environments, particularly mangrove and estuarine systems, accounting for the more homogenous hydrological conditions.

Irregular flushing and isolation from broader environmental influences also impacts the consistency of conditions within mangrove systems. Between inundations water collects in depressions surrounding mangrove roots. Hydrological conditions are then altered through variability in evaporation rates, pool depth, sediment colour, exposure to direct sunlight, and surface area (Knight et al. 2008) to form a series of isolated pool-specific environments. As molluscan shell isotope values reflect conditions during carbonate precipitation, environmental archives found within the shells of *G. erosa* inhabiting different pools may vary significantly. Similar variability has been observed in supra-tidal rock pools with authors deeming associated taxa unsuitable for use as an environmental proxy record (see Firth and Williams 2009; Killingley 1981; Shackleton 1973).

Results from targeted edge margin analysis of the two dry season cohorts collected from disparate geographic contexts provide a salient example of intra-habitat variability. The 2012 catch was sourced from Mosquito Story, while 2014 dry season specimens were gathered c.150m to the east near Mulla Island. Key differences exist in the $\delta^{18}\text{O}_{\text{shell}}$ values of the two cohorts, with individuals collected in 2012 exhibiting a significantly broader set of values and more negative mean than the 2014 catch. Given similarities in regionally scaled environmental conditions (BOM 2016), inconsistencies evident between the two dry season cohorts likely stem from intra-habitat variability linked with the frequency and periodicity of tidal inundation. The Mosquito Story collection site is located further landward than the Mulla Island site, and is hence subject to less frequent tidal flushing. This facilitates a pronounced environmental divergence at Mosquito Story, and other similarly landward habitats, from more frequently flushed areas. Therefore, environmental records derived from *G. erosa* shell carbonates are best interpreted as narrow representations of highly localised conditions dependent on their collection site, making reconstructions of broader climatic conditions, including season of collection determinations, difficult to accurately approach.

The complexity of environments inhabited by *G. erosa* 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). Shell growth cessation is frequently linked to species-specific environmental tolerances, such as changes in water temperature and salinity (Burchell et al. 2013; Hallmann et al. 2009; Jones 1980). While it has been demonstrated that these factors impact *G. erosa* shell growth (Clemente 2007; Morton 1988), the timing and periodicity of aerial exposure is equally significant, given this taxon's landward positioning. 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 with water temperature and salinity impacting growth during periods of inundation – particularly in isolated pools (Firth and Williams 2009). Meanwhile, more consistent inundation during the wet season from flood runoff significantly decreases the period of aerial exposure, leaving fluctuations in temperature and salinity as principle growth controls. The key concern with environmental records derived from *G. erosa* is not that they may be 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 growth stoppages. Effective interpretation of associated stable isotopes becomes problematic as it is unclear when, for how long, and for what reason *G. erosa* shells cease recording ambient environmental conditions. Without this context, links between environment and shell stable isotopes are tenuous and extremely difficult to accurately characterise.

The weak connections between environmental conditions and stable isotope values demonstrated by this research call into question past claims that *G. erosa* is an easily interpretable palaeoenvironmental proxy (see Hinton 2012; Stephens et al. 2008). Arguments presented in favour of this position rely on the presence of ontogenetic oscillations in isotopic values, otherwise referred to as ‘saw-tooth patterning’, and correlations between observed environmental conditions and isotopic fluctuations (Hinton 2012; Stephens et al. 2008; Twaddle et al. 2016). Pairs of isotopic peaks and troughs are argued to represent annual cycles, suggesting profiles of micro-milled specimens should encompass 4 to 8 years. This does not align with the period of time covered by micro-milling, calculated to be c.2.7 to 4 months from age/growth relationships (see Clemente 2007; Dolorosa and Dangan-Galon 2014). Moreover, the average lifespan of *G. erosa* is approximately 3 to 4 years (Clemente 2007; Dolorosa and Dangan-Galon 2014), suggesting a lack of direct connection between stable isotope peak/trough pairings in *G. erosa* shell and seasonal climatic cycles.

Instead, seasonal changes in local environmental stability assist in explaining ontogenetic fluctuations in isotopic profiles. Dry season conditions expose *G. erosa* to highly variable environments owing to irregular tidal inundations and the formation of isolated habitats, linking fluctuations with tidal cycles. Between inundations evaporation preferentially removes ^{16}O isotopes resulting in an increase in $\delta^{18}\text{O}_{\text{water}}$ (and thus $\delta^{18}\text{O}_{\text{shell}}$). Moreover, evaporation, infiltration, and runoff gradually diminish the size/depth of pools allowing rapid temperature changes in associated waters. This continues until pools are re-inundated by tidal waters, essentially ‘resetting’ conditions before the tide recedes 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 the local maintenance of more consistent environmental conditions. Changing seasonal variabilities are congruous with patterns in isotopic profiles with wet season collected Specimen 1/2 exhibiting relatively constrained $\delta^{18}\text{O}_{\text{shell}}$ values, while dry season gathered Specimen 5/7 displays a significantly broader range. While it is difficult to directly link isotopic patterns found in *G. erosa* shell to individual environmental characteristics owing to the complexity of landward mangrove environments, data suggests that tidal inundations are a key driver behind these oscillations.

The final, and likely most impactful, factor reducing the efficacy of *G. erosa* as an effective proxy is ambiguity in delineating seasonality via stable isotopic analysis. Comparisons between modelled $\delta^{18}\text{O}_{\text{shell}}$ -predicted ranges and edge margin $\delta^{18}\text{O}_{\text{shell}}$ values from live-collected *G. erosa* reveal only minor differences between seasonal cohorts as-well-as numerous values falling within the overlap (Fig. 9). Moreover, while some values do fall in definitive wet or dry season predicted ranges, many do not unambiguously 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.

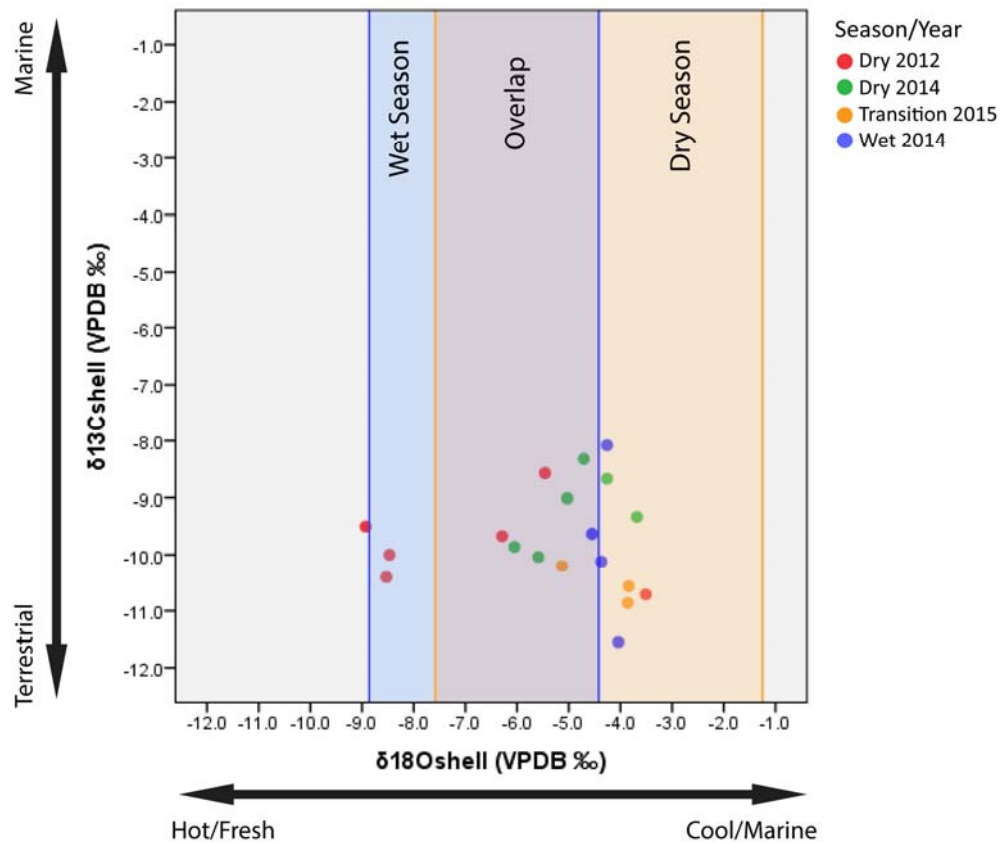


Fig. 9 A majority of edge margin values could not be unequivocally linked with specific seasons or were difficult to differentiate (orange = predicted dry season range; blue = predicted wet season range; purple = overlap in predicted seasonal ranges).

Seasonally ambiguous results can be explained by a number of factors. In particular, the application of predictive modelling to this highly complex environment may be problematic. As temperature is a key component in calculating $\delta^{18}\text{O}_{\text{shell-predicted}}$ values, highly variable water temperatures likely adversely impacted modelled values. Despite having significantly different minima and means, both wet and dry seasons display similar temperature maxima (40.1°C and 40.0°C, respectively) inflating the lower end of the modelled dry season range. While data from a fenced interquartile range was utilised for these calculations, 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.

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. Given the intra-habitat variability demonstrated by edge margin values, this data is unlikely to be directly applicable to other mangrove forests in the South Wellesley Islands, or elsewhere, and may in fact not be usable outside of the immediate habitat it was collected from. Despite these issues, 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.

In isolation, concerns associated with *G. erosa* are not insurmountable, complex hydrological or physiological approaches might be developed to better model variability 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 for this species. While it has been suggested localised offsets may assist in ameliorating *G. erosa* from at least some limitations (Brockwell et al. in press; Petchey et al. 2013), the potential for intra-habitat variability forces corrections to be highly specific and therefore difficult to implement. 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 *G. erosa* shell are sporadic, geographically and temporally limited, and have the potential to be variably offset by numerous basic physiological and ecological processes. While the wet season assemblage is somewhat limited in scope ($n = 4$), results clearly demonstrate issues faced by this species for isotopic analysis. It is therefore recommended *G. erosa* not be used as a source of palaeoenvironmental or seasonality data.

5.2 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 values can be employed to offset the mixing of differently aged marine carbon reservoirs (Ulm 2006). 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 indeterminate 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 *G. erosa* physiology negatively impact the interpretability of radiocarbon dates derived from the species.

Consistently highly negative $\delta^{13}\text{C}_{\text{shell}}$ values are evidenced throughout the entire modern *G. erosa* assemblage, irrespective of timing or location of collection. This demonstrates strong terrestrial carbon influences in *G. erosa* habitat. Previous research posits that *G. erosa* tolerance to brackish waters facilitates terrestrial ^{14}C input into shells (Petchey et al. 2013). Salinity and $\delta^{18}\text{O}_{\text{water}}$ values suggest brackish conditions typify *G. erosa* habitats in the South Wellesley Islands, enabling variable 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 $\delta^{13}\text{C}_{\text{shell}}$ values typifying *G. erosa* shell geochemistry.

The impacts of physiological mechanisms employed by *G. erosa*, including adaptive feeding and respiration strategies, are difficult to directly characterise owing to their irregular nature. However, results of stable isotope analyses offer hints as to their influence on *G. erosa* shell geochemistry. Shell $\delta^{13}\text{C}$ results reflect feeding behaviours as species that frequently ingest detrital and sedimentary matter exhibit low $\delta^{13}\text{C}_{\text{shell}}$ values (Anderson et al. 2001; Dye 1994; Meyers and Teranes 2001). Biological studies have indicated *G. erosa* are capable of shifting between filter- and detrital-feeding behaviours depending on the abundance of food and periodicity of aerial exposure (Morton 1985). Consistently negative $\delta^{13}\text{C}_{\text{shell}}$ values typifying the *G.*

erosa shell carbonates analysed here are likely a product of this process. The inclusion of detrital matter in the diet of *G. erosa* provides an additional pathway for terrestrial carbon to enter shell geochemistry.

A combination of environment, physiology, and ecology make it difficult to argue that radiocarbon determinations on *G. erosa* carbonate can be reliably interpreted as accurate radiocarbon ‘dates’. Consequently, this research agrees with the findings of Petchey et al. (2013), recommending *G. erosa* not be used in the development of radiocarbon chronologies. However, in doing so it is important to consider the broader repercussions of this recommendation for archaeological research, particularly in the context of those studies that have previously dated *G. erosa* shell. Several studies have incorporated *G. erosa* shell into radiocarbon chronologies along Australia’s north coast (e.g. Brockwell 2006a; Brockwell and Ackerman 2007; Brockwell et al. 2011; Hinton 2012; Rosendahl 2012; Sim and Wallis 2008). Reviewing $\delta^{13}\text{C}_{\text{shell}}$ values associated with these dates (note only 27 of the 41 dates report $\delta^{13}\text{C}_{\text{shell}}$) reveals low $\delta^{13}\text{C}_{\text{shell}}$ values (mean = -6.3‰; range = -10.8‰ – -1.4‰) indicative of mixing between marine and terrestrial carbon sources, much as observed in the South Wellesley Islands. Although a majority of the impacted chronologies do not rely solely on dates derived from *G. erosa* (with the exception of select mono-specific sites from Brockwell 2006a; Hinton 2012; Rosendahl 2012; Sim and Wallis 2008), the issues surrounding this species necessarily impact the validity of associated interpretation. Thus, it is recommended that dates linked with *G. erosa* are approached with extreme caution and, if possible, tested against more reliable mollusc taxa from similar temporal contexts.

Brockwell et al. (in press) have recently employed a localised $\delta^{13}\text{C}$ mixing model to account for the incorporation of both marine and terrestrial carbon in *G. erosa* shell in order to calibrate radiocarbon dates. Brockwell et al. (in press) calculate a mean $\delta^{13}\text{C}$ of -11.5‰ based on 13 *G. erosa* samples, but do not report the range of values. This mean value is used to calculate a terrestrial contribution of 37% for these samples (note that Brockwell et al. in press appear to transpose the endpoint marine and terrestrial values used and their formula appears to produce a terrestrial contribution of 47%). As demonstrated in this paper, highly localised environmental conditions may result in highly variable incorporation of terrestrial carbon into shell carbonates of contemporary samples, limiting the utility of applying uniform mixing models. Thus, while mixing models may play a future role in approaching more accurate dates from *G. erosa*, further research is required to better account for the complexities associated with this species and its pre- and post-depositional environment.

6. Conclusions

Analysis of modern live-collected *G. erosa* has revealed interpretation of isotope records archived within the carbonate shell of this species are highly complex. A combination of factors render *G. erosa* shell unsuitable as a source of palaeoenvironmental and seasonality data owing to the sporadic and inconsistent nature of the encoded environmental record, tenuous connections with seasonal shifts in ambient conditions, and high variability among mangrove habitats and broader external trends. Likewise, radiocarbon determinations derived from *G. erosa* shell are erratically offset by a variety of physiological and ecological influences.

Stable isotope results presented here mirror those presented in previous studies, suggesting that tolerances to brackish conditions and the landward positioning of *G. erosa* populations facilitate interactions with terrestrial carbon. Moreover, more difficult to test survival mechanisms such as irregularly timed detrital feeding further complicate shell carbon signals. When considered in combination these factors indicate *G. erosa* is a source of highly complex and potentially problematic palaeoenvironmental and radiocarbon data and therefore cannot be recommended for routine use in palaeoenvironmental reconstruction, seasonality studies, or radiocarbon dating.

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