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SOCIO-ECOLOGICAL DYNAMICS IN MOLLUSC FISHERIES: A CASE STUDY FROM THE KEPPEL BAY ISLANDS, GREAT BARRIER REEF, AUSTRALIA

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This research is a product of the dedication, commitment, and hard work of numerous people. It includes many years of knowledge, experience, and stewardship of socio-ecological environments by key individuals and communities. I feel honoured to be involved in this work and am delighted to know our efforts have been worthwhile. I wish to extend my respect and appreciation to the Woppaburra People, to their Elders - past, present, and emerging - and acknowledge the important role the community continues to play for the Keppel Bay Islands. I am very grateful to everyone who supported this research and my journey through it.

Like the first time I tried snorkelling as a young kid, a period of this PhD, presented a mix of challenges. Swimming in open water felt different but, mostly, it was the sharks. My fear of sharks. I vividly remember having to manifest enough strength and courage in myself to eyeball the wonderful corals and fish below me in the turquoise water, without looking over my shoulder every few minutes. Lucky for me in those terrified moments bobbing around in the middle of the Great Barrier Reef, I learned a couple of things. Resilience comes with two important ingredients: if you have a goal persist, persist stubbornly; and, invest in a decent mask, attach a durable snorkel, and wear a respectable set of fins. Truth be told, my mask, allowing me to see underwater, worked incredibly well.

Perusing through the corals one day, my mask said to me '*No, no, no – all wrong*'! … you'll never see that species of Neritidae here, go and have a look by the rocks instead … best mask I ever had. To my Primary Supervisor, Dr Katherine Szabó, University of Cambridge, for all your inspiration and profound gift to me, clarity, allowing me to see and learn through this journey, thank you. Your unfailing support and astounding knowledge of molluscs, cultural shell, and theoretical concepts, has been instrumental in the success of this research. At no other time, have I been fortunate enough to be given such overwhelmingly generous mentorship. Sincere thanks for being available at all hours, a 17kg donation of hard copy texts, numerous soft copies, invaluable advice, and incredibly hilarious tales of field adventures. You helped keep vision of this project headed in the right direction to its fulfilment.

A good few years after my introduction to snorkelling, in 2012, Annette Oertle recently 'Dr Annette Oertle', and I, decided to do our SCUBA dive certifications. We were taught the golden rule - when breathing compressed air, never, ever, hold your breath. How to provide and receive air from an alternate source when needed, was good training … a necessary skill for staying alive when submerged underwater. To my Secondary Supervisor, Prof. Andrew Hoey, James Cook University, my deepest gratitude for believing in the value of this research and for providing a pathway for it to prosper. One of the main goals of this project has been to make the research conveyable across multi-disciplinary fields and practitioner teams. Exposure to stimulating cross-disciplinary discussions, terminology adjustments and conveying the real practical advantage of this type of research was made possible with you on the team.

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Woppaburra Country, '*Konomie*' North Keppel Island, was introduced to me by A/Prof. Michael Rowland, James Cook University, as well as Christine Hansen-Doherty, Dr Harry Van-Issum, and other members of the Woppaburra community in 2016. In continuation of over 40 years of important research led by A/Prof. Michael Rowland and the Woppaburra community, it has been a privilege to work on this project. As I allude to in the final chapter of the thesis, sometimes 'Western' words can't express certain experiences or situations. I feel such that, this opportunity let me partly experience some of these types of insightful moments. Thank you all for the welcome support to not just fulfil the requirements of a research degree, but to be a part of something special.

There's a certain excitement about diving in a new destination. Even though you get some sort of a brief before plunging into the water, you never quite know what to expect or indeed, what you'll encounter along the way. This experience was kind of similar. I met and worked alongside some truly incredible people, too many names to list here – some good old faithfuls and some new who made this challenge enriching. I am particularly indebted to advice from knowledgeable people who swim through the ocean with both competence and integrity.

When I needed it most, my favourite fishes in the ocean schooled around me with love and patience. To my partner Andrew Watson, thank you for swimming the waves, for being understanding, and helping me relax. Thank you to my mum, Jackie Tusel, and my brother Chris Aird. You taught me the strength I needed to see this journey through. You were with me every step of the way and instilled my courage.

Statement of Contributions by Others

Primary supervisor, Dr Katherine Szabó/University of Cambridge, James Cook University (adjunct)
Secondary supervisor, Prof. Andrew Hoey/James Cook University
Associate supervisor, A/Prof. Michael Rowland/James Cook University (adjunct)
Associate supervisor, Dr Patrick Faulkner/The University of Sydney
Associate supervisor, Dr Amy Prendergast/The University of Melbourne

Intellectual support for this research including the project design, was in collaboration with my supervisory team and Woppaburra Traditional Owners, Christine Hansen-Doherty and Dr Harry Van Issum. I thank the Woppaburra People for the blessing to use knowledge documented in key publications throughout this thesis research. The research design posed no risk to the wellbeing of the Woppaburra community or individuals, as understood and agreed in our collaborations. The research framework and ideas presented in the theoretical chapters were developed with Dr Katherine Szabó and Dr Patrick Faulkner. Theoretical approaches were built on understandings and perspectives conveyed by the Woppaburra People (see Van Issum 2016) and in response to objectives set out in regional, national, and international frameworks and conventions as detailed in Chapters 1-4 of the thesis.

A/Prof. Michael Rowland and Woppaburra Traditional Owners shared the recordings of the excavations at Mazie Bay including field notes, reports, photographs, and datasets. The retrieval of Mazie Bay cultural materials from the Queensland Museum was completed in partnership with Dr Brit Asmussen, the Queensland Museum Aboriginal and Torres Strait Islander Consultative Committee, the Woppaburra Traditional Use of Marine Resources Agreement (TUMRA) committee, and A/Prof. Michael Rowland. Prof. Andrew Hoey held the Queensland Museum outward loan agreement for the cultural materials, permit no. AAR1137.

Live-collected metric datasets for mollusc species were collected at the Queensland Museum and the Australian Museum. Dr John Healy, Queensland Museum, granted access to mollusc collections and confirmed the identifications of some species. Ms Kylie Carroll, James Cook University, was an undergraduate volunteer during the assembly of metric data for live-collected Chitonidae and Neritidae species at the Queensland Museum. At the Australian Museum, Dr Mandy Reid, Dr Winston Ponder, and Mr Ian Loch granted access to mollusc collections and confirmed species identifications.

The North Keppel Island Environmental Education Centre permitted access to accommodation, boat transportation, and general facilities during fieldwork at North Keppel Island. A/Prof. Michael Rowland assisted with the live-collection of mollusc samples. Collections were made under permission from the Great Barrier Reef Marine Park Authority (GBRMPA) (permit no. G18/38392.1) issued to the College of Science and Engineering, James Cook University. Biometric techniques training was provided by Dr

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A 5-month professional development internship at the remote Australian Museum's Lizard Island Research Station (LIRS) was undertaken in 2016-2017 with directors, Dr Anne Hoggett and Dr Lyle Vail. During the annual leave period of the LIRS directors, Prof. Andrew Hoey was in the role of acting director.

Abstract

The existing state of the Earth and all living organisms in it, are defined by ways in which socio-ecological interactions have set trajectories in past and present contexts. Our ongoing survival depends on how socio-ecological interactions materialise into the future. In many societies, this theme has been the subject of rigorous debate, shaped political views and relationships, influenced the trade and exchange of resources, fuelled the insertion of borders, and is built into multi-generational knowledge systems. But seldom are long-term repositories of knowledge satisfactorily considered for holistic interpretations to plan for the future. Modern socio-ecological knowledge is important, although, the dilemma we experience in making sense of 'best stewardship' is the conundrum of shifting baseline understandings. Increasingly, baseline understandings deriving from deep time cultural contexts are being used to overcome this challenge in different parts of the world. Never has this approach been adopted for cases within the Great Barrier Reef (GBR) World Heritage region in Australia.

At coastal sites along the length of the GBR, many cultural deep time sites exist. The material remains in these repositories comprise of ecologically and culturally important marine fauna. However key data that are directly extractable from these materials has not been prioritised to inform conservation practitioner teams. This research contributes an original body of knowledge for a 5000-year socio-ecological trajectory at Mazie Bay, North Keppel Island. Data presented in this research can be used to inform practitioners working within the marine resource management and cultural heritage management sphere. With a view to planning for future socio-ecological resilience, an Historical Ecology framework is used to situate the case study. It prioritises the use of multiple perspectives by integrating high-resolution datasets derived from mollusc shells, with the Woppaburra Peoples' Traditional Ecological Knowledge (TEK).

Underlying the efforts of this research is a continuation of over 40-years of collaborations and work by the Woppaburra People and archaeologist A/Prof. Michael Rowland. Woppaburra's Mazie Bay is the second oldest known cultural resource use site within the GBR. It holds significance for its cultural value, its sheer size - layered in and across an extensive sand-dune, and the density of faunal materials contained within. When Rowland first opened the site with the Woppaburra People for archaeological excavation in 1979, they were situated between a palm lined stream at the landward side, and a shallow intertidal lagoon only an arm's stretch to the next island. Their efforts in recovering cultural materials appeared at first, quite grim. Although, when Rowland was being directed for interview inside the walls of the excavation by a visiting film crew, his trowel hit a hard surface – a dense layer of materials. The excavation continued over 6 weeks, seeing the recovery of a large volume of mollusc shells, and to smaller extents fish bones, turtle bones, stone tools, and fish hooks. Quantification data revealed changes in the abundances and types of species through time, with complex socio-ecological processes being targeted by Rowland as reasons for these changes. Since newly available high-resolution techniques have become available, further insight into why these changes might have occurred has been made possible.

Three main questions direct this research. The first question allows the articulation of why applied zooarchaeological datasets and TEK is integral to informing conservation initiatives. The evaluation supports that places and resources are deeply imbedded in human cultures but that the needs and ambitions of modern and future generations often differ from past generations. Indeed, socio-ecological trajectories are non-linear and dynamic. This realisation however, should not disqualify the integration of key knowledges and perspectives when planning for resilience. It argues that local baselines are crucial foundations for supporting the success of conservation goals detailed in regional, national and international frameworks, and demonstrates how the meeting of these objectives can be better achieved.

The second question initiates a critical review of the analytical techniques that can be applied to mollusc shells to understand population structures, human resource use scheduling, and to construct palaeoclimatic proxies. These techniques include: biometrics, sclerochronology and biogeochemistry. Combined employment of these techniques have been adopted to mostly temperate Northern Hemisphere cases, seldom for tropical Southern Hemisphere cases, and never for cases situated within the GBR. A degree of innovation was therefore needed to adopt these high-resolution techniques to tropical species recovered from the Mazie Bay cultural resource use site. I targeted assessments of mollusc shell sizes, species age profile estimates, sea surface temperature proxies, and Woppaburra resource use scheduling trends.

A response to the final research question offers a well-informed and integrated subset of knowledge for an aspect of the socio-ecological trajectory at Mazie Bay. The biometric dataset comprising four species, *Asaphis violascens* (Pacific asaphis), *Saccostrea cuccullata* (rock oyster), *Lunella cinerea* (moon turban) and *Nerita chamaeleon* (chamaeleon nerite), found minimal changes in shell sizes through time. The body sizes of a fifth species, *Acanthopleura gemmata* (black jewelled chiton) was found to decrease in size, with the smallest individuals being present in the most recent occupation phase. Of these species, *L. cinerea* was found to be a reliable palaeoclimatic indicator. Palaeotemperature proxies indicate only minimal changes between modern and mid-Holocene sea surface temperatures (~2ºC), ultimately pointing to other variables such as local precipitation patterns being responsible for changes in shell sizes and ontogenetic ages. The sustained seasonal use of *L. cinerea* by the Woppaburra People was also detected. Temperature values confirm harvesting trends in *Giru* and *Konomie* (or the dry season/spring on the Western calendar) which is an important time for ceremony. In the broader dialogue of planning for socio-ecological resilience, this enriched perspective is an example of the implications for how heritage sites and resource populations might be known, monitored, and conserved.

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List of Abbreviations

2D	Two-Dimensional Shape
3D	Three-Dimensional Shape
AD	Anno Domini
aDNA	Ancient Deoxyribonucleic Acid
AFMA	Australian Fisheries Management Authority
AIMS	Australian Institute of Marine Science
AISM	Australian-Indonesian Summer Monsoon
AMS	Accelerator Mass Spectrometry
ANOVA	Analysis of Variance
ANU	Australian National University
ARC	Australian Research Council
ASM	Australian Summer Monsoon
BC (BCE)	Before the Common Era
BoM	Bureau of Meteorology (Australia)
BP	Before Present (prior to AD 1950)
c.	Circa
cal BP	Calibrated Years Before Present
CBD	Convention on Biological Diversity
CITES	Convention on International Trade in Endangered Species
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DL	Disturbance Line
DNA	Deoxyribonucleic Acid
DoG	Direction of Growth
e.g.	Example

EAC	East Australian Current
EHWS	Extreme High Water Spring Tide Mark
ELWS	Extreme Low Water Spring Tide Mark
ENSO	El Niño-Southern Oscillation
EPBC	Environment Protection and Biodiversity Conservation
EPF	Extra Pallial Fluid
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park (based on contemporary zoning boundaries)
GBRMPA	Great Barrier Reef Marine Park Authority
GBRWHA	Great Barrier Reef World Heritage Area
GI	Growth Increment
GL	Growth Line
HBE	Human Behavioural Ecology
Hrs	Hours
i.e.	That Is
ILSM	Indigenous Land and Sea Management
ILUA	Indigenous Land Use Agreement
incl.	Including
IPA	Indigenous Protected Area
IPO	Interdecadel Pacific Oscillation
JCU	James Cook University
MJO	Madden-Julian Oscillation
MEB	Multiple Evidence Base
MNI	Minimum Number of Individuals
mtDNA	Mitochondrial Deoxyribonucleic Acid
NBS	National Bureau of Standards (Australia)

NISP	Number of Individual Specimens
NKIEEC	North Keppel Island Environmental Education Centre
NRE	Non-Repetitive Element
NTD	Native Title Determination
OFT	Optimal Foraging Theory
OTS	Odyssey Temperature Loggers
pH	Acidity and Alkaline Scale, Ranging Between 1 and 14
PSU	Practical Salinity Units
QMATSICC	Queensland Museum Aboriginal and Torres Strait Islander Consultative Committee
SEM	Scanning Electron Microscope
sp.	Species
spp.	Species (plural)
Sq.	Square
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SU	Stratigraphic Unit
TEK	Traditional Ecological Knowledge
TO	Traditional Owner
TUMRA	Traditional Use of Marine Resources Agreement
UNESCO	United Nations Educational, Scientific and Cultural Organization
VPDB	Vienna Pee Dee Belemnite
VSMOW	Vienna Standard Mean of Ocean Water
WSK	Western Scientific Knowledge
XRD	X-Ray Diffraction
XU	Excavation Unit

List of Symbols

%	Percent
‰	Per Mil (parts per thousand)
±	Plus or Minus
<	Less Than
>	Greater Than
~	Approximately
≤	Less Than or Equal
≥	Greater Than or Equal
^{13}C	Carbon Isotope
^{14}C	Carbon Isotope
^{15}N	Nitrogen Isotope
^{18}O	Oxygen Isotope
Br	Barium
Ca	Calcium
$CaCO_3$	Calcium Carbonate
cm	Centimetre
cm^2	Centimetres Squared
Fe	Iron
g	Grams
H^2O	Water
km	Kilometres
km^2	Kilometres Squared
Li	Lithium
m	Metres
m^2	Square Metres
Mdn	Median

Mg	Magnesium
MJm^{-2}	Megajoules Per Square Metre
mm	Millimetres
Mn	Manganese
ºC	Degrees Celsius
r^2	R-Squared
Sr	Strontium
δ	Delta
$\delta^{13}C$	Carbon Isotope Ratio in Shell
$\delta^{18}O$	Oxygen Isotope Ratio in Shell Carbonate
$\delta^{18}O$	Oxygen Isotope Ratio in Water
η^2	Eta Squared
µm	Micrometres
σ	Sigma

Glossary

Every effort to eliminate terms with potentially negative connotations has been made. Language which supports a 'decolonisation' perspective but which conveys meanings appropriate in current cross-cultural dialogues, is used throughout the thesis. These terms and phrases are presented below.

Term/Phrase	Replaces	Description	References
Country / **On Country /** **Sea Country**	Land / Aboriginal Land	Caring for Country is described as the interconnectedness between 'biophysical, spiritual, cultural, kinship relation, survival and ancestral domains' which extends across land and sea scapes (Austin et al. 2018:377).	See Austin et al. (2018) and see Van Issum (2016) for conceptualisations of Country by the Woppaburra People.
Cultural Resource Use Site / **Cultural Resource Site**	Midden / Kitchen Midden / Rubbish Heap	Removes the assumption that the remains of fauna are of low significance.	Cultural resource use sites can be formed on the bases of ritualised activities and imbued with meaning (see McNiven 2013b and see also Darvill 2009 for the definition of 'midden' in *The Oxford Concise Dictionary of Archaeology*).
Deep Time / **Deep Time Site**	Archaeological Record / Archaeology Site/ Prehistory/ Prehistoric Site	Removes the suggestion of ownership of cultural heritage by non-Indigenous practitioners with reference to particular places and with respect to changing timescales. In many cases, cultural sites are considered living and ongoing and therefore the term 'prehistoric' is also avoided. *note the term 'archaeology site' might be appropriately used during the physical undertaking of excavation work for	'Deep time' and the concept of the *longue durée* has been acknowledged and discussed in many disciplines. It attempts to decolonise the concept of time (for e.g. see overview in Silliman 2012).

Term/Phrase	Replaces	Description	References
		example. In these instances, the implied meaning has different connotations.	
Dreaming / Dreamings	The Dreamtime	Removes the assumption that all Traditional Owner groups have one and the same cosmology.	See Van Issum (2016:79) for discussion on the terms 'The Dreamtime' and 'Dreamings' in relation to the Woppaburra People.
Human / Humanity / Humankind	Man / Mankind	Gender-neutrality.	Adopted in various texts.
Influences / Drivers	Impact	Similar to the term exploitation, the terms 'influences' and 'drivers' are used to replace the term 'impact' to remove assumptions about the degree of changes or outcomes in cultural landscapes.	See Head (2008).
Infrastructure Communities	Stakeholders	Removes stereotyping of the roles of individuals and people/organisations/ groups. Traditional Owners are not considered 'stakeholders' but as primary custodians (see rationale in Dale et al. 2018:39). Although, first nation groups or individuals may be active in or lead groups within infrastructural communities (e.g. work in scientific institutions or lead commercial businesses), many Traditional Owners in these dual roles have distinct cultural rights and responsibilities.	See an example for the use of the term in Grabowski et al. (2017).
Practitioner / Practitioners	Scientist / Expert	Can be a single individual or a group	See term in relation to 'infrastructure

Term/Phrase	Replaces	Description	References
		of people with interests in, or knowledge about, a project. Practitioners can include but are not limited to Traditional Owners, researchers aligned with academic institutions, staff of government or non-government organisations, members of the general public, volunteer groups.	communities' in Grabowski et al. (2017).
Resource Use	Exploitation	Removes the assumption that resources were harvested to detrimental degrees.	See concept in relation to the term 'impact' in Head (2008).
Traditional Owner / Traditional Owner Group (TO)	Indigenous Group	Traditional Owner/s (or Traditional Custodian/s) is the term used in Australia for first nations peoples. The term describes a person or group with unique cultural lore, rights, interests, beliefs, responsibilities and practices relating to their own and ancestors' place of birth.	See Traditional Owner Settlement Act (2010) and the Native Title Act (1993).
Western Scientific Knowledge (WSK)		Issues relating to the appropriateness of the terms 'western' and 'scientific' and 'modern' are problematic.	The rationale for the use of such terms in this research follows that of Ingold (see Ingold 2000:6-7).

1

Introduction

1.0 Introduction

Oceans and associated shorelines are the largest ecological zone on Earth. They cover 70% of our planet and ensure the survival of approximately 3 billion people globally, but are now in critical danger of irreversible depletion (Hughes et al. 2017; Pauly and Zeller 2015; Pauly et al. 1998; Worm 2016; Worm et al. 2006). Large-scale mechanisms driving ecosystem changes resulting in the decline of environmental, cultural, and economic health of coastal communities, raises serious concern (Hughes et al. 2017, 2018; Worm et al. 2006). Understanding the operation and interrelationship between variables driven by human, climatic and environmental mechanisms is key to effective management. Indeed, management initiatives of different magnitudes endlessly grapple with strategies to maintain or re-establish marine resource populations for present and future generations (see for e.g. Bellwood et al. 2019; and see Morrison et al. 2020). The terms 'sustainability' and 'resilience' are often used to describe idealised outcomes by such initiatives (and see Robinson and Bennett 2000:xv-vxiii). With a diversity of community needs and contexts, and particularly since addressing global-scale drivers such as climate change, seem like unattainable goals, we often lose sight of existing 'grass-roots' knowledge that is potentially available for addressing issues (Rockman 2012b:197; and see Tengö et al. 2014).

Grass-roots or local level knowledge may be used to reveal baseline information to assess factors driving human, environmental, and climatic changes over the long-term - knowledge that is particularly useful in planning and management initiatives (Hambrecht and Rockman 2017:629; Tengö et al. 2014). To varying degrees, local scale knowledge is being used by practitioners to understand factors driving change. Although, the ways in which knowledge is extracted, prioritised, assessed, and communicated to inform management initiatives, has had some limitations. These issues are mostly owing to the 'validation' and 'legitimacy' of knowledge experienced within infrastructure communities (see discussion in Tengö et al. 2014) (see Glossary for infrastructure communities). The management of marine resources is additionally complicated by the need to address issues across large geographic expanses. In Australia, the monitoring of commercial and non-commercial fishing activities takes place across a 10 million km^2 Exclusive Economic Zone, larger than the country's land mass itself, which aims to provide economic security, ecosystem health, and cultural wellbeing to both national and associated international communities (Geoscience Australia 2018).

Inside this zone, in the tropics and subtropical region of eastern Australia, is the Great Barrier Reef (GBR) which has an 'economic, social and icon asset value of $56 billion' (Dale et al. 2018:xiii). In 1981, the GBR was formally recognised as a World Heritage site by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) for its outstanding 'natural' values (UNESCO 2019). Recently, debates concerning the 'current status' or 'current health' of the GBR have triggered a series of scientific vulnerability assessments. In 2012, the UNESCO monitoring team determined the GBR as 'not in-danger' yet, effective and ongoing management of the GBR's socio-ecological domain requires innovative strategies to ensure its resilience (Dale et al. 2018:9). Despite the GBR's nomination to UNESCO by the Commonwealth of Australia including grass-roots or Indigenous and non-Indigenous cultural heritage values, these have never been formally recognised (GBRMPA 1981). To many local communities, the very functioning of the GBR is, and has always been considered a biocultural or socio-ecological system (Dale et al. 2018). For Aboriginal and Torres Strait Islander Peoples, having deep connection to Country recognised, and having autonomy in the management of resources, is critical in their livelihoods and wellbeing (see Glossary for definition of Country). At this time, 16% of the GBR is officially recognised as 'Indigenous owned' (Dale et al. 2018:1).

1.1 Shifting Baselines

Short-term records (i.e. spanning a few years or decades, or up to 1 or 2 centuries) are often used to document socio-ecological interactions which are then routinely used to respond to large longer-term issues. For example, contemporary fisheries planning typically relies on modern catch records to develop overarching cross-regional or nation-wide management strategies. There are two problems with this approach. The first relates to potential scale misalignments: using short-term place-based data to model strategies for larger regional or nationally scaled issues (see e.g. discussion in Bellwood et al. 2019). The result of these types of approaches is the missed opportunity to apply appropriate resilience strategies at local grass-roots levels, which often have unique sets of circumstances needing attention. Secondly, because datasets are routinely collected at short-term resolutions, interpretations result in limited single-generation evaluations. Consequently, as each generation of practitioners (see Glossary for definition of a practitioner) replaces the next, the variables driving change, ways for capturing data and interpreting datasets also changes (Pauly 1995). Pauly (1995) describes this phenomenon as the 'shifting baselines syndrome'. The shifting baselines syndrome applies to both scientific and non-scientific evaluations (Faulkner et al. 2019). To illustrate this point, across three generations of local fishers in the Gulf of California, Saenz-Arroyo et al. (2005:1959) found that older generations held more historical knowledge compared to middle-age and younger generations. They identified that the loss of fisheries knowledge being transmitted through generations has been a key reason for society being 'tolerant of the creeping loss of biodiversity' (Saenz-Arroyo et al. 2005:1957).

Variability in knowledge across temporal scales should be anticipated. Reasons for knowledge change might include the non-linear nature of knowledge transmission, or other reasons driving change in socio-ecological systems (e.g. community relocation to an unknown environmental setting or *in situ* environmental or climatic changes). Change in knowledge is inevitable, although harnessing long-term grass-roots understandings is central to planning for and managing successful socio-ecological resilience strategies. Rockman (2010:4) and Rockman and Steele (2003:4) define three postulates governing ecological knowledge that manifest across different but often blurred temporal and spatial boundaries:

- *locational* - 'physical characteristics' of land or seascapes and locality of resources,
- *limitational* - boundaries associated with accessing resources, (e.g. 'seasonal variation'),
- *social* - 'attribution of names, meanings, and patterns to natural features'.

The landscape learning process model posits that the above three postulates are initiated when humans enter new environments or when humans respond to environmental changes *in situ* (Rockman 2010:4). In either of these scenarios, knowledge embodies both physical and non-physical domains which can exist over short-term or longer-term trajectories. Social knowledge, also interconnected with locational and limitational knowledge, can be conveyed verbally or in material form (Rockman 2010:5). For example, Australian Aboriginal song-lines and Dreamings (see glossary) describe creation events, cosmological and spiritual beliefs, life-ways, and socio-ecological knowledges, which have continued for thousands of years (Van Issum 2016). In material form, environmental knowledge manifests throughout landscapes - i.e. collection and use of resources and manufacturing of artefacts: tools, shelters, houses; the creation of sacred sites - shrines, temples, bora rings, stone arrangements; and, morphological changes to land or seascape features: farming, agriculture, and mariculture. This embeddedness, which forges interrelationships between humans and the environment, is the 'cultural landscape' (Head 2012). Working with the three postulates of ecological knowledge, Traditional Ecological Knowledge (TEK) and Western Scientific Knowledge (WSK) may be generated.

1.2 Traditional Ecological Knowledge and Western Scientific Knowledge

TEK was first described within the discipline of cultural ecology in the 1980s (Berkes 1993:1-2). Since then, the term has undergone several revisions which centre on the appropriate use of the term 'traditional' as opposed to 'local' or 'Indigenous' when defining ecological knowledge (for debates see Berkes 1993:3, 1999:5). Berkes' (1993:3) early definition of TEK explains it as:

> *… a cumulative body of knowledge and beliefs, handed down through generations by cultural transmission, about relationships of living beings (including humans) with one another and*

> *with their environment. Further, TEK is an attribute of societies with historical continuity in resource use practices; by and large, these are non-industrial or less technologically advanced societies, many of them indigenous or tribal.*

TEK is based on non-linear reciprocal knowledge sharing that is embedded through communities and into cultural landscapes (Berkes 1993; Levi-Strauss 1962; and see Menzies 2006). Cultural identity is conveyed through spiritual and cosmological beliefs often practiced and instilled through TEK, which is also an integral part to the functioning of TEK itself (Johannes 1989; Peterson et al. 2010:7).

In contrast to Berkes' (1993:3) definition that TEK exists in 'less technologically advanced' societies, the Balinese rice-field-temple irrigation system or '*Subak*' demonstrates how TEK can operate within technologically advanced societies. *Subak* is an important aspect in Balinese terraced rice-crop production. The system, which is built upon local knowledge and instilled by socio-ecological and socio-cultural values, has operated since at least the 9th century CE (Lansing et al. 2009, 2012) (for archaeological evidence see Lansing and de Vet 2012:465). The earliest irrigation of water from high terraced rice-fields to lower terraced rice-fields was introduced by Balinese kings, and then adopted during the historic period by Dutch settlers (Lansing and de Vet 2012:454). The functioning of the *Subak* system employs the three ecological knowledge postulates outlined above through TEK, by using for example, geomorphological structures (soil terraces), seasonal use of water (Bali receives a monsoon season), and humans (to ensure cyclic renewal of the socio-ecological system with respect to spiritual beliefs and cosmological responsibilities). Ritual activities for the success of the irrigation system are performed to meet survival, ecological and cultural prosperity needs, which operate as one functioning system (see a specific case of insect and rodent pest control in Lansing and de Vet 2012:454-455). As the Balinese *Subak* system demonstrates, long-term multi-generational practice and transmission of TEK, shows remarkable connection between people and their environments because it can be used to actively and repeatedly predict outcomes in everyday lives (e.g. animal behaviours, biochemical plant reactions). Similarly, but not explicitly the same, WSK can also be employed to predict and forecast socio-ecological interactions.

TEK and WSK are defined as two different knowledge systems which may highlight differing world views (Berkes 1993:6; Johannes 1989) or, work on similar principles (Menzies and Butler 2006:6; Ross et al. 2011:46-47). In keeping with the general accepted use of the terms TEK and WSK, common principles that operate within each knowledge system can be identified (Table 1.1). Importantly, not every situation fits these principles, and indeed deductive scientific models have more recently moved to incorporate socio-cultural aspects (Ross et al. 2011:40; and see examples in Tengö et al. 2014). In the case of resource use, not all TEK driven or WSK driven systems seek conservation outcomes (see Hames 2007). In some cases, knowledge strategies are specifically employed to increase resource yield.

Conservation goals might therefore not be pre-determined, be actively pre-determined, or outcomes might occur epiphenomenally (see Jones et al. 2016; and see e.g. in Codding et al. 2014a). When examining resource use using TEK and WSK, assessments should be made on case-by-case bases and for each temporal and spatial setting.

Table 1.1 Traditional Ecological Knowledge (TEK) and Western Scientific Knowledge (WSK) comparison summary (after Berkes 1993:4-5).

TEK Principle vs.	**WSK Principle**
Qualitative	Quantitative
Intuitive	Rational
Holistic integrated system	Single reductionist system
Spiritually moral	Spiritually value-free
Empirical experiences	Methodically systematic
Data pool built by any member of community	Data pool built by scientists
Predictions are limited	Predictions are numerous
Slow accumulation	Fast accumulation

Many resource management cases within the TEK-WSK sphere are contentious, mostly due to unequal power structures between local grass-roots communities and top-down infrastructure communities (Berkes 1993:6; Tengö et al. 2014; Thomas et al. 2019:3). Reconciling this disjunction without neglecting the complexities steeped in sensitive issues begins with innovative strategies merging knowledge sharing at the TEK-WSK interface. These ‘cross-border’ (see Peterson 2010:6) initiatives primarily include local communities and groups within infrastructure communities, such as multidisciplinary research teams and policy makers (Berkes 2006:1-2; Robson 2009:174; Tengö et al. 2014; Thomas et al. 2019:12). The Multiple Evidence Base (MEB) approach, argues for cross-cultural and interdisciplinary knowledge, and is best applied in cases with numerous and complex needs (Figure 1.1) (Tengö et al. 2014). The dimension of time is not illustrated in this model nonetheless, as the following discussion argues, long-term records deriving from deep time archives are critical in these approaches (see Glossary for deep time).

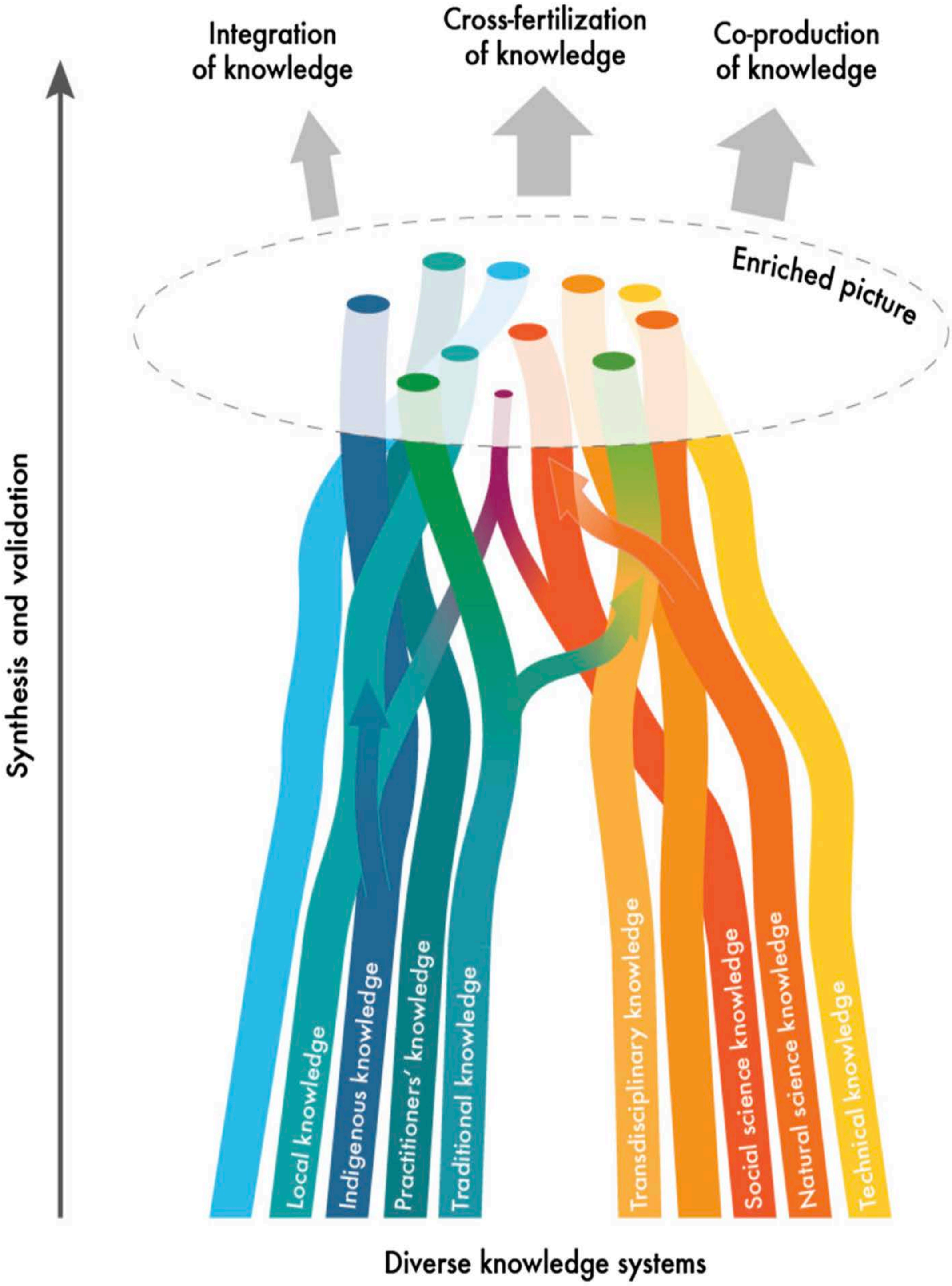


Figure 1.1 The Multiple Evidence Base approach, demonstrating how multi-streams of knowledge can build holistic understandings (i.e. by fostering multidirectional triangulations of knowledge in cross-cultural practitioner teams) (Tengö et al. 2014).

Extracting long-term knowledge from deep time in the forms of TEK and WSK proposes an ideal platform to initiate MEB led projects. MEB projects using deep time records can:

- collect low-resolution and high-resolution datasets derived by local communities and multidisciplinary research teams,

- potentially identify mechanisms or variables prompting human, climatic or environmental changes through time,
- recover longer-term knowledge or 'memories lost due to colonial rule, forced displacement, and outmigration' (Thomas et al. 2019:12),
- eliminate shifting baseline processes, and;
- collate knowledge to inform management initiatives during planning phases (e.g. resource resilience and conservation, community wellbeing, location of significant cultural sites) (after Aswani and Allen 2009:623; Pauly 1995; Pauly et al. 2005; Rockman 2012a, 2012b, 2015; Tengö et al. 2014).

1.3 Long-Term Knowledge Using Multiple Evidence Based Approaches

TEK-WSK grass-roots collaborations are underway in many parts of the globe with some cases having more success than others. Traditional versus commercial fishing interests, and the intensity of resource extraction between inshore versus deeper offshore waters, has been the focus of many investigations (Aswani and Allen 2009:614; Pauly et al. 2005). In the northern hemisphere, investigation of beluga whale or 'white whale' (*Delphinapterus leucas*) hunting for traditional and commercial purposes is ongoing. Accounts reveal beluga whales were intensively hunted by non-Indigenous fishers during the historic period, resulting in population declines across the Canadian Arctic, Alaska, and surrounding waters (Carter and Nielson 2011; Harwood et al. 2002). In the historic period they were prized for their meat, *maktak* (traditionally preserved meat), fat content to make oils, and skin to make leather goods (Morseth 1997). In Indigenous communities across the Canadian Arctic and Alaska, beluga whale cosmological beliefs and hunting practices are regarded as the fabric of identity (see Pearce et al. 2011:273). Indeed, the Inuit hold extensive knowledge of the species ecology and regard beluga whales as spiritual beings (Breton-Honeyman et al. 2016; Pearce et al. 2011). Undertakings to document social knowledge through The Inuvialuit Living History Project, engaged with elders' TEK on beluga whale hunting and other socio-ecological Inuvialut-beluga whale dynamics (Lyons 2014). Findings showed '[i]n traditional Inuit education, learning and living were the same things' - a testimony to the importance of engaging younger generations in TEK (Pearce et al. 2011).

Climate change and changing availabilities of fish prey are considered by Choy (2014) to be key drivers influencing beluga whale populations. Indeed, debates around the formulation of appropriate management strategies in response to hunting rights, climate change, and fish prey, are ongoing (Huntington 2000; Huntington et al. 1999; Lewis et al. 2009; Tyrell 2007). Depending on fisheries laws within each region, hunting of beluga whales by contemporary communities either continues to be practiced through cultural tradition, is restricted, or completely off limits (Carter and Nielson 2011). The implementation of TEK and knowledge extracted from deep time in environmental management planning is variable, and usually results in unequal socio-ecological understandings. For example, Breton-Honeyman et al. (2016) suggest that longer-term beluga whale fisheries baselines, compared with those already accounted for in the historic and modern catch records, are irretrievable (see Harwood et al. 2002 for historic catch records, consider Hollesen et al. 2018). Frieson and Arnold's (1995) retrieval of beluga whale bones from an Inuit cultural site however, is evidence for the existence of deep time archives. Their study produced information on seasonal hunting practices and diets, catch record approximations and deeper understandings of TEK. This study, albeit published ~25 years ago, demonstrates the ability for TEK and WSK to provide more holistic insights into beluga whale hunting dynamics. More MEB understandings, documenting different aspects of socio-ecological interactions across time and space, would equip contemporary management initiatives with a more powerful toolkit to plan for future resilience.

1.4 Baseline Knowledge: Sustainability or Resilience?

In northern Australia, cross-cultural multidisciplinary practitioner teams have demonstrated where TEK and the employment of archaeological techniques (WSK) have been particularly useful. Key to the success of collaborations between Indigenous and non-Indigenous practitioners has been on-the-ground 'knowledge sharing' via participation on Country and translation of information to co-inform management initiatives (see Robinson et al. 2016:44). Since the settlement of non-Indigenous people in Australia, ways to continue caring for Country using traditional fire regimes, has been extremely challenging (see Robinson et al. 2016:8). Assessment of deep time archives using TEK and archaeological techniques have managed to uncover the long-term benefits of alternating 'patch mosaic burning' or 'fire-stick farming' strategies. These include, but are not limited to: who should control burns – according to knowledge status; when to pursue burning according to seasonal indicators; where to install fire-breaks to mitigate impacts from uncontrolled natural fires (e.g. protection of cultural sites); how to drive fauna into non-burnt refugia during firing and then, resettlement of fauna into burnt areas post-firing (e.g. for faunal species to access young plant shoots for food); and 'sustainability' of selected species populations (see Codding et al. 2014a and review within Robinson et al. 2016).

Although it is critical to respond to local needs that might be influenced by large scale drivers such as global warming for instance, it is important to utilise both local TEK and WSK to assist in responding to challenges. Challenges which might arise include but are not limited to biodiversity loss or preservation of important cultural sites. In Martu Country, in Western Australia's Little Sandy Desert, the use of fire is guided by 'spiritual relationships known as the Jukurrpa or law passed down by the Dreamtime ancestors' (Codding et al. 2014a). The Martu People state that sustainable outcomes from their interactions with the environment is not due to intentional management, but rather as outcomes of a series of responses guided by ancestral domains (Codding et al. 2014a). Interpreted scientifically, Codding et al. (2014a) suggest this is a case of epiphenomenal sustainability, whereby long-term interspecific cooperation or co-evolution between the Martu and the environment, by way of traditional firing practices and resource use patterns, has resulted in unintended macropod population resilience (e.g. hill kangaroos). The pathway leading to macropod population 'resilience' and the 'sustainable' outcome of this system can be explained in alternate ways using both TEK and WSK, which agree on similar physical occurrences. At these agreed intersections, practitioners are best suited to negotiate and implement management strategies. Table 1.2 summarises how TEK and WSK can operate successfully in shared knowledge spaces.

Table 1.2 Traditional Ecological Knowledge (TEK) and Western Scientific Knowledge (WSK) identifiers for successful outcomes in resource management and conservation (after McGoodwin 2006:189-190).

TEK Success Identifier	**WSK Success Identifier**
Establishment of long-term TEK imbedded into the local community.	Establishment of WSK research, respect and recognition of TEK.
History of TEK identification and responses to past species or ecological collapse/decline.	History of WSK identification and responses to past species or ecological collapse/decline.
Holders of TEK have clear conservation goals.	Holders of WSK have clear conservation goals.
TEK holders generate knowledge independent of external forces.	WSK holders generate knowledge independent of external forces.
Commitment of TEK holders to implement their knowledge into management plans.	Commitment of WSK holders to implement their knowledge into management plans.
TEK holders work independently of external WSK in the local community to promote conservation in the past.	WSK holders work independently of external TEK at their home institution or on other cases to promote conservation in the past.
Commitment of TEK holders to implement knowledge into management plans.	Commitment of WSK holders to implement knowledge into management plans.
TEK holders support collaboration with scientific research and government policies.	Scientific research supports collaboration with TEK holders and government policies.

Deep time records, evaluated by TEK and WSK, may serve as an opportunity to understand constructive responses 'to resource depletion in the past' (McGoodwin 2006:180). In northern Australia where fire is frequently used to manage cultural landscapes, practice-based stewardship and the implementation of TEK and WSK has achieved: vegetation regeneration, weed and pest control, reduced carbon emissions, environmental conservation, handing-down of cultural knowledge to younger generations (including oral histories and initiation ceremonies), up-skilling and training, and wider community education (Robinson et al. 2016). Resembling the Martu Little Sandy Desert case, socio-ecological prosperity and continuation of cultural traditions is also instilled via this process (see also Ross et al. 2011:235-260 for the *Indigenous Stewardship Model*). Viewed this way - when ecosystem health regenerates, cultural identity and economic prosperity can also rejuvenate (McGoodwin 2006:117; Peterson et al. 2010:8). This concept is explained well in the *Strong People Strong Country Framework* in Dale et al. (2018:92).

1.5 Traditional Resource Use in the Great Barrier Reef

Across the GBR region, Aboriginal and Torres Strait Islander communities are active in managing cultural and natural resources through sea ranger programs and other initiatives. Management of Marine Protected Areas (MPAs) and Traditional Use of Marine Resources Agreements (TUMRAs) are efforts implemented with the Great Barrier Reef Marine Park Authority (GBRMPA) (GBRMPA 2018a) (Figure 1.2). TEK is actively drawn upon and recognised to some degree by non-Indigenous management practitioners; however, improved cross-cultural communication and co-management strategies at local grass-roots levels are needed. In December 2018, community representatives came together to create the *Traditional Owners of the Great Barrier Reef: The Next Generation of Reef 2050 Actions* (referred to hereafter as TO 2050 Actions) (Dale et al. 2018), which details the Aboriginal and Torres Strait Islander aspirations and interests within land and sea Countries respectively. Indigenous empowerment through co-managed collaborations with infrastructure groups using the MEB approach is outlined in that document (see summary recommendations in Appendix A). With over 70 Aboriginal and Torres Strait Islander traditional language groups within the contemporary boundaries of the GBRMP there appears to be no shortage of potential cases where the MEB approach could also include knowledge derived from deep time archives. Reasons as to why these archives have not been utilised to the fullest potential in resource management initiatives in the past might include but are not be limited to: lack of funding, limited access to project resources, unequal agreements on the benefits arising from such projects, poor cross-cultural communication or openness to understand cultural systems alternate to peoples' own (e.g. Aboriginal and Torres Strait Islander cultural practices might be viewed as a static entity existing only from the deep past and without growth into the future). These views are problematic, particularly when dealing with operational tasks within a project.

The TO 2050 Actions document clearly states: 'Traditional Owners have legal and inherent rights and interests that differ from historical Aboriginal and/or Torres Strait Islander People connected to the GBR' (Dale et al. 2018:63); nevertheless, cultural obligations connected to ancestral lore should be maintained through time. The obligation of Traditional Owners (TOs) to meet both traditional customs and modern needs for Country is therefore challenging and complex (see Glossary for TO). One avenue these complexities have been afforded to be met and maintained is through TUMRAs (Dale et al. 2018:63):

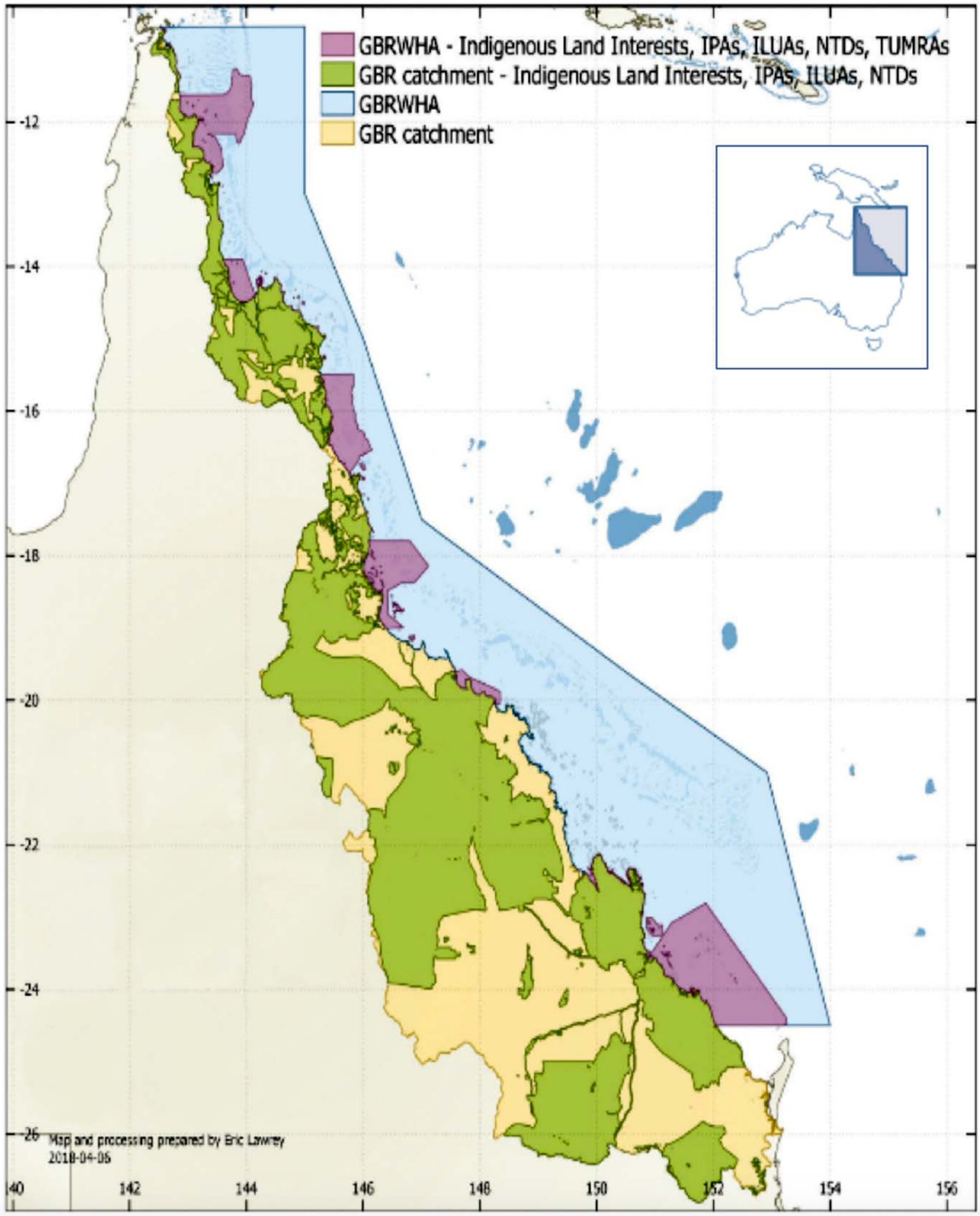


Figure 1.2 Aboriginal and Torres Strait Islander land and sea Country interests within the Great Barrier Reef Marine Park. Pink shaded area shows nine Traditional Use of Marine Resource Agreements (TUMRAs) held by the Girringun, Gunggandji, Lama Lama, Port Curtis Coral Coast, Woppaburra, Wuthathi, Yirrganydji, Mandubarra and Yuku Baja Muliku Peoples respectively (after Dale et al. 2018:11, 27). GBRWHA = Great Barrier Reef World Heritage Area, IPA = Indigenous Protected Area, ILUAs = Indigenous Land Use Agreements, NTDs = Native Title Determinations.

> *[t]he TUMRA may describe specific management strategies for the conservation and sustainable use of key species and habitats; restoring and maintaining waterways and coastal ecosystems, maintenance and protection of significant heritage values including important places, traditional ecological knowledge, culture and language; research and monitoring of sea country (including partnerships with the Authority and other leading scientific institutes and individuals); leadership and governance including knowledge management; education and information exchange; and enhanced compliance*.

The Woppaburra People, TOs of the Keppel Bay Islands, southern GBR, actively lead and co-manage conservation goals through their TUMRA. Their record of marine resource use extends to at least 5000 years ago (Rowland 1999a), since which time the they have been engaged in the ongoing protection of cultural sites and connection to Country. On invitation by the Woppaburra Elders and Woppaburra TUMRA steering committee to continue collaborations across TEK and WSK domains, an agreed project to build on existing knowledge using new and available technologies resulted in this research. This research is designed to record traditional resource use patterns from the deep past using newly available scientific techniques, and to further understand these findings based on Woppaburra TEK.

1.6 Research Questions and Objectives

This research uses documented TEK and high-resolution scientific techniques to investigate one case of long-term marine resource use from North Keppel Island, southern GBR. Human harvesting patterns and climatic changes recorded in a 5000-year-old marine resource use site at Mazie Bay are examined using the Woppaburra seasonal resource use calendar and results derived from biometric, sclerochronological and biogeochemical datasets. These techniques are applied to the remains of key mollusc species that were recovered by archaeologist A/Prof. Mike Rowland in 1979. The objective of this research is to record a long-term socio-ecological baseline for the use of key mollusc taxa at North Keppel Island, which is useful for management and conservation initiatives. The following research questions and objectives guide this research:

Question 1: How can TEK and archaeological data contribute to contemporary marine resource management?
Objective: To assess current trends, methods and issues related to contemporary marine resource management and evaluate the role and effectiveness of deep time derived datasets in the development of management plans.

Question 2: What analytical techniques can be used to define variables driving change in past socio-ecological systems and what are their potential limitations?

Objective: To define analytical methods to test cultural and environmental variables contributing to change and to communicate these findings on appropriate scales and resolutions.

Question 3: What do results tell us about the long-term socio-ecological trajectory at the Keppel Bay Islands?
Objective: To compile information about seasonal resource use and build an archive of palaeoclimate proxies using selected mollusc species from Woppaburra's Mazie Bay cultural resource use site (see Glossary for definition of cultural resource use site).

1.7 Research Significance

Dominant ideology across political, academic, and public spheres currently posits a biased view towards environmental and climatic changes – stipulating 'impact' as an unchanging negative force (Head 2008). The human-environment-climate feedback loop is not only a shared space but a hugely dynamic and complex one – interactions may be positive, neutral or negative. Flexibility and sensitivity in the way in which we approach and derive information from this archive to assist in managing socio-ecological contexts is a challenging task. Responding to issues such as the shifting baselines syndrome, considered part of the problem, calls for a more insightful and equitable approach to address modern community needs. Rockman (2015:44) explains: '[n]o past society is a direct stand-in for the present. However, these pasts allow us to challenge our assumptions about what change and adjustments can look like' - an 'attitude shift' in the way we interpret and plan for our future. Within the GBR, resource use, ecosystem health and community welfare are our primary responsibilities. Although it is an unreasonable request to completely return ecosystems to historic or deep time baselines, it is critical to understand the dynamics of past socio-ecological systems to appropriately advance decision making processes and management initiatives into the future.

The Woppaburra People have a deep and enduring connection with the Keppel Bay Islands. For over 5000 years, marine fauna including fish and molluscs have been a primary resource in Woppaburra culture and diet. Seasonal use of marine fauna, including but not limited to molluscs, has a resounding importance in Woppaburra lifeways, which extends across the entirety of their salt-water Country. Seasonal resource use, which is responded to and acted upon by the Woppaburra People using a range of annually-cyclic environmental and climatic indicators, is communicated through TEK. The cultural resource use site at Mazie Bay, North Keppel Island, is the second oldest and densest accumulation of marine resources known within the modern boundaries of the GBRMP. In material form, it is a long-term multi-generational fisheries archive - a baseline of socio-ecological interactions which can be useful for comparisons to historic and contemporary fisheries catch evaluations (see Aswani and Allen 2009:614; Erlandson and Rick 2008; Reitz 2004; Rick and Lockwood 2013; Steneck et al. 2002). Long-term harvesting patterns, fishing strategies, species availabilities, species growth cues (e.g. types of food supply), and population growth and decline, may be documented from this archive. With these data, local grass-roots projects can better respond to issues of resource depression, ecosystem decline, the ability to practice cultural activities (i.e. traditional hunting and ceremonial activities), and intellectual property rights (Berkes 2006:1). Equally, these data may assist in documenting a more ‘flexible’ structure for seasonal management of resources in modern contexts, by critically analysing what socio-ecological cues and temporal thresholds govern the growth and decline of certain mollusc species (e.g. temperature and salinity).

At this time, no GBR research has used biogeochemical techniques, which can be directly evaluated with TEK, to understand the seasonal use of molluscs deriving from deep time. In international studies, biometric techniques, sclerochronology, and stable isotope analyses have been used to successfully record influences in long-term socio-ecological trajectories (e.g. Antipushna 2014; Hausmann et al. 2017a; and see Makarewicz 2016). These studies have made positive impacts on the way in which contemporary resource management is approached because they directly assess key variables influencing human resource use patterns and species growth. From samples extracted from faunal remains deposited at cultural resource use sites, proxy palaeoclimate data may also be derived (for instance, sea surface temperatures and/or sea surface salinities). A few inquiries have recently adopted metrical approaches to assessing marine fauna sizes from GBR deep time cultural resource use sites (Aird 2014; Barker 2004; Forde 2014) but sclerochronology and isotopic analyses has never been attempted. A common shortcoming of existing metrical assessments is that they use ‘pre-determined’ assumptions to explain findings – either environmental or socio-cultural justifications which do not account for underlying complexities in the drivers of change in metrical datasets (see discussion Grabowski et al. 2017).

In response to the global fisheries crisis, this research contributes a pre-commercial fishery catch dataset for long-term use of molluscs at North Keppel Island, southern GBR. Given the current theme, which advocates for MEB approaches and which favours socio-ecological resilience outcomes, an Historical Ecology framework is used in this research. Most importantly, Historical Ecology encourages the equal testing of assumptions until proven otherwise; therefore, eliminating culturally or environmentally deterministic arguments (Balée 1998; Balée 2006; Crumley 1994; Lyman 2015; and see Armstrong et al. 2017). The consolidation of Woppaburra TEK and scientific techniques will provide a common frame-of-reference for management and contribute to a clearer cross-cultural articulation of long-term socio-ecological values for the Keppel Bay Islands. Additionally, both ‘natural’ and cultural values were described in the Australian Commonwealth government’s nomination of the GBR to UNESCO in 1981. Although not articulated well, this included a description of the seasonal use of marine resources in Aboriginal and Torres Strait Islander Peoples’ culture (GBRMPA 1981:16). Findings arising from this research will also serve to articulate a common-frame-of-reference, for which long-term cultural marine resource use can be clearly recognised.

More positively, traditional owner aspirations to care for Country (detailed in Dale et al. 2018), are already strongly supported by overarching international conventions promoting the conservation and resilience of biocultural systems. The Convention on Biological Diversity (CBD) AICHI targets summarises the global conservation aims agreed to by several countries, enforced 12 October 2014 (CBD 2018). Target 18 in the convention states:

> *[b]y 2020, the traditional knowledge, innovations and practices of indigenous and local communities relevant for the conservation and sustainable use of biodiversity, and their customary use of biological resources, are respected, subject to national legislation and relevant international obligations, and fully integrated and reflected in the implementation of the Convention with the full and effective participation of indigenous and local communities, at all relevant levels.*

Additionally, the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilisation, administered by the CBD, is a legal agreement on the use of genetic resources and the benefits arising from such use (CBD 2018). The protocol argues for transboundary cooperation to benefit sharing on ‘mutually agreed terms’, acknowledging TEK and ‘thereby contributing to the conservation and sustainable use of biodiversity’ (CBD 2018) (and see discussion in Tengö et al. 2014 for how the MEB fits into these conventions). Woppaburra’s Mazie Bay cultural resource use site presents a unique opportunity to gain insightful knowledge about long-term marine resource use, and how to plan for and implement resilience strategies. This research directly supports the efforts of local conservation initiatives, and national and international sustainability priorities.

1.8 Thesis Organisation

This thesis is organised in three parts. Part I includes Chapters 1-4 which introduces the context and underlying theoretical framework of the research. Chapter 1 has outlined the principals motivating the research inquiry into the Keppel Islands case study. Chapter 2 defines how an Historical Ecology framework can serve to guide an holistic approach to understanding long-term marine resource use. The GBR region and the Keppel Bay Islands ecology and cultural context are detailed in Chapter 3. Chapter 4 critiques methodological approaches to marine molluscs which have employed biometric, sclerochronological and biogeochemistry techniques in the past. Part II of the thesis, Chapters 5, 6 and 7, feature the biometric, sclerochronological, and stable isotope results for key molluscan species deriving from Woppaburra’s cultural resource use site. Part III, comprising Chapter 8, synthesises the findings and provides a summary of the socio-ecological dynamics at Mazie Bay since the mid-Holocene. The chapter concludes by discussing the implications of the research and significance of using deep time archives in resource use management and socio-ecological resilience initiatives.

1.9 Summary

Humanity depends on the conservation of the world's oceans for future prosperity which starts at grass-roots local level governance. Western trained scientists have grappled with the task of understanding and recording fisheries complexities within the Southern and Northern Hemispheres with some success, although shifting baselines and unequal power dynamics between cultural groups, has limited the capacity to evaluate long-term trends for ongoing conservation and resilience solutions. TEK is based on long-term practice and understandings of culture and ecology, which is integral to the success of management initiatives. Creating a 'shared knowledge sharing space' – an innovative MEB co-collaborative sphere, can initiate advanced understandings of long-term socio-ecological trajectories. The Keppel Bay Islands presents a unique case where advanced understandings can inform management initiatives and join the global discussion on resource management issues and successes.

2

Historical Ecology

2.0 Introduction

The framework directing this research is Historical Ecology. A key theme in Historical Ecology projects is the desire to understand resource depression, which is targeted for review in this chapter. Finding that resource use in socio-ecological settings are complex and dynamic, my review turns to the implications of applying multi-analytical techniques and multi-variable analyses in zooarchaeology. The Velondriake Historical Ecology project (Madagascar) and the Tombigbee River Historical Ecology project (United States of America) exemplifies some of the issues with, and yet significance of, generating appropriate applied zooarchaeological datasets for conservation management initiatives. Considering the Great Barrier Reef (GBR) more broadly, I reflect on how national and international conventions can use applied zooarchaeological baseline datasets to support management strategies and goals. I conclude by proposing an applied zooarchaeology model, working within the Historical Ecology framework for the Woppaburra Peoples' North Keppel Island cultural resource assemblage.

2.1 Background: Historical Ecology

Historical Ecology is based on principles defined by early 20th century cultural geographer, Carl Sauer. Sauer's theory defined 'landscape' to include 'both physical and cultural' phenomena (Sauer 1925). His emphasis on including human and cultural aspects into geography improved holistic interpretations of socio-ecological events. Sauer (1925) recognised landscapes to be in a 'continuous process of development or of dissolution and replacement', an important observation that anthropologist Julian Steward progressed in his ethnographic research. Steward's 'Cultural Ecology' is similar in approach to Sauer's, but has received criticism over the years for favouring technocentric explanations for change (i.e. that the human use of technologies primarily drove changes in the environment) (see Steward 1973, and see also Fitzhugh et al. 2019 for further discussion on related theoretical histories and comparisons). An important consideration of these earlier works, despite their limitations, is the way in which some aspects of human and environmental influences have contributed to total phenomena. Culture is a result of actions and beliefs in a human community that navigates and produces change, but this of course is only one mechanism.

As is often the case in Western scientifically-framed research, the role of humans is addressed separately to other potential drivers of change, or overlooked altogether (Head 2008). The externalism of humans from the environment is, as Head (2008:374; and see Ingold 2000) explains, limiting our ability to recognise and define multi-complexities which have shaped and continue to shape our world. These changes, which can be defined as the sequence of interactions and outcomes occurring within the biosphere, are consequences of complex human-environmental interrelationships that are 'inextricably embedded in all earth surface processes' (Head 2008:374). This explanation, the best description of the 'cultural landscape', is inclusive of earth-scapes (comprising organisms and terrain on dry land and the atmosphere) and aquatic-scapes (comprising organisms and terrain in marine and terrestrial waters) (see Head 2012 for in-depth criticisms and comprehensive definitions). It is important to be able to distinguish how variables have operated, and might perform, under a range of different driving forces – human, environmental, climatic, or combinations of these through time (Head 2008:374). The research program of Historical Ecology aims to incorporate these mechanisms to explain socio-ecological phenomena and provide practical outcomes of new knowledge to modern contexts.

In the 1980s Historical Ecology developed into a research program aimed at connecting physical science and social science research to investigate socio-ecology (Crumley 1993:xiv). Historical Ecology recognises humans as the keystone species but without bias to cultural explanations (Balée 1998, 2006; Crumley 1994; Crumley et al. 2017; Thompson and Waggoner 2013:2). The program encourages unlimited multi-variable testing, aiming to examine all assumptions equally until proven otherwise, thereby eliminating cultural or environmentally deterministic arguments (Balée 1998, 2006; Crumley 1994; Crumley et al. 2017; Isendhal 2016:142). Internal, external, direct and indirect drivers of change shape landscapes, seascapes and the cultural communities that live within those socio-ecological spheres. Faulkner (2013:3) explains that:

> *[t]he environment provides the framework that people have to live within, but it is how people structure their economic and social activities within that framework, depending on the configuration and availability of given resources, that promotes change and variability through time.*

Working within a Historical Ecology framework, we would expect to incorporate both tangible and intangible evidence to inform research questions (for example cultural materials and forms of verbal knowledge). In Sauer's earlier work, he expressed the importance of reviewing the timing of complex changes within socio-ecological environments. Historical Ecology aims to define changes using datasets derived from environments before, during, and after human interactions. Ultimately this encourages and allows for reconstructions built from palaeontological, archaeological, historic, and modern datasets (Rick and Lockwood 2013:47). These data can be interpreted at defined temporal and spatial scales or combined to facilitate longer-term understandings of socio-ecological interactions (Balée 1998, 2006; Crumley 1994; Crumley et al. 2017; Isendhal 2016:142). Datasets incorporated into historical ecological research are based on cyclic human-environmental interrelationships at the local and regional levels but are aimed at having practical application to address local, regional and global conservation issues (Balée 2006:82; Crumley et al. 2017; Isendhal 2016:142; Thompson and Waggoner 2013:2). Balée (1998:14-24) defines four essential postulates of Historical Ecology. These postulates are summarised below in Table 2.1.

Table 2.1 Postulates of Historical Ecology (after Balée 1998:14-24).

Postulate	Description
1	Most, if not all, environments have been interacted with by humans.
2	Human interaction in environments does not necessarily promote or demote the extinction or overabundance of a species.
3	Human socio-political systems affect the ecology of regional settings.
4	Long-term human-environmental interactions 'can be understood as total phenomena'.

Balée's (1998) postulates imply that in any given Historical Ecology case, complexity should be anticipated. Dincauze's (2000:78) four research principles offer further guidance for examining a range of questions in such contexts. Firstly, the major *variables* owing to the result of any or all four postulates outlined above must be identified. Secondly, investigation of the *mechanisms* driving variable outcomes should be verified. Thirdly, any *equifinalities* resulting from variables or mechanisms need to be identified and evaluated; and lastly, 'key to situational context[s] and systematic mechanisms' is the definition of sequential *chronologies*. These principles are particularly important in projects where the aim is to translate results into practical resource management and conservation applications. Indeed, addressing these principles in the construction of historical ecologies and using long time-series datasets is fundamental when aiming to achieve conservation outcomes (Lyman 2012, 2015; Rick and Lockwood 2013:48). Three other important considerations are also offered by Dincauze (2000:78): the importance of *recovery* methods, the clear identification of *preservation* biases in sample assemblages, and attention to the fact that *ideologies* guiding decision-making processes in past human communities are not always readily transparent, even in cases where Traditional Ecological Knowledge (TEK) might be available (see firestick farming example in Chapter 1 and consider equifinal results). These considerations might also pose difficulties with presenting datasets on appropriate temporal and spatial scales (discussed in more detail below). Linking time-series datasets for long term understandings in Historical Ecology projects has been a limitation in the past (e.g. linking archaeological datasets to historical datasets) (Rick and Lockwood 2013:46). Therefore, datasets that can be scaled to adequate *resolutions* for meaningful interpretations should also be accounted for.

2.2 Resource Use Dynamics and Applied Zooarchaeology

Since the earliest human interactions with aquatic environments, complex patterns and processes have woven multifaceted records of socio-ecological events. Archaeological research assessing the dynamics in human-aquatic resource use has had a long history but has also been subject to significant critique. The largest criticisms by the wider research community are that zooarchaeological datasets often suffer from (after Erlandson and Rick 2010:234; Peacock et al. 2012; Pennings 2013:167-175):

- a lack of appropriate sample types and sizes,
- materials subjected to taphonomic processes,
- a lack of species ecology knowledge and integration into methodological applications,
- insufficient knowledge to account for environmental complexities, and methods of testing for those variables using faunal remains (e.g. temperature, salinity and geomorphological changes), and;
- a common frame-of-reference for transparent cross-cultural and interdisciplinary communication.

Non-archaeological interpretations of human-environmental interactions have generally assumed that either Indigenous peoples had little or no impact on the environment in the past, or that available archaeological datasets are culturally biased (Fitzpatrick and Keegan 2007:40; see the ‘cultural filter’ in Peacock et al. 2012; Pennings 2013:170). Importantly, as Fitzpatrick and Keegan (2007:40) suitably describe, archaeology is a ‘nexus’ where social science meets natural science, and is where cross-cultural and multidisciplinary efforts can collaborate to address common conservation goals (Peacock et al. 2012, 2018; Peacock and Seltzer 2008; Mitchell and Peacock 2014; for discussion see Rick and Lockwood 2013). Contemporary datasets often lack the appropriate long-term foundations to reconstruct the dynamics of human resource use for future resource resilience forecasting (see Chapter 1 for the shifting baselines syndrome, and see Pauly 1995). Importantly, archaeological research has the advantage of recording human-environmental interactions in the past that could still be contributing to ecological patterns and processes in contemporary contexts (Pennings 2013:170). While Historical Ecology situates the research focus, applied zooarchaeology contributes datasets to achieve common goals within the framework.

Applied zooarchaeology, or conservation zooarchaeology, aims to establish long-term datasets to identify potential socio-ecological changes that occurred in the deep past (Peacock et al. 2012:1446; Wolverton and Lyman 2012:1, see also Barnosky et al. 2017, Dietl et al. 2015, Lyman 2012, 2015, 2016). These types of datasets can be used to reconstruct human-resource use dynamics in the following ways: species presence or absence data, species abundance and diversity indices (including potentially extinct species), species range distributions and mapping, climatic and/or environmental change influencing species populations, human use of species, human management of species, and other socio-cultural connections to species (e.g. spiritual and cosmological beliefs) (see Mitchell and Peacock 2014; Peacock 2012:46; Peacock et al. 2018; Wolverton and Lyman 2012). Data such as these are useful for identifying and negating the shifting baselines syndrome and make invaluable contributions to the planning stages in conservation management. Strategies to overcome limitations in applied zooarchaeological datasets, as described above, are best implemented by integrating multi-disciplinary approaches to test and communicate results. When this happens, the kinds of issues that can be addressed include habitat preservation and maintenance, species breeding and reintroductions, fisheries catch limits and no take zoning, establishment of traditional use of marine resources, ranger and public training and education, and support for national heritage or United Nations Educational, Scientific and Cultural Organisation (UNESCO) register listings (Peacock 2012; Peacock et al. 2018; Rick et al. 2016:6572). A key research theme with consideration to the conservation needs and issues listed above centres on the degree of resource depression. This aspect is usually, but not exclusively, tackled on species-by-species, site-by-site or case-by-case bases.

2.3 Resource Depression, Resource Exploitation and Extinction

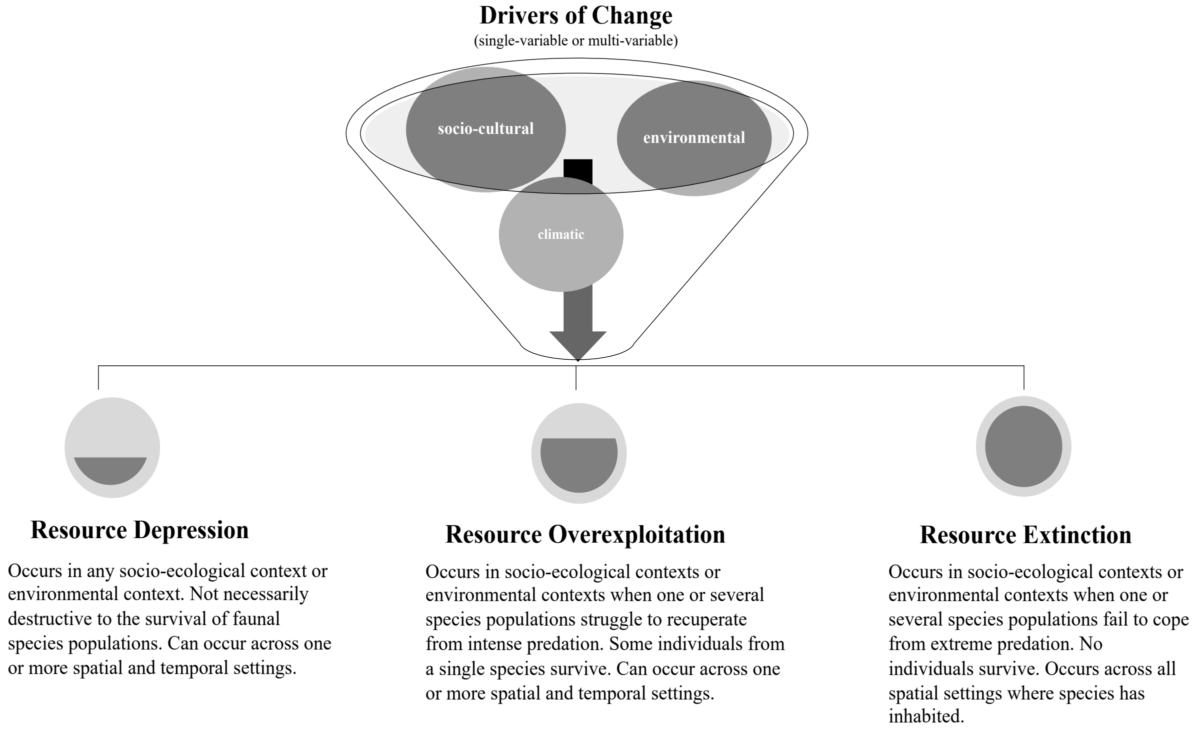
Resource depression is one of the main foci in Historical Ecology and applied zooarchaeological research. Resource depression is defined as 'the reduction of the abundance or availability' of particular faunal resources in the environment (Nagaoka 2002:420; and see e.g. Lasiak 1991a, 1991b). Resource depression shows an alteration to a species population where reductions might undermine resilience strategies. Table 2.2 defines the three main types of resource depression. Debates on the mechanisms or drivers of resource use leading to depression, overexploitation or extinction are contentious. In zooarchaeological research, previous theoretical ideologies have fallen into one of a series of archetypes. The *Homo devastans* (see Balée 1998) camp argues for the constant and unfailing destruction of resources by humanity, ultimately resulting in extinction. Alternatively, the 'Ecologically Noble Savage' camp argues for unfailing sustainability of resources by humanity which constantly aims to achieve a state of socio-ecological homeostasis (see Hames 2007 and Rowland 2004 for review; and see Alvard 1993 and Redford 1991). In some cases, resource depression might be characterised as sustainable through intended conservation practices, and/or, through 'epiphenomenal' sustainability (based on cosmological or spiritual lore collection and consumption taboos) (for comprehensive of epiphenomenal sustainability definition see Smith and Wishnie 2000; see also Jones et al. 2016) or combinations of these across changing spatial and temporal scales. Ruddle et al. (1992) provides a good account of the customary sustainable management of resources at Morovo Lagoon, Solomon Islands. Traditional allocations of space across these customary managed systems include resources in both land and seascapes, which are defined as 'integrated corporate estates' (Ruddle et al. 1992:251). Another example, from New Zealand, shows how integrated corporate estates have precedence in long-term socio-ecological trajectories.

Table 2.2 Types of resource depression after Charnov et al. (1976) and Nagaoka (2002).

Depression Type	Description	Example	Encounter Outcome
Exploitation	Population alteration due to predation.	Harvesting by humans or natural predators such as fish, birds, crustaceans, cephalopods, marine mammals.	Populations can either be sustained, overexploited, or in extreme cases depleted to the point of extinction.
Behavioural	Prey behaviour varies due to increased predator threats or environmental activity.	Sensory alertness increases for protection such as sight, smell and touch to ensure ongoing survival.	Scarcity of prey due to adopted protective measures.
Microhabitat	Prey availability changes due to population relocation from either predator impacts or habitat transformation.	Prey sensitivity actions into locomotion or burrowing to ensure ongoing survival.	Movement of prey to new locations due to microhabitat impacts.

In Maori culture, *rahui* is a term defining the intentional customary management of resources. Evidence showing *rahui* from non-contemporary cultural sites is debated by both Maori and non-Maori people invested in modern conservation management interests of New Zealand (see discussion in Szabó 1999 and citations included in Anderson 1997; Best 1942; Gardner 1988; Orbell and Moon 1985). Though the intensity of these debates have relevance dating back to the early 1840s signing of the *Treaty of Waitangi* between the British Crown and Maori Chiefs, approaches to contemporary fisheries management in New Zealand, of late, has somewhat progressed. After decades-long arguments surrounding sovereignty, land and resource rights, and after a review of communications setting out rights and responsibilities, the *Treaty of Waitangi* was re-signed in 1974. The Muriwhenua Fishing Report (see Waitangi Tribunal 1988) delivers a comprehensive review of these communications and expectations with respect to the *Treaty of Waitangi Act 1975* and fisheries management, now under jurisdiction by the New Zealand *Fisheries Act 1996*. Despite more recent and likely ongoing amendments to the *Treaty of Waitangi Act 1975* (e.g. 1985 amendment) and the New Zealand *Fisheries Act 1996*, the management of marine resources through *rahui* can now be legally instilled by honouring the agreed principles - ‘partnership, participation, protection’.

Underpinning where the governance of marine resources sits today with the people of New Zealand is a long and rich history of non-linear complex relationships between Maori, non-Maori and coastal marine environments. One of the prevailing findings, fuelling a need for a review of the contemporary management of resources, was of course the finding of declining and overexploited marine faunal populations. Oyster beds were the first of these resources to undergo rapid population decline during the historic period due to intense harvesting for commercial interests (Waitangi Tribunal 1988:xv-xvi). Following protests about declines in marine fauna, outcomes favoured the implementation of a conservation ethic through an amalgamation of Maori TEK (including *rahui*) and non-traditional understandings – key ingredients for successful grass-roots community-based resource stewardship. As Chapter 1 demonstrated, successful resource management strategies are built upon constructive Multiple Evidence Based (MEB) responses and decisions that are centred on the need for a conservation ethic, usually but not explicitly linked to the observation of past resource depletion events (McGoodwin 2006:180; Szabó 1999:54). Figure 2.1 conceptualises resource depression, resource overexploitation, and resource extinction scenarios over any given spatial and/or temporal context. Single and multi-variables driving changes should be identified and examined on a species by species basis, as species tolerances and responses to variables likely differ. For example, under certain conditions species that exhibit greater resilience to turbid conditions might suffer, whereas this may not be the case for other species (Krebs 1985).



Resource Depression

Occurs in any socio-ecological context or environmental context. Not necessarily destructive to the survival of faunal species populations. Can occur across one or more spatial and temporal settings.

Resource Overexploitation

Occurs in socio-ecological contexts or environmental contexts when one or several species populations struggle to recuperate from intense predation. Some individuals from a single species survive. Can occur across one or more spatial and temporal settings.

Resource Extinction

Occurs in socio-ecological contexts or environmental contexts when one or several species populations fail to cope from extreme predation. No individuals survive. Occurs across all spatial settings where species has inhabited.

Figure 2.1 Conceptualisation diagram for resource depression, resource overexploitation and resource extinction.

On the theme of resource depression, linearity is related to the response time of species populations but does not necessarily suggest human harvesting practices were linear or non-complex. In shorter-term situations where variables might remain unchanged, however, and a species does not have time to develop anti-predation strategies, a case for linearity might be appropriate. Occasions such as these are likely rare but worth investigating because they are often isolated examples that signal extreme events. For instance, an intense tropical storm that influenced the availability of faunal taxa might lead to changed human resource harvesting patterns or other behaviours such as site re-location. Table 2.3 explores these themes further.

Table 2.3 Themes in resource depression, resource overexploitation, and resource extinction scenarios.

Theme	Linear	Non-Linear	Cyclic
Drivers	Constant but unchanged single-variable or multi-variables.	Constant but changing single-variable or multi-variables.	Repetitive changing single-variable or multi-variable drivers.
Temporal Context	Single event.	Within any temporal period.	Predictable recurring temporal phases.
Frequency	Typically fast, single hit.	Fast or slow, multiple hits.	Typically slow, multiple hits.
Example	Harvesting by humans, or intense geomorphological change such as land clearing or logging.	Harvesting by humans and oscillating sea-levels.	Constant or periodic harvesting by humans, or seasonal storms such as tropical cyclones.

Non-linear or cyclic explanations for change are more traditionally employed in Historical Ecology and applied zooarchaeology with the use of available palaeoclimate and palaeoenvironmental models (Balée 2006; Cosgrove 1995). In Cosgrove's (1995) assessment of Pleistocene sites in southeast and southwest Tasmania, Australia, he posits that employment of 'mega-scale' or regional palaeoclimate/palaeoenvironmental modelling in the interpretation of cultural site and resource use is highly problematic. He explains that attempting to fit regional models, built on sets of their own 'disciplinary assumptions', to local scales comes at the expense of misinterpreting complex socio-ecological patterns and processes that might show very different explanations for change (Cosgrove 1995:94). At the time of Cosgrove's assessment of Tasmanian sites, access to newly available analytical techniques which might have served to 'cross-check' local socio-ecological trajectories with regional models were limited. Nevertheless, he makes a good point in explaining that without adopting cautionary approaches, fitting regional models to local cases can be notoriously difficult, insightfully arguing that interpretations should be based on multi-site analyses (Cosgrove 1995:94). Socio-cultural interpretations suffer similar consequences if caution is not exercised with respect to scale and resolution. In comparison to deep time archives, socio-cultural interpretations can potentially reflect shorter-term 'low resolution' or 'coarse scale[d]' analogies (Faulkner et al. 2018a:77). Further complications present themselves in these instances when faced with biased recordings (for e.g. see Moss' 1993:637 review of early Tlingit use of faunal resources).

In the example Faulkner et al. (2018a) use in the zooarchaeological analysis of selected faunal remain sites in Zanzibar, eastern Africa, they identify that uncritically applying shorter-term modern analogies for longer-term archives dishonours socio-ecological variability through deep time and space. For instance, a consequence of doing so following common disciplinary assumptions about the role of small-bodied resources, might infer molluscs were 'secondary, fallback, or low-ranked resources'

(Faulkner et al. 2018b:2; Moss 1993), when in some cases they might not have been (for the GBR, see Barker 2004 who argues molluscs were used as a secondary resource at the Whitsunday Islands). The effects of single or cumulative variables, that are ongoing or ending in equifinal conditions (see also the *holon* effect in Rockman 2010:9) and resembling certain socio-cultural, or socio-ecological, or ecological conditions in these instances, risk being misinterpreted in place of other explanations. For example, explanations might show logic in the short-term or long-term use of molluscs as 'key low-cost, high return buffering resources' harvested according to environmental conditions (e.g. tidal cycles) and socio-demographic needs (e.g. population increase) (Faulkner et al. 2018a:77-78 and references within) rather than having been used as secondary resources. Other explanations might entail eating taboos placed on molluscs due to toxicity (e.g. from red tide events), during spawning (e.g. due to undesirable taste, tenderness, and meat content), consumption or harvesting norms which symbolises social status (e.g. gendered divisions of labour, and/or association to 'poor foods' and 'rich foods'), or periodic ceremonial consumption events (e.g. seasonal ceremonial feasting of chitons among Manhoust women) (Moss 1993 provides a good discussion covering these themes using Tlingit examples). Therefore, the use of targeted analyses of materials and analogies is an appropriate approach through which to tease out socio-ecological complexities (Faulkner et al. 2018a:77). I return to this point later (and refer to Figure 2.1 illustrating socio-cultural, environmental, climatic or combinations of these variables, driving resource population outcomes). Indeed, 'cumulative effect' models agree with this approach (Crain et al. 2009; Fitzhugh et al. 2019).

2.3.1 Human Behavioural Ecology and Optimal Foraging Theory

Human Behavioural Ecology (HBE) approaches are often employed in applied zooarchaeology to assist in the explanation of human resource use patterns (for examples see Bird and O'Connell 2006; Codding et al. 2014b; Nagaoka 2002; Zeder 2012). Zooarchaeological studies adopting HBE models recognise human behaviour as the key driver of change in socio-ecological contexts. In HBE, Optimal Foraging Theory (OFT) assumes humans behave 'to maximise the net rate of energy or nutrients per unit foraging time' (Zeder 2012:244), and implies that continued *optimal* resource procurement may lead to resource depression, overexploitation, and perhaps even extinction of taxa (for key arguments and extensive applications see Bird and O'Connell 2006; Charnov 1976; Gremillion 2002; Levi et al. 2011; Mannino and Thomas 2001; Nagaoka 2002; Smith 1983; Smith and Winterhalder 1992; Whitaker 2008; Winterhalder 1986; Winterhalder and Smith 2000; Zeder 2012 among others). *Optimality* in these examples is defined as the ability for foragers to maximise the net rate of energy or calories in exchange for the minimal expenditure of energy required for securing prey. Prey species are generally considered to be lower ranked if they require more energy to capture or process with lower calorific returns. Higher-ranking species are considered easier to capture and process, and have higher calorific return rates. OFT predicts that as one or more high-ranked species decline, driven by socio-ecological or climatic or environmental variables, foragers will exploit lower-ranked species on encounter. New Zealand's moa case study offers an example for the use of OFT models in applied archaeological research.

Moa, megafaunal birds in the family Dinornithidae, were an important food and ceremonial resource during the initial human occupation period of New Zealand. Their remains are described to be of 'high cultural value' - tools and jewellery carved from the bones of moa, eggshells used to carry water, items in burial sites, and other moa remains recovered from cultural sites shows the extent of their use (Oskam et al. 2012). With each animal weighing between 20-250kg, not more than 2.5m high and having short home-ranges, they would have made an ideal predatory target (Allentoft et al. 2014:4922; Anderson 1989:144; Holdaway and Jacomb 2000; Nagaoka 2001:103). Moa were exploited regardless of ontogenetic age, sex, or sexual maturity (including the eggs), thereby restricting populations' ability to rebound from exploitation (Anderson 1989; Holdaway et al. 2014; Oskam et al. 2012:41). Nine species of moa on the islands of New Zealand went extinct during the late-Holocene over a period of ~150 years, falling in line with the 'rapid extinction model', contrary to 'gradual extinction model' arguments (Holdaway et al. 2014:7; Holdaway and Jacomb 2000:2250; Perry et al. 2014:126; also see Wood 2008; and see Anderson 1988, 1989 for earlier arguments). The drivers for the extinction of moa are now relatively undisputed – deforestation caused by clearing and burning, and continued human overexploitation (Allentoft et al. 2014; Anderson 1988, 1989; Holdaway and Jacomb 2000; Nagaoka 2001, 2005; Oskam et al. 2012; Perry et al. 2014). It is still not clear however, whether certain species were driven to extinction before others (Perry et al. 2014:126), the exact timing of each species extinction; and, what human population sizes might have looked like (currently modelled to be not more than 2000 people at any given time) (Holdaway et al. 2014:3, 4).

Using foraging models derived from OFT, Nagaoka (2005:1328) identifies moa as high-ranked taxa because of their calorific return rate in meat and bone marrow, their grease content, and bone utility (i.e. for artefact manufacture). As moa populations initially decreased at coastal locales on the North and South islands, hunting strategies that incorporated longer travel times into mountainous inland areas were adopted by foragers (Anderson 1989:144; Nagaoka 2005:1337). During the exploitation of coastal and inland moa populations, other taxa were also used, but not to the same extent (Anderson 1989:143, 144). At the demise of the last remaining moa, diet breadth increased leading to more intensive use of other faunal and floral taxa (Nagaoka 2001). At 'classic period' sites, no moa remains are found, although mollusc, fish and plant remains are in abundance (Holdaway and Jacomb 2000). These findings are based on taxonomic quantification and statistical models, such as abundance and diversity measures that estimate species richness and evenness from the period/s of human occupation (see Nagaoka 2001, 2005). Assumption-based OFT principles infer here, that all moa populations were in a state of relative stability before human settlement, but were targeted by humans as 'optimal' choices because of their large body size (Nagaoka 2001, 2005; Perry et al. 2014). As the discussion below demonstrates, large bodied fauna are not always targeted as the optimal choice by foragers.

OFT studies typically accept from the outset that large bodied fauna are higher-ranking in terms of energy return (Broughton 1997, 2002; Wolverton et al. 2015). Rick and Erlandson (2000) provide a compelling example for the use of 'small' fish from Santa Barbara, southern California. Their example, in contradistinction, makes the argument that smaller resources, when harvested en-mass, can in fact be high-ranking. They show small bodied fish, including sardines, herrings, and surfperch, were captured in large numbers from the Santa Barbara area using netting technologies beginning ~8300 years ago (Rick and Erlandson 2000:627, 630). Nets were used to catch smaller game, and spears and fishing lines with hooks, were probably used to catch other marine fauna (Rick and Erlandson 2000:627). In addition to strategic use of technologies, other debates have argued for increases in human populations, changes to social organisation, or environmental and climatic shifts either influencing the acceleration of, or impediment, of faunal growth (Rick and Erlandson 2000:630). In different locations and temporal contexts, other datasets have shown no size selection preference for species (i.e. gleaning), or, explicit size selection regardless of species (e.g. Anderson's 1981 Black Rocks, New Zealand, case study). Size and species preferences are dependent on (1) the availability of resources to the foraging community, and (2) the intention for the use of resources, based on decision making processes by the foraging community (Ingold 2000:27-39) (e.g. taste or tenderness qualities for food, or for artefact or tool manufacture). When models such as those from OFT are used in zooarchaeological research, which are borrowed from ecology and typically applied to non-human cases, they either (1) do not acknowledge culture as a powerful enough force to result in change, or (2) use culture, without invoking its complexities through multi-variable analysis to explain change, which then creates a basis for ethnocentrically biased arguments (Anderson 2009; Balée 1998:13; Ingold 2000:31).

In some contexts, the principles of HBE models might be useful in describing human resource use patterns. In others, these models are probably more beneficial in the exploration of data but best used to justify counter arguments; for example, when more than one socio-ecological variable is found to have influenced human resource use. Neo-Darwinian models, including those in OFT which are rooted in natural selection, are reductionist by nature and therefore deny explanation for socio-cultural influences for change in any given context. TEK (defined in Chapter 1, section 1.2) is akin to the same principles Ingold (2000:37) observes for culture itself - a multi-generational non-linear entity that ensures the 'practical involvement [of humans in contexts e.g. resource use] … under the guidance of more experienced mentors'. For this reason, and in pursuit of arguing the relevance of and appropriate implementation of TEK in modern resource management, OFT is not well suited for application in isolation from other explanations and therefore, projects situated within Historical Ecology. Multi-variable analysis which includes the exploration of cultural, environmental and climatic mechanisms influencing change, without prior assumptions, is more appropriate.

2.3.2 The Need for Multi-Variable Analyses

Identifying variables that influence change in socio-ecological settings is complex. The examination of environmental and climatic variables is critical because they influence changes in species populations, species habitats, species growth tolerances, and how human behaviour is potentially altered in response to these (e.g. hunting strategies, resource locales). Environmental variables contributing to change might include but are not limited to, an increase or decrease in sea surface or atmospheric temperatures (i.e. climate change), salinity, sea-level rise and fall, tropical storms or earthquakes. Consideration must also be given to situations where one species might suffer resource depression or overexploitation, but which triggers another species population to benefit, in the long or short term, from higher accessibility to food, habitat space, or other environmental conditions accelerating growth (Krebs 1985). At these intervals, species population size, body size, and recruitment patterns may undergo changes.

An example from the GBR shows population irruptions of the coral-destroying *Acanthaster solaris* (crown-of-thorns starfish). The overabundance of *A. solaris* has devastating effects on established and living corals, which in turn influences the health of other marine resources such as fish and molluscs - important reef builders (Wilmes et al. 2020a; 2020b). Research into the causes of *A. solaris* outbreaks is ongoing. The likely influences include a heightened supply of nutrients from warmer water temperatures promoting spawning (~60 million eggs per female), reductions in predatory fish populations, and low populations of *Charonia tritonis* (Triton shell) due to human overharvesting – a key predator of the crown-of-thorns starfish (Andean 1977; Babcock et al. 2016; GBRMPA 2018b; and see e.g. case studies in Wilmes et al. 2020a, 2020b). In the Caribbean, human harvesting of *Strombus pugilis* over long periods resulted in changes to their body sizes at sexual maturity (O'Dea et al. 2014). This 'evolutionary change' has flow-on ecological and population structure implications (O'Dea et al. 2014). Importantly, these findings were made possible using *S. pugilis* data from pre-human, deep time and modern times, allowing a long-term reconstruction of key variables and mechanisms driving this change (O'Dea et al. 2014). O'Dea et al. (2014:4) identify that size-selective evolution due to human harvesting only occurred in modern contexts, although the species from the study location, Bocas del Toro, was subjected to either 'persistent low-intensity harvesting' or 'ephemeral bursts of more intensive harvesting' through time. This research employed key biological and ecological information for the species, used metrical values to record shell length and lip thicknesses, and incorporated biological examinations of the soft tissues of live samples.

Returning again to the case of New Zealand moa, while it is clear moa extinctions were driven by a short and intense period of human overexploitation and habitat alterations, other aspects of moa survivorship, prior to and during human occupation, have not been adequately addressed. Models based on aDNA analyses show that moa populations were stable before human occupation (Allentoft 2014; see Gemmell et al. 2004 for mtDNA counter argument; and see Perry et al. 2014), but moa growth success in response to climatic and environmental variables is not yet defined. These data have important consequences for the way in which we refine understandings for how and what variables contributed to the extinction of moa. For example, if palaeoclimatic or palaeoenvironmental conditions had a negative influence on the growth of moa populations prior to and/or during human occupation, then these factors need to be considered in terms of moa life history traits which might include resilience adaptations.

Wood (2008) engaged in a preliminary investigation of moa foraging patterns by looking at seasonal fruits and pollens in coprolites collected from nests in rock shelters. Seasonal food and nutrient intake data such as these might be translatable to confirm the stability of moa populations at certain periods of time (i.e. in this case spring to summer) (Wood 2008) or verify any evolutionary changes in growth or population dynamics. Identifying when and how species respond to different variables, and how and if species activate resilience strategies, is at the crux of knowledge needed to implement effective resource management strategies for other populations of species surviving in the modern world. Applied zooarchaeological research is significant for this very reason. Identifying human and environmental drivers of change on species populations, or combinations of these factors, are key for forecasting future resource resilience before irreversible alterations to species populations or extinctions occur. In response to this theme, and more recently with the availability of advanced analytical techniques, several notable applied zooarchaeology cases working within a Historical Ecology framework are worth discussing.

2.4 Applied Zooarchaeology Datasets in Historical Ecology Projects

Western scientific understandings of socio-ecological phenomena have evolved dramatically over the last few centuries. *Homo devastans* and noble savage debates, and the view that environmental settings were pristine before human occupation, or explicitly European colonisation in naïve landscapes, are static representations devoid of explanations encompassing the dynamic interrelationships and complexities within socio-ecological systems. The realisation that socio-ecological systems embody a multitude of situations and outcomes across different geographic locations and temporal periods makes our job, as stewards for the delivery of a new type of knowledge which incorporates Western and non-Western understandings, more challenging. Nevertheless, nuanced understandings pave the way for informed, agreed, and strategic options for managing socio-ecological systems into the future. Applied zooarchaeology datasets are uniquely situated because they can provide key 'response information' for how and why human communities, and resource populations, responded to a set or sets of variables through time. For example, deep time materials might signal human population dispersals and colonisation to new locales, the human use of flora and faunal resources, the transportation of flora and fauna to new locales (translocation), changes to resource populations due to human or climatic or environmental influences, domestication and horticultural practices using native or introduced species, the introduction of new or different harvesting or resource processing technologies among other possibilities (see Braje et al. 2017:287-288; Douglass et al. 2019b:264).

Available palaeoclimate/palaeoenvironmental models assembled by research teams, sometimes external to the Historical Ecology project at hand, are commonly used in applied zooarchaeology cases to explain human resource use. Difficulties with this approach include the overlaying of large-scale regional palaeoclimate/palaeoenvironmental models to explain changes in local settings (Cosgrove 1995). Douglass and Zinke (2015:274) also acknowledge difficulties with scale and resolution, but with their applied zooarchaeology project in Madagascar, aim to incorporate local site-specific datasets to 'cross-check' regional scale palaeoclimate/palaeoenvironmental models. Importantly, as Douglass and Zinke (2015:270) explain, 'correlation does not necessarily imply causation'. So, while high-resolution datasets extracted from other materials, such as historical growth rates from cores of massive *Porites* corals, are important for uniting local and regionally scaled explanations of palaeoclimatic/palaeoenvironmental change, they do not provide direct evidence for socio-ecological interactions or outcomes of interactive processes. High-resolution datasets extracted from faunal remains capable of explaining local socio-ecological dynamics consequently become primary datasets, that need to be linked with regional palaeoclimate and palaeoenvironmental models for holistic interpretations.

2.4.1 Madagascar: Humans in a Highly Biodiverse Hotspot

Madagascar is known for its high faunal biodiversity, but also known for loss of megafauna and certain microfauna within the last ~2000 years (Anderson et al. 2018; Douglass 2017; Douglass et al. 2018; Douglass et al. 2019b; Douglass and Zinke 2015; Vences et al. 2009). Reasons for the extinction of Madagascan megafauna, like many megafaunal extinction debates elsewhere, are highly contentious (see Godfrey et al. 2019 for a comprehensive review). Elephant birds (Aepyornithidae), giant tortoise (*Aldabrachelys grandidieri*), pygmy hippo (*Hippopotamus lemerlei*) and lemurs (Lemuridae) are some of the taxa that have received attention in applied zooarchaeological research. In response to faunal population depletion in past and present contexts, and issues faced by modern communities living within Madagascar, ongoing research is now aimed at being situated within a Historical Ecology framework to assist in the conservation of existing resources and for improving the livelihoods of local peoples (Douglass et al. 2019b:261). The known history of Madagascar paints a multidimensional picture of a slow-moving island-scape which underwent highly variable climatic and environmental shifts juxtaposed against multiple waves of human migrations through time (Douglass and Zinke 2015:270, 281-283). As we know it today, Madagascar shares similar conditions to that of other tropical islands – an annual monsoon season (December-March) with the likelihood of tropical storms, extensive mangrove and coral reef habitats, and dominant reliance on marine resources by local human communities (Douglass 2017; Douglass et al. 2018; Douglass and Zinke 2015).

Applied zooarchaeological research in the southwest of Madagascar reveals human occupation since at least c. 2000 cal BP; however, more recent investigations suggest human occupation might have been present since the mid-Holocene (see Anderson et al. 2018, 2019; Dewar 2014; Douglass et al. 2019a; Mitchell 2019). High-resolution datasets extracted from faunal taxa using innovative analytical techniques have shaped new understandings about past socio-ecological conditions in Madagascar. For example, aDNA bulk bone metabarcoding of fish remains improved the visibility of taxonomic identifications by 35%, allowing better abundance and diversity approximations, resource habitat type interpretations, human trade and exchange patterns, and insight into the use of fishing technologies (Douglass et al. 2018:123; Douglass et al. 2019b:266; Grealy et al. 2016). Other examples of research have concentrated on butchering signatures on terrestrial megafauna bone remains, sedimentology, and human occupation chronologies (Anderson et al. 2018); stable isotope ($^{15}N/^{14}N$) values on terrestrial megafauna and the potential impact of aridification and/or deforestation (Crowley et al. 2017); stable isotope (^{13}C, $^{18}O/^{16}O$) values on stalagmites to model climate and megafauna population collapses (Godfrey et al. 2019); and amino acid racemisation and stable isotope (^{13}C, $^{18}O/^{16}O$) analysis on elephant bird eggshells (Clarke et al. 2006). These studies demonstrate the application of multi-disciplinary and multi-analytical techniques to the Madagascan Historical Ecology case. However, despite the importance of marine resources in contemporary Madagascan communities and need for baseline datasets to inform contemporary resource management initiatives, no analytical techniques, excluding aDNA sequencing on fish taxa, have been applied to marine fauna (Douglass et al. 2019b:266).

The zooarchaeological record in Madagascar presents a similar situation to that of the New Zealand moa case, where datasets show early use of terrestrial megafauna followed by heightened use of marine resources (Douglass 2017:351). Fish and molluscs were primary targets in the post-megafaunal period in Madagascar, giving rise to 'specialised shellfishing' practices (Douglass 2017:351). Key response information demonstrating why and how marine taxa responded in socio-ecological conditions can be examined by applying multi-analytical techniques to fauna cultural materials (Douglass and Zinke 2015; Douglass et al. 2018; Douglass et al. 2019b). High-resolution stable isotope analyses applied to marine taxa from Madagascan deep time deposits have been proposed as a means to model food-webs, identify possible trophic cascades, organism growth responses, seasonal resource use by humans, and local climate reconstructions, but results are yet to be reported (Douglass et al. 2018:123; Douglass et al. 2019b:266). These datasets are critical for providing local socio-ecological signatures useful for cross-checking with other available local datasets (e.g. from coral cores), regional models (e.g. palaeoclimate proxies), and ultimately useful for informing fisheries management. Assuredly, evidence from multiple sites and using multiple taxa is ideal for untangling complexities revealed in such datasets. Currently, limited fish otolith (i.e. middle ear bones) samples recovered from southwest Madagascan sites and proposed for such studies, make the identification of seasonal growth trends and modelling climate proxies using biogeochemical techniques problematic (n=3 across 3 site locations) (Douglass et al. 2018:129). Molluscan remains, on the other hand, are reported to be more numerous and better preserved across southwest Madagascan sites (e.g. see Douglass 2017).

Of the molluscan remains recovered from Velondriake, southwest Madagascar, several species appear promising for the application of biogeochemical techniques including sclerochronology and stable isotope analyses. Faunal remain quantifications, including fragments from 6 cultural sites shows an exhaustive archive of *Onithochiton literatus* (chiton) fragments (NISP=15742) in comparison to bivalves (NISP=3980) and gastropods (NISP=12343) (Douglass 2017:348). Fragment or NISP counts are reported as above but the Minimum Number of Individuals (MNIs), indicative of individual animal counts, are not. The remains of *O. literatus* appear across all 6 sites with more than half, (i.e., 65%) appearing unburnt (Douglass 2017:348), making the species a possible candidate for biogeochemical analyses and ideal for inter-site comparisons. Despite chiton skeletal structures remaining unchanged for at least 300 million years (Sigwart 2009), taphonomic impacts including but not limited to diagenesis and dissolution would need to be examined on each sample to render biogeochemical testing appropriate. Results could potentially value-add to the Madagascar Historical Ecology project by:

(1) construction of high-resolution local and *in situ* palaeoclimate proxies such as sea surface temperatures (SSTs) and sea surface salinities (SSSs), possibly comparable to other available datasets and regional models,

(2) further explanation of taxonomic variation at Madagascan sites due to geomorphological shifts or human resource use patterns. Douglass and Zinke (2015:286) explain that '[t]he region's biota is highly endemic and varies according to the underlying geology (Du Puy and Moat 2003)'. *Onithochiton literatus* is not endemic to Madagascar but is a shallow rocky shore species that may provide a valuable link to geomorphological processes and sea-level oscillations. Samples may also occur in palaeontological deposits useful for longer-term comparisons. Comparisons to endemic faunal datasets might refine interpretations of socio-ecological conditions that shaped the presence or absence of taxa through time, and;

(3) the seasonal use of *O. literatus* and inferences about the seasonal use of other taxa by human communities. Results might confirm if Velondriake rock shelters or other sites were utilised periodically as seasonal foraging camps (see Douglass 2017:338), or occupied permanently but with seasonal use of resources.

When considered with ethnographic evidence and TEK, investigations might confirm or consider alternate uses for *O. literatus* - other than the resource being harvested as a famine or 'starvation food' (Douglass 2017:350). Even though the appearance of *O. literatus* in one deposit coincides with 'a degree of poverty' through observation of artefact types (Douglass 2017:350), alternate explanations for the use of the species at this site and at other sites during different temporal phases is possible. For instance, chitons could have been used as a 'snack food for children' (Douglass 2017:350), as bait for fishing, for use as a traditional medicine or for combinations of these uses (Herbert et al. 2003:339). The use of chitons in traditional medicine and magico-medicine practices is common in Africa today – they are harvested from wild populations and sold dried or alive in markets, and traded across local, regional, and international borders (Herbert et al. 2003; Kyle et al. 1997). They are highly valued commodities, so much so that conservation concerns exist for some species (Herbert et al. 2003; Kyle et al. 1997). *O. literatus* is the most common species for sale in South African market stalls (Herbert et al. 2003). Pharmaceutical research of Persian Gulf chitons confirms they are a rich source of antioxidants that contain 20 times the amount of iron (Fe) than some crustaceans (Rasti et al. 2017:366). Other properties in chitons, such as chitin and chitosan (fibre) contained in chiton shell valves and soft anatomy components, show 'antimicrobial activity' (anti-bacterial properties), 'wound healing properties', and 'haemostatic activity' (the ability to stop haemorrhaging) (Rasti et al. 2017:367 and references within).

While *O. literatus* might be an interesting candidate for biogeochemical and socio-cultural examinations, other molluscan species might also prove viable for multi-analytical analyses. Douglass and Zinke (2015:281) explain that '[t]he southwest coast of Madagascar presents an especially good opportunity to explore land-sea connections because of the rich archaeological and palaeontological remains that can be used to ground-truth regional climate records'. In cases elsewhere, biogeochemical analyses of mollusc shells have been coupled with other techniques to interrogate palaeoclimatic and palaeoenvironmental change. Indeed, the analytical techniques Peacock and colleagues have applied to the remains of mussel shells, has proven valuable for the Tombigbee River Historical Ecology project.

2.4.2 Tombigbee River: Humans and Mussels

Peacock and colleagues have published widely on freshwater mussel shell assemblages from the Mississippi region. Perhaps the best example, showcasing the use of multi-variable and multi-analytical techniques, comes from the Vaughn Mound, Tombigbee River, in eastern Mississippi. Alterations in freshwater mussel populations are apparent since at least the mid-Holocene, with AMS radiocarbon dates demonstrating human occupation in the area from ~6000 BC (Peacock and Seltzer 2008:2557). Changes in geomorphological and palaeoenvironmental processes were identified through inspections of shell morphologies and body sizes (Peacock and Seltzer 2008). Indeed, metrical data were collected to determine if shell valve size increased or decreased through spatial and temporal sequences. Results confirmed larger shell sizes in the most recent phases of the deposit and smaller shell sizes were recorded in the oldest phases of the deposit (Peacock and Seltzer 2008:2559). Peacock and Seltzer (2008:2559) suggest shell size changes were due to the expansion and contraction of the river system, ultimately influencing shell growing conditions. Morphological observations of mussel shell sculptures focused on outer surface accentuations (e.g. pustules or nodules). Peacock and Seltzer (2008:2562) propose that environmental conditions (e.g. abrasion from consistent water movement) would be detectable '[if] the shell sculpture on different species changes in the same direction over time'. The Vaughn Mound mussel samples showed more abrasion to the outer surfaces in the earlier phases than those from the more recent phases, suggesting that more turbid conditions existed along the Tombigbee River in the earliest phases of human occupation (Peacock and Seltzer 2008:2560).

A further improvement to Peacock and Seltzer's (2008) interpretations was made using biogeochemical techniques. Stable isotope signatures were directly measured on mussel shells to test for changes in palaeoclimatic conditions, $^{18}O/^{16}O$ for variability in temperature (i.e. warmer versus cooler periods) and ^{13}C to test carbon intake (Peacock and Seltzer 2008:2561). Although only small differences in ^{18}O and ^{13}C values were found, this result was nonetheless necessary for teasing out complexities in mussel shell habitats and variables influencing growth. Trace element analyses confirmed higher water levels in the late-Holocene compared to the mid Holocene, appearing coincidental with shell size changes and arguments made for changes in turbidity (Peacock and Seltzer 2008:2562). While the application of scientific techniques in this study are clear, there appears a lack of consideration to human influences that might have contributed to changes within the Tombigbee River through time (see discussion Peacock and Seltzer 2008:2563). Despite agreeing with this limitation, Peacock and Seltzer (2008) strongly advocate for multi-analytical techniques and examination of multi-variables to interrogate datasets.

2.4.3 Discussion

Using the deep time Tombigbee River mussel assemblage, Peacock and Seltzer's (2008:2562) explicit aim in their study was to 'retrodict past river conditions as a proxy for past climate'. To this end, Peacock and Seltzer's (2008) applied zooarchaeological dataset has a threefold advantage: (1) it provides to some degree, a record of cultural heritage and past climatic and environmental conditions using multi-variable analyses, (2) it is translatable to other long-term Historical Ecology records, and (3) it is relevant to modern resource management initiatives. Peacock and Seltzer's (2008) use of multi-variable techniques is a good example for how interpretations can be improved when examining complex socio-ecological case studies. Identifying species responses to palaeoclimate and palaeoenvironmental conditions, and seasonal growth trends using biogeochemical data, might also control for implementing seasonal fishing restrictions. Indeed, a limitation as Rick et al. (2016:6568) and others have recognised, is the lack of historic fisheries data within modern management initiatives, particularly at early planning stages. These records are imperative for assessing how and why resource populations have responded to different human and ecological drivers of change through temporal and spatial contexts.

Ethnographic information, TEK, and other fisheries knowledge including data extracted from modern fisheries databases, could prove useful for projects such as those discussed above (and see Armstrong et al. 2017). Important with these types of data is the awareness that practices appearing in records from the deep past do not necessarily resemble those of ethnographic or modern conditions, and indisputably in *vis-à-vis* situations (see discussions in Faulkner et al. 2018a, 2018b:2). The inclusion of each of these types of knowledge and participation of local stakeholder groups is key to the success of modern fisheries management initiatives. In Velondriake, ~30 local community groups actively participate with Blue Ventures Conservation Organisation in fisheries management, although baseline understandings of fishing practices from the deep past are not clearly comprehended (Douglass et al. 2019b:266). This is a case where community members are willing to actively participate in conserving or instilling resilience strategies at coastal sites, but do not clearly understand past conditions. Establishing as a priority the reconstruction of high-resolution data from marine resource remains from Velondriake cultural deposits, as Douglass et al. (2019b) have argued, will prove invaluable for refining understandings of past socio-ecological conditions.

These data, will of course have more practical application in modern fisheries management trajectories which can also be compared with other Madagascan and eastern African areas for broader regional understandings (e.g. compilation of datasets from the Zanzibar and Mafia Archipelagos is well underway, see e.g. Crowther et al. 2016; Faulkner et al. 2018a, 2018b; 2019). Rick et al. (2016) suggest these types of data should be collected from Pleistocene, Holocene, historic, and modern assemblages where available, for long-term and holistic marine resource use understandings. In another Historical Ecology example, formed in response to finding a 98% loss in Chesapeake Bay oyster populations in the 1990s, applied zooarchaeological datasets have helped achieve the following outcomes: (1) understandings of long-term changes to oyster populations and habitats (2) documentation of the consequences of human and environmental drivers of change; and, (3) co-managed oyster reseeding initiatives to replenish oyster stocks (see Rick et al. 2016; Rick and Lockwood 2013; Steppe et al. 2016; and see Bilkovic et al. 2019 for overview). Peacock et al.'s objective (2016:130), as others have advocated, explains that 'continental-scale zooarchaeological database[s]' built from local and regional cases are imperative for recording past socio-ecological structures to benefit future conservation. Currently, no management initiatives using applied zooarchaeological datasets exist for the GBR.

2.5 Applied Zooarchaeology in Great Barrier Reef Fisheries Management

The GBR is listed as a UNESCO World Heritage area based on its unique 'natural' values (UNESCO 2019). Despite the status of the GBR on the UNESCO World Heritage list, evidence is available attesting to influences affecting its overall health (for e.g. see the *Great Barrier Reef Outlook Report* 2019a and see Esparon et al. 2015; Jones and Berkelmans 2014; Pendleton et al. 2016; Simpson et al. 2016; Stone-Jovicich et al. 2014). Cultural values are of high priority and significance in these debates, but always receive less attention. Although acknowledgement of cultural connections to sea Country and marine resources are incorporated into plans and reports to some degree, no zooarchaeological datasets have been considered in management plans or conservation initiatives. Ranger programs facilitate the use of TEK, but baseline zooarchaeological datasets to inform and support these efforts is lacking. Historical Ecology research programs employing the use of applied zooarchaeology datasets with TEK is sorely needed for GBR cases.

Conservation management plans for GBR marine resources are currently built using datasets from contemporary fisheries records, less so from historic records, and hitherto never from deep time records. The Australian Fisheries Management Authority (AFMA) is the Commonwealth governing body for commercial Australian fisheries (http://www.afma.gov.au). AFMAs primary goal is to manage commercial fisheries catches to reasonable standards while ensuring sustainable outcomes of marine resources for future generations (AFMA 2018). Catch records are based on contemporary fisheries logbooks and research that informs conservation management plans, such as the *Reef 2050 Long-Term Sustainability Plan* (see Reef 2050). This plan outlines threats to the sustainability of the GBR and sets conservation goals to be achieved by the year 2050. Despite the plan acknowledging Indigenous cultural heritage, cultural use of resources, and aims to incorporate TEK (Reef 2050:39, 40, 41, 77), there is room for improvement.

In other examples of Australian ecology projects, such as the Tropical Rivers and Coastal Knowledge program, Indigenous seasonal calendars are important translations of cultural and environmental knowledge (see TRaCK 2019). Seasonal calendars are built on TEK and are linked to specific ecological areas, floral and faunal resources, and climatic regimes (see Figure 2.2) (CSIRO 2019a; and see also BoM 2019 for coastal GBR Yirrganydji group seasonal calendar). Cultural materials such as those located at cultural resource use sites (e.g. shell deposits) might be interpreted as foundations or physical manifestations from which TEK can be translated. As Chapter 1 acknowledged, cultural practices, cultural beliefs, and TEK are not static and may have undergone several modifications over the long term. On a further note, Indigenous Land and Sea Management (ILSM) might be described as ‘a rough and imperfect translation of the concept’ ‘caring for Country’ – an interconnectedness between ‘biophysical, spiritual, cultural, kinship relation, survival and ancestral domains’ (see Austin et al. 2018:377). Important Aboriginal and Torres Strait Islander cultural resource use sites are included in these domains, and in many situations might be described as one type of reference point or 'anchor' to TEK. Engagement with deep time records by Indigenous custodians, and appropriate engagement by others, is imperative for holistic intercultural understandings of TEK, caring for Country responsibilities, and long-term sociocultural aspirations.

Figure 2.2 The Gulumoerrgin (Larrakia) seasonal calendar based on Traditional Ecological Knowledge (Williams et al. 2012b).

The use of GBR marine resources in Indigenous communities prior to and during European settlement has a long and significant history. Indigenous use of large marine fauna, such as dugongs and turtles for example, has received significant attention in contemporary fisheries management, particularly across the Torres Strait Islands and the Northern Territory (for e.g. see Kennett et al. 2004; Marsh et al. 1997, 2004). Key to the success of turtle conservation goals in Arnhem Land has been understanding and integrating both scientific and Yolngu TEK using bottom-up project management strategies (see Kennett 2013 and Kennett et al. 2004). For many Aboriginal and Torres Strait Islander peoples, ILSM projects assists in maintaining long-term sociocultural responsibilities and outcomes: handing down of knowledge to younger generations, documentation of languages, additional training opportunities, self-determination and autonomy (Austin et al. 2018:734).

By acknowledging and incorporating data from cultural resource use sites, caring for Country, and offering intercultural exchanges, management plans can be strengthened. For example, work detailing the long-term cultural use of dugong and turtles in deep time, has been recorded by McNiven and others for areas of the Torres Strait Islands (see for e.g. McNiven and Bedingfield 2008). These types of efforts facilitate strong intercultural foundations which can be collated with historic and modern catch records (and see Mulrennan 1992 for overview of Torres Strait Islander connections to Country, and environmental concerns with 1980s commercial development initiatives; see also Johannes and Macfarlane 1991 for discussion on Torres Strait Island 'conservation ethics'). On reflection of the significance of multi-knowledge datasets that provide a window into deep time, and governing documents such as the *Environment Protection and Biodiversity Conservation Act 1999* and *Environment Protection and Biodiversity Conservation Regulations 2000* which covers the Commonwealth and international protection for Australian biodiversity (EPBC), I describe a list of potential contributions (see Table 2.4).

Table 2.4 Summarised objectives of the Environment Protection and Biodiversity Conservation Act (1999) and where deep time baseline archives can contribute using multi-knowledge datasets.

EPBC Objective	Contribution of Baseline Datasets
'*conserve Australian biodiversity*'	Deep time archives encapsulate longer-term understandings for the significance of communities that have existed through time, contributing to evidence for why the conservation of Australian biodiversity is essential.
'*provide protection of the environment, especially matters of national environmental significance*'	The GBR is of national and international significance and recognised as a UNESCO World Heritage area for its outstanding natural values. Deep time data can contribute to long-term environmental reconstructions, providing evidence for how the GBR has undergone change overtime but has maintained its outstanding values.
'*enhance the protection and management of important natural and cultural places*'	Research undertaken on deep time archives, in collaboration with Indigenous and non-Indigenous peoples, can be used to identify important natural and cultural places (surveys, excavations and other recordings).
'*recognise the role of Indigenous people in the conservation and ecologically sustainable use of Australia's biodiversity*'	Deep time archives can provide evidence for Indigenous-resource use dynamics and Indigenous occupation trends through time. Important conservation practices can be learned from long-term Indigenous interaction with the environment.
'*promote the use of Indigenous peoples' knowledge of biodiversity with the involvement of, and in cooperation with, the owners of the knowledge*'	Projects using deep time archives provide a platform to empower Indigenous peoples with cultural heritage which is inseparable to the natural environment. Other initiatives such as Indigenous ranger programs can use deep time data to assist in the decision making and conservation implementation processes.
'*provide streamlined national environmental assessment and approvals process*'	Deep time archives provide a unique avenue for cross-cultural education, communication and understandings. National environmental approval processes are successful when Indigenous and non-

EPBC Objective	Contribution of Baseline Datasets
	Indigenous practitioners participate in effective communication and shared decision making.
'*promote ecologically sustainable development through the conservation and ecologically sustainable use of natural resources*'	Historical Ecology aims to promote conservation efforts. Promotional and educational activities for the conservation and ecologically sustainable use of natural resources are successful when cultural and commercial interests are considered and planned for.
'*control the international movement of plants and animals (wildlife), wildlife specimens and products made or derived from wildlife*'	The long-term use of plants and animals by Indigenous peoples is evidenced in deep time archives. Cultural heritage and TEK is complex, non-linear and dynamic where knowledge is learned through apprenticeship over time. The movement of culturally important plants and animals from cultural places should be on approval by senior knowledge holders.

Many important cultural resource use sites along the length of the GBR are inclusive of molluscan remains. Despite the importance of molluscs as important cultural and ecological resources, they are given considerably less consideration in conservation planning and ecological assessments in comparison to other marine fauna (i.e. typically iconic fauna or fish species are targeted, see Bellwood et al. 2019). As well as other calcium accreting organisms (i.e. corals), molluscs contribute to the 'formation and maintenance' of reefs (Bellwood et al. 2019; Brooke et al. 2017:32). They are also considered important in reef ecology for their ability to filter water and in commercial and non-commercial settings, molluscs are prized as a raw material resource (i.e. shell) and food resource (i.e. meat) (e.g Nell 2001). Given these points, conservation initiatives would benefit from more inclusive assessments of modern and deep time mollusc populations. Long-term datasets for species population increases, population decreases or potential extinction of species would assist in trophic cascade research, as molluscs are important to the overall functioning of ecological structures (for an example situated within an Historical Ecology framework examining the relationships between humans, sea otters, kelp forests, molluscs, and urchins at the Channel Islands see Braje and Erlandson 2007, 2009; Braje et al. 2009, 2012; Erlandson 2008). Commercially, GBR molluscs have been harvested from historic to modern times. Their high commercial values saw large harvests of trochus shell (Trochidae), pearl shells (*Pinctada* spp.), giant clams (*Tridacna* spp.) and oysters (Ostreidae), during the historic period (see examples in Daley 2014 and Nell 2001). The availability of online archival datasets, like those available through AFMA, but including deep time and historic records (with appropriate cultural permissions) would likely initiate, engage, and integrate datasets in conservation management efforts. These databases might then be used to perform resilience assessments.

One initiative that attempts to assess the global conservation status of flora and fauna, including molluscs, is the International Union for the Conservation of Nature (IUCN). Criteria for determining the conservation status of a species can be found in the *IUCN Red List Categories and Criteria* (2012). Conservation status' for the IUCN Red list of Threatened Species is also routinely informed by contemporary datasets and are placed in one of the following categories: EX: extinct, EW: extinct in the wild, CR: critically endangered, EN: endangered, VU: vulnerable, NT: near threatened, DD: data deficient, LC: least concern (IUCN 2018). Global data suggest 788 species of Bivalvia fall into one of these categories, with 32 cases extinct, 333 cases of least concern and 175 cases being data deficient (IUCN 2018). Gastropoda retrieved a total of 7131 species with 269 cases extinct, 2594 of least concern and 1635 data deficient cases (IUCN 2018). Records for those species with long histories in Indigenous cultures and important in commercial initiatives such as *Tridacna (Tridacna) gigas* and *Tridacna derasa* (giant clams) for example, are currently registered as vulnerable. Conversely, other mollusc species appearing in southern GBR deep time cultural sites, have not been assessed and do not appear on the Convention on International Trade in Endangered Species (CITES) list. Data such as these could contribute to International conservation initiatives aligned with the IUCN, and support goals set by the Aichi Convention on Biological Diversity (CBD) and The Nagoya Protocol. Australia's participation in international conventions can be found at: http://www.environment.gov.au/marine/international-activities.

2.6 An Historical Ecology Framework for North Keppel Island

The importance of coastal resources in modern contexts spans socio-ecological responsibilities and socio-economic needs. 'Climate change, biodiversity conservation, ecosystem structure and function, habitat and seabed integrity, food security including human consumption patterns and exploitation, and human dimensions and governance' are priority themes (Englehard et al. 2016). At present, local, regional, and national interests for the Keppel Bay Island region includes but is not limited to: cultural practices, environmental conservation, tourism, and recreational and commercial fishing. To meet these needs most effectively, efforts supporting these initiatives can advance when practitioners and community members are equipped with baseline socio-ecological knowledge. Due to the complexity of current needs across the region, the generation of multiple lines of evidence to effectively predict outcomes is best supported by a Historical Ecology framework. Currently, datasets deriving from GBR deep time sites are not used to their maximum potentials in conservation initiatives at the planning stages. One key phylum in the GBR – Mollusca, has had little attention in environmental impact and threatened species assessment projects which report directly to local and international initiatives. Status assessments for several molluscan species, and that appear in Woppaburra cultural resource use sites within the Keppel Bay Islands, have not yet been confirmed. Many culturally important species populations are situated in immediate intertidal shoreline contexts. Six cases including species within the Mazie Bay cultural resource use site, returned a 'not assessed' status from the IUCN (2018).

As the Woppaburra People have occupied the Keppel Bay Islands for at least the past 5000 years (Rowland 1999a), the temporal sequence under examination at Mazie Bay is considered to have never been strictly isolated from human influences – even during periods when the Woppaburra People may have temporarily abandoned a camp locale or use of a marine resource. The next chapter begins enquiry into the Keppel Bay Islands case by outlining already recorded knowledge which details the cultural and environmental background of the Woppaburra People and their sea Country. Deciphering the dominant variables most likely influencing socio-ecological change through time is anticipated to be challenging as some or all variables may have contributed to change at different temporal and spatial scales. Nevertheless, by critiquing the way other international studies have applied analytical techniques to molluscan remains is useful for realising potential advantages and limitations of metrical, sclerochronological and biogeochemical applications to selected Mazie Bay species. Working with the species recovered from the Mazie Bay cultural resource use site, I prioritise which species are more suitable than others according to each analytical technique. The following questions serve as a directive for the research working under the Keppel Bay Islands Historical Ecology framework:

(1) Identify the dominant variables likely contributing to changes in resource populations and Woppaburra harvesting trends through time.
(2) Apply appropriate techniques to mollusc shell samples to interpret how and when these changes occurred (e.g. peaks and troughs in human harvesting).
(3) Detail how these changes are recognisable in mollusc shell and human harvesting patterns.
(4) Integrate these findings with Woppaburra TEK.
(5) Explain how these datasets can be used to address short- and long-term resilience goals in resource use and cultural heritage management.

2.7 Summary

Historical Ecology is an appropriate framework for the Keppel Islands to map the long-term and dynamic nature for the use of marine resources. Applied zooarchaeology techniques have the advantage of showing long-term resource use trends and are invaluable for reconstructing socio-ecological relationships and forecasting future resource resilience. When considered with other temporal datasets, these data are valuable for determining but not limited to no take zones, seasonal catch limits, bag limits, and documenting the cultural significance of resources. Objectives of the EPBC and Aichi CBD, along with the co-collaboration of multidisciplinary practitioners and cross-cultural teams, would then be better positioned to continue and achieve common conservation goals across 'integrated corporate estates'.

3

The Study Region

3.0 Introduction

This chapter introduces the physical and cultural setting of the Great Barrier Reef (GBR), with the Keppel Bay Island group targeted more specifically for review. My evaluation of knowledge already available to the project further highlights the significance of recording long-term socio-ecological dynamics using a Multiple Evidence Based (MEB) approach. The Woppaburra cultural map is discussed at length before detailing previous archaeological research conducted at the Keppel Bay Islands. The 1979 archaeological excavation of cultural resource materials at Mazie Bay, North Keppel Island, offers an exceptional archive of molluscan remains to examine human and resource population responses to change over a 5000-year period.

3.1 Physical Setting

Being the largest reef system in the world and making up 10% of reef systems globally, the Great Barrier Reef Marine Park (GBRMP) covers ~345000km^2, across latitude 14° (10°S to 24°S), extending from the tip of Cape York to Gladstone (UNESCO 2019) (Figure 3.1). At its widest point, the GBR spans ~250km off the coast of Yeppoon (southern GBR), and at its narrowest point ~15km off the coast of Cape Melville (northern GBR). There are an astonishing ~3000 reefs comprising 7% of the complete system which includes ~900 islands - continental islands, sandy cays and coral cays (Hutchings et al. 2008:9; UNESCO 2019).

The Keppel Bay Island group is part of the Capricorn Coast in the southern GBR (Figure 3.2). There are 18 continental islands in this archipelago situated approximately 12km from the mainland coast. Of these islands, 13 are included as part of the Keppel Bay Islands National Park (excluding Great Keppel Island) (NPSR 2018). Great Keppel Island (1450ha) and North Keppel Island (627ha) are the largest (NPSR 2018). Great Keppel Island and Pumpkin Island have commercial tourist resorts, while South Keppel Island has only one small eco-resort run by local oyster fisherman, Carl Svensden. Two small-scale family managed oyster leases exist, but no other commercial mollusc fisheries operate within the group. One private residence thought to be the site of an historic oyster fishery house, (NKIEEC Staff pers. comm. 2018) and the North Keppel Island Environmental Education Centre

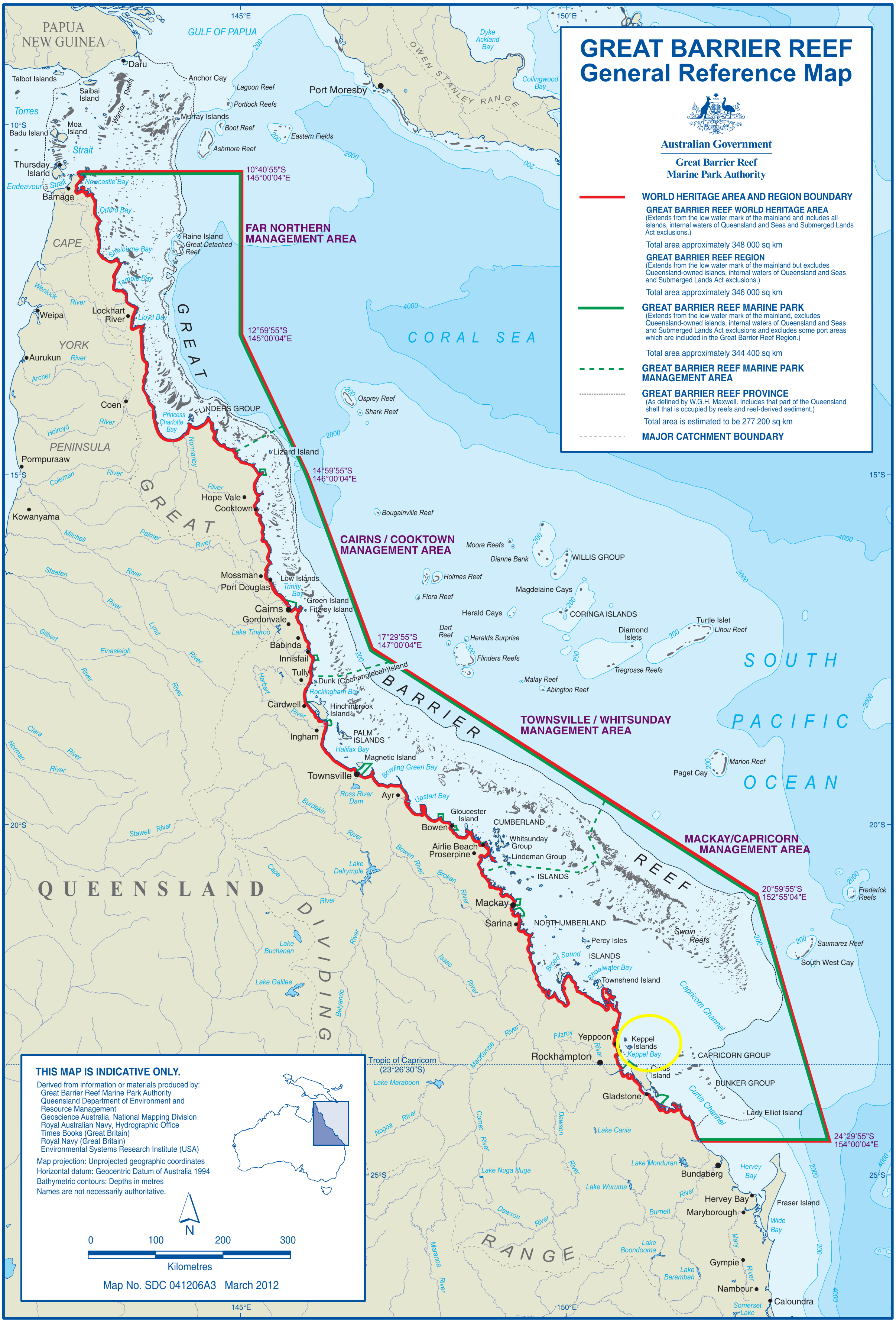


Figure 3.1 Map showing the east coast of Queensland, the World Heritage boundary, the Great Barrier Reef Marine Park boundary, and the location of the Keppel Bay Islands (after GBRMPA 2018c).

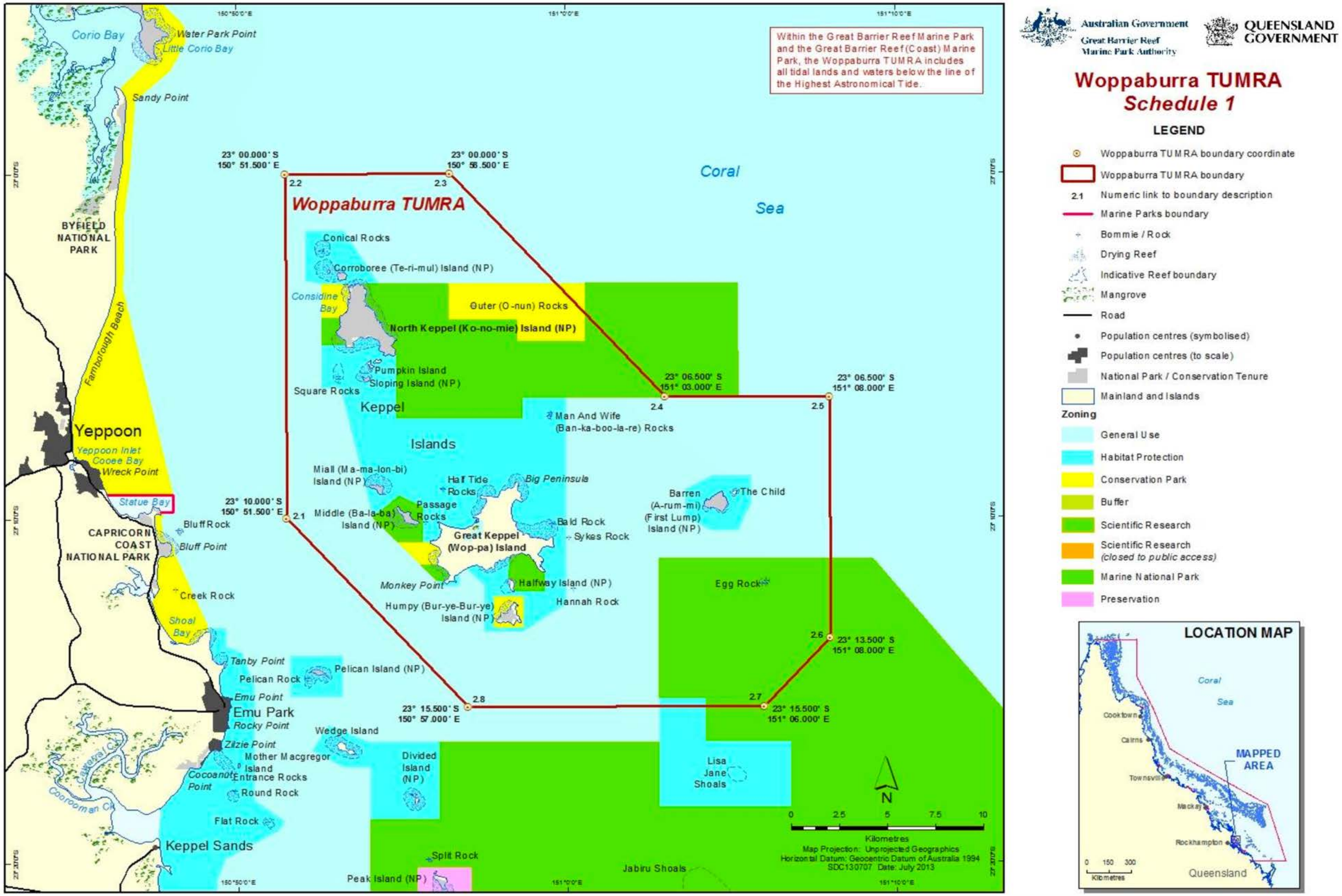


Figure 3.2 Location of the Keppel Bay Islands, Capricorn Coast, and the Woppaburra Traditional Use of Marine Resources Agreement (TUMRA) zone (WTOHA 2019).

(NKIEEC) are on North Keppel Island. Plans for a new resort on Great Keppel Island by Tower Holdings have been ongoing and contentious (Rowland 2017). On the adjacent mainland within the Fitzroy River Basin, over 80% of land is used for agricultural purposes (Radke et al. 2010:4; Ryan et al. 2007:200). The following review outlines important biocultural processes operating within these contexts and within the GBR more broadly.

3.1.1 Geology and Geomorphology

The GBR structure, as we know it today, has been built over millions of years (Brooke et al. 2017; Pandolfi and Greenstein 2007:719). Since 25 million years ago, due to tectonic plate activity, the Australian continent has moved ~7cm per year from a southern position to a more northern position (Hopley et al. 2007:27-29; Hutchings et al. 2008:5). It rests on limestone calcium carbonate foundations which, in combination with other factors, have given rise to the building of the GBR. Oscillating sea-levels, surface erosion, and sedimentation initiated by turbidity and other environmental variables, including but not limited to temperature, light and salinity, combine to form the GBR's morphology (Brooke et al. 2017; Hopley et al. 2007). Larvae from mass coral spawning events and from fauna including molluscs, algae, and bio-eroding organisms, settle into crevices and reef rubble where growing conditions are favourable (Hutchings et al. 2008:5; Wolstenholme et al. 2018). This process is responsible for the formation of coral reef foundations (see Brooke et al. 2017:32).

Reef structures are situated in three zones: the inner-shelf, the mid-shelf and the outer-shelf (Hutchings et al. 2008:10-11). Inner-shelf reefs are located close to the mainland coast with individual fringing reefs forming a myriad of non-uniform shapes and sizes (see Stephenson and Stephenson 1972 for early reef descriptions). Mid-shelf reefs, situated between the inner-shelf and the outer-shelf, offer the greatest diversity of reef types: Pleistocene reefs, patch reefs, shoal reefs (juvenile growth stage), lagoon and crescent shaped reefs (mature growth stage), and planar reefs (senile growth stage) (Hutchings et al. 2008:11). The outer-shelf encompasses the northern region's horizontal ribbon reefs, while the eastern extremities of the central and southern regions, are characterised by irregular shaped reefs. The Keppel Bay Islands reside within the inner-shelf and inside a tectonically stable region (see Ryan et al. 2007). The islands are predominantly comprised of sandstone and granite, although over 100 different types of rocks have been identified within the adjacent Fitzroy River area (Radke et al. 2010; Smith 1998). Figure 3.3 shows the underlying geology in the region.

Large sand dunes dominate the beaches at the Keppel Bay Islands, while other shorelines are made up of rocky boulders or exist as sheer cliff faces. On the adjacent mainland coast at Keppel Bay, beach dunes dominate the coastline. Brooke et al. (2008) identify four distinct beach dune formation phases on the mainland coast (1500 BP, 1000 BP, 450 BP and 250 BP), however since 1000 BP sedimentation accumulation has reduced. This finding is 'consistent with other coastal records in eastern Australia' and is coherent with arguments made for a 'relatively wetter phase of climate in the late-Holocene compared to the present' (Brooke et al. 2008:195). Data describing sand dune formation processes is currently not clear for North Keppel Island. Suspended and bedload sediments from the Fitzroy River are transported northward towards the Keppel Bay Islands during heavy precipitation, episodic flooding, wind, wave, current, and tidal events (Brooke et al. 2008; Ryan et al. 2007:197, 209). Over '70% of terrigenous sediment input into the GBR lagoon (19.6 Mt yr^{-1}) comes from the combined Burdekin and Fitzroy Rivers' (Ryan et al. 2007:200).

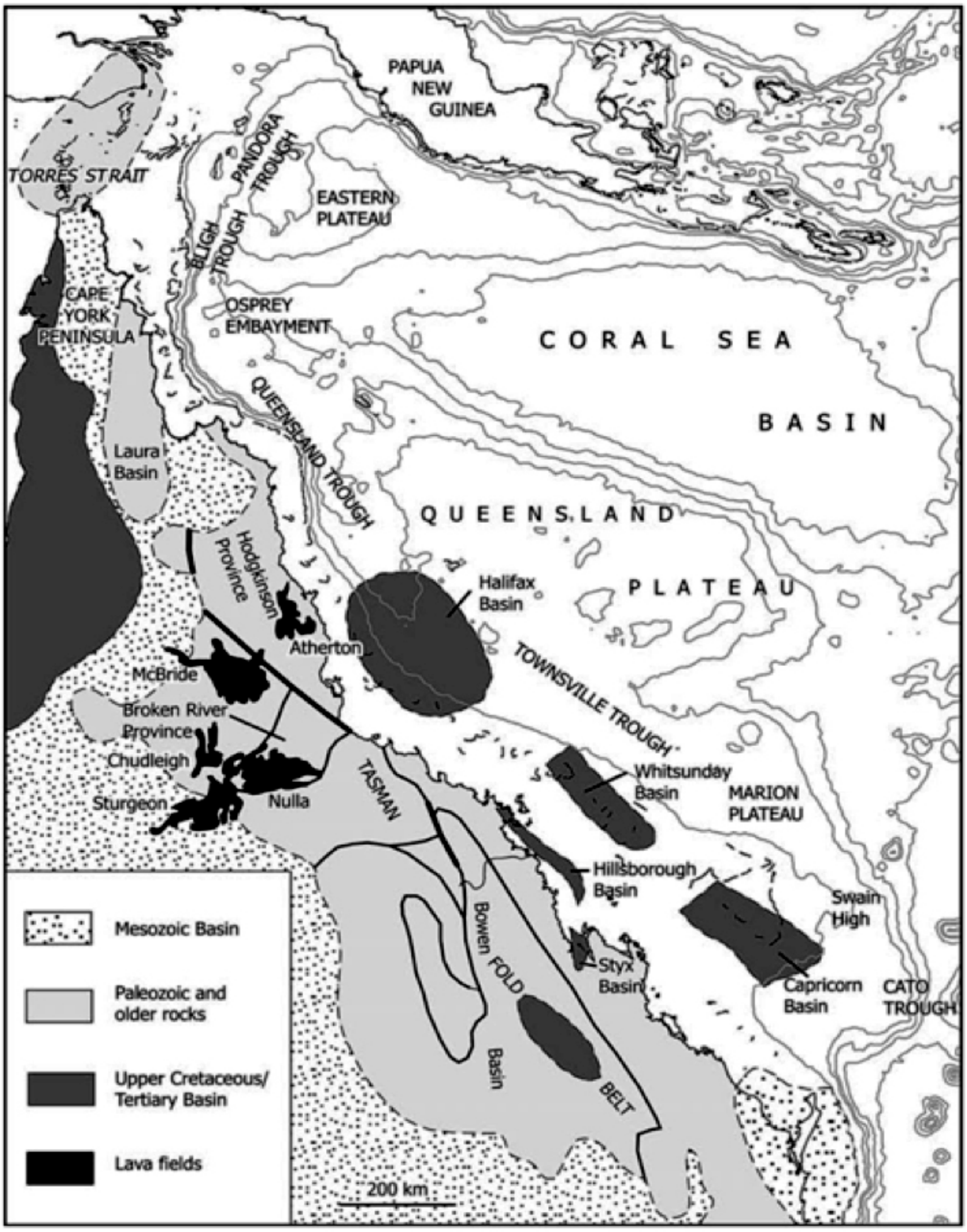


Figure 3.3 Underlying geology by region and surrounding areas (Hopley et al. 2007:20).

3.1.2 Hydrology

Foundational structures within the GBR region share interconnectedness through the circulation and distribution of water: sea-levels, currents, precipitation and flooding (Waterhouse et al. 2016). The continental shelf vertical drop-off at the outer-shelf extends to more than 1000m depth. East of the continental shelf established reefs are generally no deeper than 40m and juvenile reefs no deeper than 5-25m (Hutchings et al. 2008:11; Ryan et al. 2007:198). Palaeoshorelines existing within this zone were sequentially inundated by rising sea-levels throughout the Late Quaternary (Brooke et al. 2017). Prior to the Holocene, 'during six episodes', sea-levels are recorded to have been ~30-40m lower than present (Brooke et al. 2017:30). At 6000 years ago, sea-levels reached relative modern heights which have tended to fluctuate between ~1-3m (Leonard et al. 2016; Lewis et al. 2008, 2013, 2015; Wolanski 1994). Indeed, periods of sea-level variability coincident with vertical coral reef accretion since the mid-Holocene, is debated. I return to this point below in section 3.1.3. Today, waters surrounding the Keppel Bay Island group are generally no deeper than 22m with spring tides measuring ~4m and neap tides to ~2.5m (see Ryan et al. 2007:201 for a bathymetric representation).

Deep ocean currents, turbid ocean currents and surface ocean currents are responsible for reef growth, bringing warmer water, nutrients, and larvae to the GBR ecosystem (Figure 3.4) (Hopley et al. 2007:100-102). The East Australian Current (EAC) moves in a southerly direction into the Capricorn Channel but other inner-shelf currents generally move in northerly directions (Ryan et al. 2007:200). Wave heights can reach ≤ 2m high, particularly during the summer months (Ryan et al. 2007:200). As discussed above, the Fitzroy River is the largest catchment in Queensland (~480km long/~142.660km^2) that directly discharges into the GBR (Figure 3.5) (Radke et al. 2010; and see the Fitzroy River Basin map at BoM 2018a). It brings episodic bouts of flooding, sedimentation, and nutrients to local fauna and flora (Jones and Berkelmans 2014; Radke et al. 2010). Indeed, the GBRMPA zonation definition of the Capricorn Coast describes it as a 'high nutrients coastal strip' (see the reef explorer map GBRMPA 2018c). A general summary of nutrient transportation into Keppel Bay can be consulted in Radke et al. (2010) who report on results derived from water column samples. Similar nutrient load results might mirror those at North Keppel Island, although confirmation cannot be provided at this time due to limited data. It is suspected that sediment loads and flood plumes correspond with seasonal changes and storm events (e.g. Jones and Berkelmans 2014).

A Note on Defining Seasonal Changes

Generally accepted descriptions for seasonal change in the GBR region, are based on annually cyclic precipitation patterns defined by the Australian Summer Monsoon (ASM) system. The ASM is part of the larger Australian-Indonesian Summer Monsoon (AISM) which occurs in the summer months or the 'wet season', December to March (see Lough 2007:22; Suppiah 1992). The 'dry season' occurs in the cooler months, April to November. Although temperatures throughout the year fluctuate within and between the wet and dry seasons, there is considerably less distinction in seasonal temperature changes defined in the standard Gregorian calendar (i.e. between summer and spring, and autumn and winter). Spring, and seldom autumn, are typically only referred to when communicating events aligning to times and dates set out in the Gregorian calendar (e.g. September spring-neap tides).

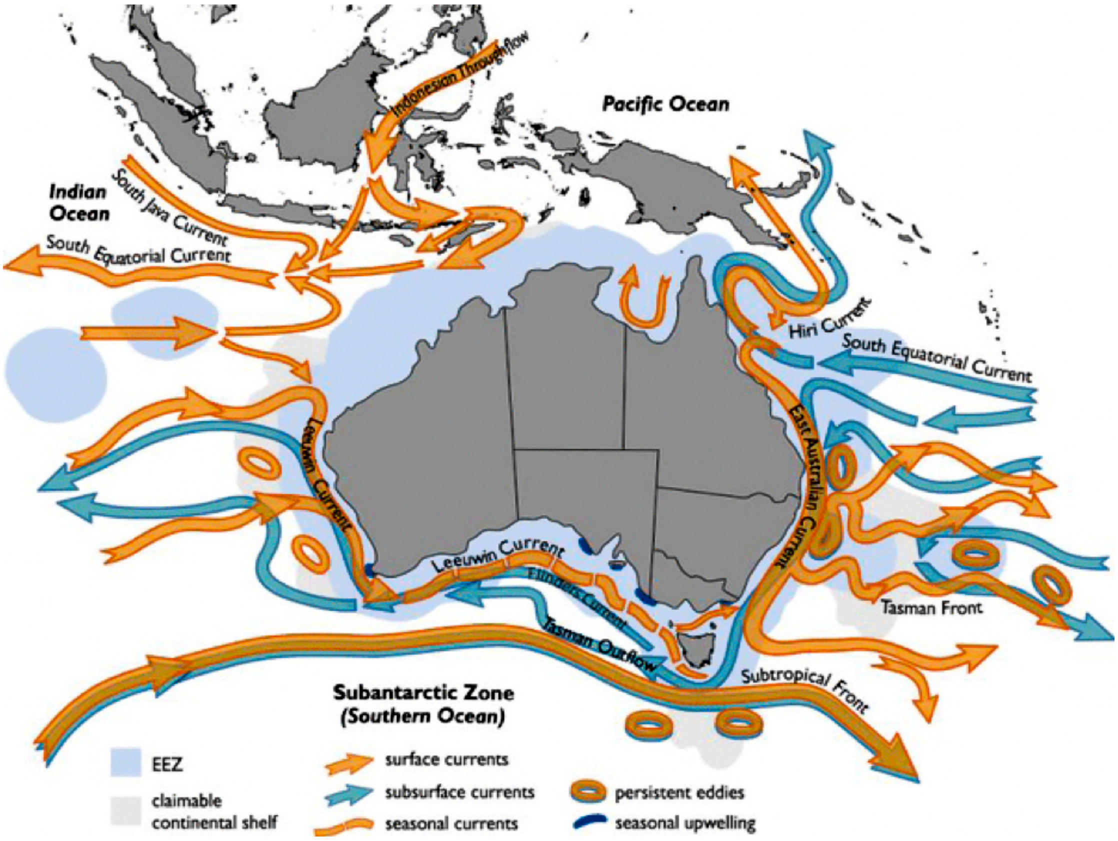


Figure 3.4 Showing the major ocean currents in Australasia. Note the location of the East Australian Current in the Great Barrier Reef (CSIRO 2019b).

Figure 3.5 The Fitzroy River (Photograph, FBA 2018).

3.1.3 Climate and Palaeoenvironmental Change

Average sea surface temperatures (SSTs) in the GBR reach ~29°C in the northern region and ~27°C in the southern region during the summer months, with optimum temperatures estimated between 26°C and 27°C (Hutchings et al. 2008:5; Lough 2007). Air temperatures for the Keppel Bay Islands are typically ~22°C in the cooler months, with warmer temperatures expected during the summer months (maximum ~35ºC) (NPSR 2018). South-easterly trade winds occur during the dry season, with prevailing winds alternating between easterlies and north-westerlies during the wet season (Ryan et al. 2007:200; Kench and Brander 2006). Annual precipitation patterns average 2049mm per year (Dechnick et al. 2017:222), with sea surface salinity (SSS) averaging 36‰ (Hutchings et al. 2008:5). During the wet and dry seasons, larger climatic oscillations operate within the GBR region. Key climate modulators include the Pacific Decadal Oscillation (PDO), the interannual El Niño- Southern Oscillation (ENSO) (characteristically drier) and La Niña oscillation (characteristically wetter) (Lough 2007, 2011; Lough et al. 2014). During the mid-Holocene, a short time after reef stabilisation, modern ENSO regimes became established but are explained to have been 'less extreme and less frequent' in comparison to modern records (Dechnick et al. 2017:224; Leonard et al. 2016:1248).

Reef growth during the Holocene is defined as a 'high energy window' (Hopley 1984) where climatic variables 'enable[d] calcium carbonate levels to be increased' (Hopley et al. 2007:216-217). Initial growth of coral reef structures began just after the Pleistocene ~9000 years ago, with maximum growth heights estimated for the GBR at ~5500 years ago (Hutchings et al. 2008:10; Leonard et al. 2020a). Despite a period of unprecedented reef growth, a series of reef 'turn-off' phases occurred after the mid-Holocene. Recent analyses of percussion cores from the Keppel Bay Islands show changes coincident with sea-level rise and fall but perhaps more importantly, reef growth 'turn-on' and 'turn-off' were specific to localised environmental changes experienced within each individual reef structure (Leonard et al. 2020a, 2020b). Sedimentation accumulation rates, including the types of sediments, shows good agreement with differences in vertical accretion rates between each reef site (see Leonard et al. 2020a, 2020b). At Mazie Bay, vertical reef accretion rates averaged 5mm year^{-1} between ~6900 BP and ~5000 BP (Leonard et al. 2020b). After this time, the reef continued to grow but prograded seaward, and then experienced 'turn-off' at ~400 BP (Leonard et al. 2020b). Leonard et al. (2020b:5) report a change in the sediment matrices, from sandy-mud in the lower units to 'coarse rubble' in the upper units where ~70% of 'abraded coral clasts' were encrusted with algae, 'bryozoans, and serpulid worms' from ~5500 BP.

At this time, limited application of biogeochemical testing of fossil and modern coral cores exist for GBR sites (and none include Mazie Bay). General consensus posits that tropical storms were not completely responsible for discontinuous reef growth (see Nott and Hayne 2001), but rather other variables contributed to key changes. Studies targeting climatic influences in the mid-Holocene, suggest temperature, higher precipitation rates further marked by flooding events and fluctuating salinities as the main variables driving changes (Brooke et al. 2008; Gagan et al. 2004; Roche et al. 2014). Sea surface temperatures are estimated to have been ~2.75-1.30ºC cooler during the mid-Holocene in comparison to the current modern period (Leonard et al. 2016:1248; Sadler et al. 2016:1395). Many variables and climate systems have supported the expansion and contraction of GBR flora and fauna communities through time (Dechnick et al. 2017:221; Kroon et al. 2016; Pandolfi and Greenstein 2007; Pandolfi et al. 2003). Exactly what long-term effects these variables and climate systems have had on marine resource populations and human communities through time remains to be confirmed. Broad-scale regional trends and more localised effects are likely to have taken place across different spatial and temporal settings. This point remains a theme throughout the thesis.

3.1.4 Biodiversity and Ecology

Approximately 4000 species of mollusc (3000 gastropods, 1000 bivalves), 1600 species of bony fish, 180 large marine animals including sharks and rays (31 whales, dolphins and dugong), 3550 species of coral and sponges (3000 sponges, 400 hard corals, 150 soft corals), 410 echinoderms and 240 species of birds has been identified across the GBR (UNESCO 2019). Diverse vegetation consisting of mangrove forests, grasslands, Pandanus swamps, Acacia, Eucalyptus, coastal dune vines and saltbush occupy coastal settings to which many fauna rely on for survival. Species habitats are important for understanding the parameters in which each species can survive, food web structures, and symbiotic interconnectedness within the entire GBR ecosystem. Like other GBR sites, the Keppel Bay Islands are characterised by a diversity of habitats consisting of rocky shores, mangroves and estuaries, sand-mud flats, sandy seagrass meadows, and coral reefs.

Rocky Shore Habitats

Steep rocky shores and gentle sloping rocky beaches are important for understanding the formations and changes in coastal geology and settlement of species populations. Rocky shores are situated between the upper high tide mark and intertidal zones, consisting of sheer cliffs displaying bands of stratified sedimentary layers, beach rock filled with pumice, faunal remains, colourful rock conglomerates, large boulders and small cobbles and pebbles. Tidal cycles from the coast's east and terrestrial run-off from the coast's west, make rocky shore substrates an interesting mix of beach rock rubble, fine- and coarse-grained sands, faunal debris, and vegetation detritus. Molluscs living within this habitat commonly share aerial respiration qualities to survive ever-changing tidal cycles and turbidity (Beesley 1998:32).

Mangrove and Estuary Habitats

Mangroves are extremely important ecological habitats for the success of GBR biodiversity (Goudcamp and Chin 2006). Many fauna rely on mangrove and estuarine habitats to breed. They act as nurseries for fish, molluscs, and other vertebrate and invertebrate species (Goudcamp and Chin 2006). Mangrove plant detritus provides nutrients for fauna while root systems and higher vertical mangrove branch profiles act as havens for crustaceans and gastropods (Beesley 1998:40-41). On the landward side, mangrove forests extend into freshwater swamps, brackish creeks, and river mouths. On the seaward side, situated between the mid-high tidemarks, mangroves survive in higher salinities and are frequently inundated by rising tides (Beesley 1998:40-41). Defined as low energy 'blue carbon' environments, mangroves and estuaries cope first-hand with tidal cycles and currents, offering a protective barrier during tropical storms (Beesley 1998:40-41; Goudcamp and Chin 2006; and see McLeod et al. 2011).

Sand-Mud Flat Habitats

Largely exposed at low tides, sand-mud flat habitats are an extension of mangroves, estuaries and upper-tidal mud flats. Substrates are made of fine, medium, and coarse-grained sands mixed with vegetation detritus and mollusc debris. Currents, tides, and high turbidity frequently change the configurations of sand-mud flats, however these processes deliver nutrients to fauna living in the habitat (Beesley 1998:37-39). Most fauna living within sand-mudflat habitats have vertical burrowing abilities, offering an escape from seabirds and other predators.

Sandy Seagrass Meadow Habitats

Sandy seagrass meadows are situated in low-energy lagoon environments that border larger patches of shallow sandy seafloors. They offer protection from high sedimentation and turbidity, with the vertical profile of seagrass blades catching nutrient particles as they drift by (e.g. algae and detritus) (Beesley 1998:39). With time, sand from river mouths and flood plume events change the formation of bordering sand spits and meadows. These habitats offer nutrients to large marine animals like turtles, dugongs, and smaller molluscs. There are 15 species of seagrass in the GBR (GBRMPA 2018d).

Coral Reef Habitats

Coral reef definitions depend on their formation type and their juvenile-senile growth phase regardless of their position within the inner-shelf, mid-shelf or outer-shelf ranges. They are built on fine and coarse-grained sands, rubble and rock substrates (Hutchings et al. 2008:48). Different levels of energy penetration (e.g. turbidity and current activity) and environmental factors such as the availability of nutrients, water temperature, light, and salinity determine the growth success of soft and hard corals at various reef locations including: reef slopes, algal pavements, rubble zones, reef flats and aligned coral zones. Many invertebrate and vertebrate species rely on coral reefs and are generally smaller than other larger game species such as sportfish and sharks that live in deeper waters.

3.2 Cultural Setting

The cultural setting of the GBR is complex and extends across more than the established contemporary boundaries of the GBRMP. Long-term connections with cultural groups in Papua New Guinea, the Torres Strait, and southern Queensland for example, have been in operation for thousands of years (McNiven 2015; Rowland 2018). Defined as 'sea peoples' or 'saltwater peoples', Aboriginal people and Torres Strait Islander people of this region identify as maritime specialists (Chase and Sutton 1987; Hale and Tindale 1933; Thomson 1934; Trigger 1987). Williams et al. (2015) and McNiven et al. (2014) speculate that during the Holocene each language group was comprised of small, highly mobile bands of no more than 100 people each (excluding periodic ceremonial group gatherings of >100 people), connected throughout the region by the sea. The use of traditional watercrafts, such as double outrigger canoes, single dugout canoes and swimming logs, played important roles in transportation, the procurement of resources (e.g. fishing), trade and exchange practices, and transmission of knowledge and languages between groups (for watercraft typological debates see Barker 2004:39; Davidson 1935; Haddon 1937; Mills 1992:38; Rowland 1987). Cosmological and spiritual beliefs are enmeshed with land and sea Country, but are often conceptualised beyond just physical domains (e.g. included in Dreamings, resources and places have special ceremonial significances, resources for foods and raw materials for the manufacture of tools and prestigious goods) (for Torres Strait examples see David and Badulgal 2006; David et al. 2004; McNiven 2013a, 2013b, 2016; McNiven et al. 2015; Urwin et al. 2016). The boundaries of 'Country' in the physical sense are generally distinguished by the spatial occupation of each cultural group, usually separated by linguistic and cultural differences (see Dixon 1976). Each language group or family clan group shares responsibility for the management of resources.

3.2.1 The Woppaburra People and Sea Country

The Woppaburra People are the Traditional Owners (TOs) of the Keppel Bay Islands who identify as saltwater people. Although the Woppaburra People are part of the larger Darambal Nation, they are a smaller cultural clan comprised of five family groups (Van Issum 2016:5). The Woppaburra People define themselves as a 'distinct population' from neighbouring groups (including the mainland) due to unique cultural traditions and semi-isolated occupation of sea Country by their ancestors (Van Issum 2016:96, 132). *Mugga mugga,* the humpback whale, is the Woppaburra clan group totem. Totems also exist for each of the five family groups as well as for each individual family member (Van Issum 2019:106). Ancestral family members hold timeless responsibility for sea Country and are deeply appreciated (Christine Hansen-Doherty pers. comm. 2017). The traditional naming of *Konomie* (North Keppel Island) (see Figure 3.6) pays respect to 'Grandmother Conomie', an important Elder within the Woppaburra community (Christine Hansen-Doherty pers. comm. 2017; and see notes on spelling *Conomie*/*Konomie* in Van Issum 2016:210).

Despite the inexcusable and brutal atrocities resulting from the arrival of European settlers, which has had lasting impact on traditional lifeways, long-term connections with Country have been maintained by the Woppaburra People (Van Issum 2016). The continuation of traditional cultural practices, beliefs, identity, and ways of being is expressed below (WTOHA 2019):

> *[a]s Woppaburra people, we have a lifelong physical, cultural and spiritual connection to the land and sea. We have a lifelong responsibility to our ancestors to care for land and sea country. Our knowledge of the islands is intimate due to our ancestors who have passed down traditional knowledge of the islands and their natural resources, the seasons, the tides and ocean movements, the coastal flora and marine species. Our culture dictated the species and time we would be allowed to hunt and harvest by seasonal indicators*.

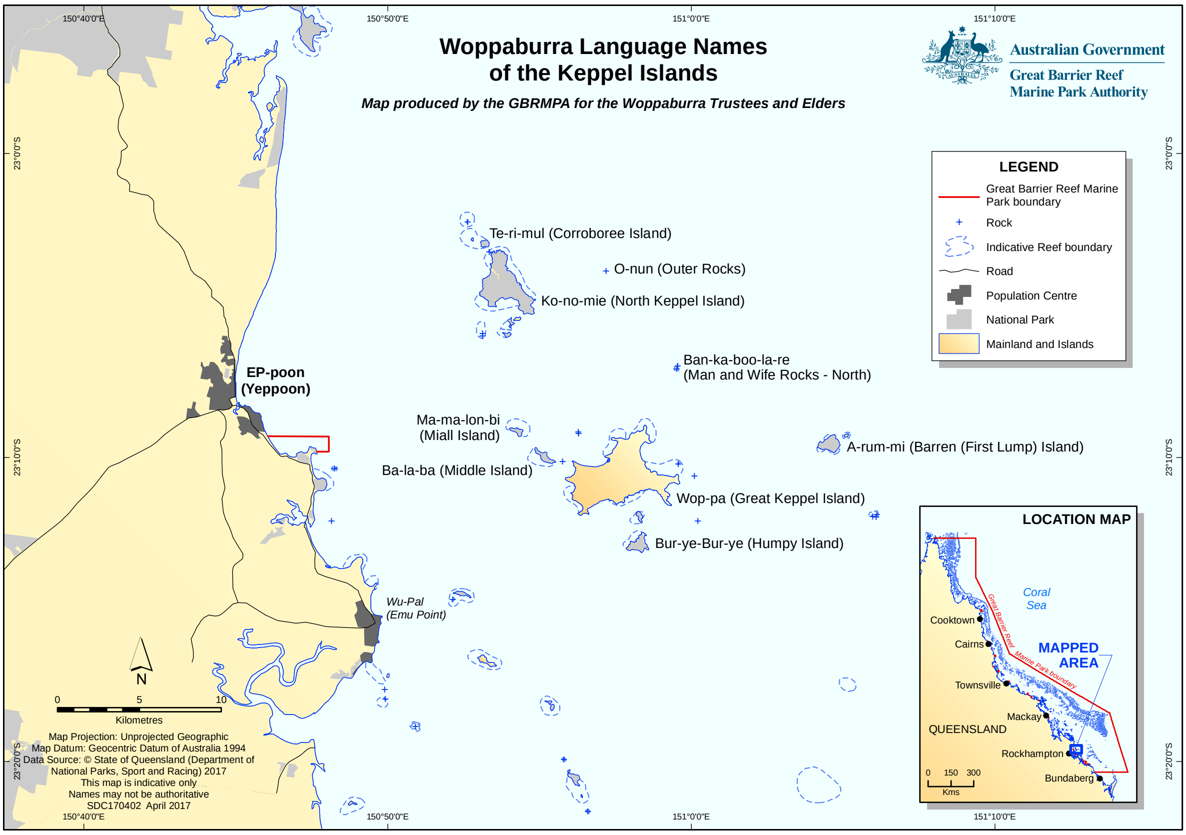


Figure 3.6 Woppaburra language names of the Keppel Bay Islands (GBRMPA 2017).

Today, the Woppaburra People engage in the continuation of cultural traditions and use of marine resources through both traditional and contemporary stewardship practices. These objectives are met in collaboration with family-operated oyster farmers and the Great Barrier Reef Marine Park Authority (GBRMPA). The Traditional Use of Marine Resources Agreement (TUMRA) maintained by the Woppaburra People, delivers caring for Country responsibilities via Indigenous sea ranger programs and overseeing of spiritual and physical activities by Woppaburra Elders. The *Balban Dara Guya*

(Leeke's Creek) Fish Habitat Area, declared in 2016, is a testament to the success of collaborations between local community members, the Woppaburra People, scientific research teams and the Queensland State Government (see DES 2017) (see Figures 3.7 and 3.8). Facilitating an important role in this initiative and ongoing cultural and environmental education, is the NKIEEC which is available to international, interstate and local school groups.

Figures 3.7 and 3.8 Left, Woppaburra Traditional Owner committee launching the Leeke's Creek Fish Habitat Area *Balban Dara Guya* in 2017 (Photograph, Australian Museum 2017); right, North Keppel Island Environmental Education Centre (Photograph, NKIEEC 2018).

3.2.2 Woppaburra Traditional Ecological Knowledge

Traditional Ecological Knowledge (TEK) plays an integral role in Woppaburra culture and everyday lifeways. The use of marine resources, and terrestrial plants and animals for food and ceremonial activities is based on generational transmission of knowledge. This knowledge is at the centre of Woppaburra cosmology, spirituality and identity. As explained by Van Issum (2016:98), land and sea Country, resources, material culture, and spiritual and cosmological practices are as significant as each other for 'the survival and ongoing cultural practice of the Woppaburra'. These aspects are encapsulated in the Woppaburra cultural map - a visual and symbolic representation of Elders' TEK. It explains the 'trinity between human, physical and spiritual worlds' and is 'a contemporary representation of traditional practice' (Van Issum 2016:109, 131) (Figure 3.10 and Table 3.1). Creation stories, storytelling and song-lines facilitate the transmission of such knowledge, revealing connections to the clan group totem *Mugga mugga*, ceremony, use and harvesting of resources, and movement across land and sea Country (Van Issum 2016:103, 106). Whale Song – the start of the Woppaburra song-line, pays homage to *Mugga mugga* - believed to 'contain the spirits of ancestors' (Van Issum 2016). During *Konomie* (September to October) the Woppaburra People engage in ceremony which includes fertility and birthing celebrations, and male initiation or 'coming-of-age' trials which follow the seasonal behaviours of *Mugga mugga* (e.g. fasting traditions, see Van Issum 2016 for comprehensive details).

Male initiation ceremonies are traditionally held at bora rings (circular shaped initiation sites on sacred ground) oriented with the southern cross constellation (Van Issum 2016:87). In the past, initiation trials included a number of mental and physical tests, of which body scarring was achieved by cuts to the body with sharp edges of *waku* (oyster) or *eugari* (pipi) shells (Elkin 1994; Roth 1898a, 1898b). These markings represent the throat grooves of *Mugga mugga* (Roth 1898a, 1898b). Figure 3.9 shows Ulowa, an initiated Woppaburra ancestor with scars to the chest area symbolising status and identity. Patterns painted onto Woppaburra dancers during important ceremonies also depict the throat grooves of *Mugga mugga* (Van Issum 2016:85). Just prior to *Mugga mugga's* arrival and the commencement of ceremonies, cooler conditions were taken advantage of to manufacture tools and to attend to the repairing of fishing nets (Van Issum 2016:129).

Indeed, TEK, oral histories, archaeological evidence and ethnographic recordings emphasise the importance and style of tools used to procure marine resources. Ethnographic recordings of Woppaburra material culture by Roth (1898a, 1898b, 1908, 1910a, 1910b, 1910c, 1910d, 1910e) (summarised by Rowland 1992) and archaeological work by Rowland (see Rowland 1980, 1981, 1992; and see Horsfall 1982), describe a range of materials, including: fish hooks made from turtle bone, fish hooks made from pearl shell (*Pinctada* spp.) and coconut shell and/or wood, fishnets, wooden oyster picks, nautilus shell necklaces and jewellery, coral files, stone artefacts including quartz drills, harpoons, dilly bags, boomerangs, swords and shields, swimming logs, three piece canoes and dug-out canoes. In particular, the use of shell fishhooks made from *Pinctada* spp. are testament to long-term (~1200 years) hook and line fishing in the area by the Woppaburra People (Rowland 1981, 1992). A photographic guide to Woppaburra material culture can be found at: https://australianmuseum.net.au/objects-of-the-woppaburra-people. Other uses of cultural materials arranged throughout the cultural landscape are also noted.

Increase sites, which are typically recognised as arrangement/s of piled stones and bones of large marine fauna at high 'lookouts', were probably used by the Woppaburra People to access ancestral assistance when hunting for turtle and dugong (see McIntyre-Tamwoy and Harrison 2004, and discussed by Van Issum 2016:124). Dugong were probably only opportunistically hunted due to their main habitat, sandy-seagrass meadows, being fairly limited in the area (WTOHA 2019:12). The extent of sandy-seagrass meadows that might have existed in the past, however, has not been established. Indeed, sandy-seagrass meadows are also favoured by turtles for the acquisition of food. Turtle, dugong and fish were caught during the day by hand, and other fish were attracted with soldier crab bait around rocky substrates at night (see Van Issum 2016:96; WTOHA 2019:12). At the blooming of flowering wattles, the Woppaburra People know that blue-tailed mullet and other schooling fish become available, especially at Mazie Bay and Clam Bay which consist of shallow sandy substrates (Van Issum 2016:107; WTOHA 2019:12). Other seasonal indicators signify the time of year when turtles and turtle eggs become available (e.g. *Yamal*, *Dana*, *Tang-go-I*). In the past, the Woppaburra People consumed turtle eggs and meat immediately, or stored them for later use when other food resources were not as abundant during the year (WTOHA 2019:12). The pandanus swimming log, depicted across *Garimal* (summer) in the cultural map, is representative of inter-island water crossings which the Woppaburra frequently used to access and harvest resources in preparation for the wet season (Van Issum 2016:81). Ancestral dolphins assisted the Woppaburra during these crossings to 'show the safest route home through the water' (Van Issum 2016:107). Rich socio-ecological connectedness where the Woppaburra People take, and in past contexts 'took council from nature', is an act of nurturing the ongoing access and availability of resources and respect for cultural practices (Van Issum 2016:122).

Figure 3.9 Ulowa (c. 1897) with *waku* (oyster) scarring. This historic photograph is held in the H.A. Craig Collection at the Rockhampton Municipal Library (courtesy, Van Issum 2017).

Figure 3.10 The Woppaburra cultural map. The Woppaburra lifecycle and connection to Country as a visual and symbolic expression showing the seven overlapping seasonal phases, totemic fauna and flora, and references to resource use (by artist Glenn Barry, in Van Issum 2016:113).

Table 3.1 Corresponding information to the seven overlapping seasonal changes presented in the Woppaburra calendar (WTOHA 2019 and Van Issum 2016). Please note that some wording is taken directly from key sources to maintain the integrity of meaning intended for interpretation. Note that naming of seasonal phases are recorded by place, climatic element/s, or important totemic or food resources. The first phase, *Konomie*, is represented with *Mugga mugga* and continues in a cyclical anti-clockwise direction. Loosely corresponding Western calendar months: *Konomie* = September and October, *Tang-go-I* = November, *Garimal* = December, *Yamal* = January and February, *Yamal/Dana* = March, *Bapam* = April and May, *Giru* = June, July and August.

Woppaburra Seasonal Descriptions	Fauna and Flora	TEK/Resource Use	Specific Cultural Practices
Konomie (North Wind, North Keppel Island) occasional rain, morning south-easterly winds, afternoon north-easterly winds, some northerly winds, large tidal changes, clear skies	*Mugga mugga* (humpback whales)	return in October, *Mugga mugga* consume little food, Woppaburra group totem, never hunted or consumed	most important time for male initiation 'coming of age ceremonies' which might occur once per year or only a few every few years, celebration of fertility and birthing, family groups resided in one large camp, communal gathering and fasting common at this time of year, social behaviour and symbolism mimics *Mugga mugga*
	box jellyfish	arrive with the winds	
	cocky apple	flowers at night, bark and roots used as medicine and as a poison to 'stun' fish	
	do-Ion, gunda (white current, cabbage tree palm)	flowering	
	nuni, ombo ombi (sandpiper fig, bush palm)	flowering	
	wan-di, wander (pandanus nut, grasstree)	flowering	
	wandoon, ya-win-yob (scrub honeysuckle, wild cherry)	flowering	
	coral spawn	presence and odour signal seasonal change	
Tang-go-I (turtles) warm air temperature	*Tang-go-I* (green turtle, loggerhead turtle, flatback turtle)	adult turtles return to lay eggs, sticks used to locate nests 30-50cm below soft sand, eggs harden in 60 days, mid-sized turtles also harvested in deeper water by 'diving in and	

Woppaburra Seasonal Descriptions	Fauna and Flora	TEK/Resource Use	Specific Cultural Practices
		holding onto the shell', food resource, personal totem animal (no hunting or consumption allowed), northern oriented beaches important for sourcing turtle	
Garimal (heat) long cloudy (*burum*) days, hot air temperature, rains begin, summer high tides			
Yamal (rain) summer rains, warm air temperature, higher humidity, strong winds, tropical storms	*Tang-go-I* (green turtle, loggerhead turtle, flatback turtle)	warm climate helps to hatch turtle eggs (about 120 in each nest)	greater access to freshwater, flowering plants and their fruits become more important food resources during these months, travel between islands to harvest turtle eggs before hatchings emerge, travel then slows down as summer rains settle and tropical storms become likely, occupation on one island persists throughout this season, ceremony discontinues until the return of *Mugga mugga*
Yamal/Dana (wet/humid) summer rains, warm air temperature, high humidity, strong south-easterly winds, tropical storms	*Tang-go-I* (green turtle, loggerhead turtle, flatback turtle)	turtle hatchlings migrate towards the ocean and continue north with ocean currents at night	northern and western locations on the islands were used as refuges from rough weather, turbid waves and strong tides, occupation on one island continues
Bapam (moon) reduced rain, cooler air temperatures, average winds, large tidal changes	*waku* (oysters)	low tides give exposure to oysters and coral reefs, fish become more abundant	good time to burn parts of Country for regeneration of plants

Woppaburra Seasonal Descriptions	Fauna and Flora	TEK/Resource Use	Specific Cultural Practices
Giru (cold) short days, low rainfall, slow winds, westerly winds	*guriala* (large sea eagle)	common at this time of year, totem animal	good time to burn parts of Country for regeneration of plants, travel between islands to permanent freshwater sources due to scarcity of water elsewhere
	gural (mullet)	migrations from estuaries into the sea 'shallow costal flats', catch with surface nets, food resource	
	waku (oysters)	harvesting a few days before the full moon is best, food and artefact resource	
	mud crabs	become more abundant at the end of this season, food resource	

3.2.3 Ethnography and European Contact

The first European sighting of people occupying the Keppel Bay Islands was in 1770 by crew on-board Captain Cook's Endeavour (Beaglehole 1955; 1963). Records from these sightings documented only a few people and smoke from fires, which resulted in minimal contact and communications (see accounts in Matthew Flinders 1814, Captain Phillip King 1827, and John MacGillivray 1852). Although these potential early encounters for the arrival of European people cannot be easily recalled by Woppaburra Elders (see interviews conducted in Van Issum 2016), accounts of the historic period survive in the memories of the Woppaburra People. A little time after Captain Cook's Endeavour sailed through the area, in the mid-1800s on the adjacent mainland coast, European people became interested in the region for gold mining and sheep farming (Rowland 1992:8). By 1866, the first cattle station lease on Great Keppel Island commenced which led to hostile and aggressive attacks on the Woppaburra People (Rowland 1992:8-10). Rowland notes: 'it appears a number of North Keppel Islanders were shot at this time' (Rowland 1992:10), and these continuing brutalities led to the displacement of the Woppaburra people. European oyster farming also made quite a large contribution to the commercial market which continued throughout the historic period, as did the continual growth of goat populations that decimated, to varying extents, local flora and fauna (Creighton 1984:10, 124-125; Rowland 1992). Rowland (1992:ii) notes that after the forceful removal of Aboriginal peoples in 1904, the first physical contact Woppaburra Elders had with the Keppel Bay Islands was in 1984.

3.3 Previous Archaeological Research

Archaeological research within the northern, central and southern regions of the GBR is still in its infancy. Nonetheless, within offshore island groups located inside the modern GBRMP boundary, numerous cultural resource use sites, rock art, ceremonial stone arrangement complexes, stone tools and quarry sites have been documented (for key adjacent mainland research and other GBR offshore islands see for e.g. Barker 1991, 1996, 1999, 2004; Beaton 1973, 1985, Border 1993; Cribb and Minnegal 1989, Minnegal 1984a, Minnegal 1984b for Princess Charlotte Bay). One of the earliest known Aboriginal occupation sites within the GBR is located at Mazie Bay on North Keppel Island.

3.3.1 The Keppel Bay Islands, Southern Great Barrier Reef

Between 1978 and 1991, Rowland conducted the most extensive archaeological surveys of the Keppel Bay Islands. Details from early survey work covering sites across North Keppel Island, South Keppel Island, Corroboree Island, Pumpkin Island, Sloping Island, Miall Island, Middle Island, Halfway Island and Humpy Island are summarised in Rowland 1992 (see also Rowland 1980). Excavations by Rowland took place at South Keppel Island in 1980, and at Mazie Bay on North Keppel Island in 1979 (Trench A) and 1981 (Trench B) (Rowland 1992:84-85). The 1981 site plan for Mazie Bay can be consulted in Appendix B. Preliminary radiocarbon dates from Trench A revealed an occupation chronology extending from 4200 BP to modern times (Rowland 2007; and see McNiven et al. 2014 for similar occupation chronology for the neighbouring Shoalwater Bay Islands, and see Barker 2004 for Whitsunday Island occupation extending to ~9000 years ago). Rowland (1999a) argues for continuous occupation at the Mazie Bay site and proposed a significant change in sand dune formation ~3500 BP. Lithic artefacts were examined by Horsfall (1982) who suggests a 'small tool tradition' operated within the Keppel Bay Island group (see Darvill 2009 for definition of the Australian Small Tool Tradition). Horsfall's (1982:77) small tool tradition model proposes island-to-mainland trade of lithic artefacts, where silcrete tools were traded in from the mainland. Whether this was a continuous tradition throughout the Holocene remains to be determined (Horsfall 1982:77). Other Keppel Bay Island group stone artefacts are made from quartz, greywacke, igneous rock, rhyolite, chert and mudstone (Horsfall 1982:74-75). Hall and Barker (1989) and Hall (1991) later completed smaller archaeological surveys in proposed areas for development on South Keppel Island.

3.3.2 Mazie Bay, North Keppel Island

Mazie Bay is located on the southern side of North Keppel Island and is the largest known cultural site within the Keppel Bay Island group (Figure 3.11) (Rowland 1992, 1999a, 2007). A marine lagoon area comprising soft sands and no deeper than ~4m extends ~520m to a reef slope that drops to 7m depth (Leonard et al. 2020b). Extensive rocky outcrops are located at each end of the beach and beyond the high tide mark. Three aeolian sand dune ridges dominate the site, with the middle ridge containing the Woppaburra cultural resource use site (Rowland 2007, 1999a). A swamp area runs along the back length and northern end of the dune system and is lined with Cabbage Tree Palms (*Livistona decipiens*). The 1979 archaeological excavation at Mazie Bay comprised 5 (2m x 2m) contiguous squares (squares A1-A5, Trench A) (see Figures 3.12, 3.13 and 3.14) (Rowland 2007, 1999a). Square A1 and Square A5 are representative of the pre- and post 3500 BP units identified by Rowland (see Rowland 1999a). The molluscan assemblages comprising Square A1 and Square A5 returned a high quantity of materials and are targeted in this research for further examination. Rowland's excavation approach and quantification details is provided below. Squares A2, A3, and A4 are not included in this review.

Excavation Approach

The recovery of materials from the Mazie Bay cultural resource use site in 1979 presented a number of challenges to Rowland and the excavation team. Given the site was based in a sloping sand dune, 1m baulks were installed between each of the excavation squares to assist in maintaining the integrity of the stratigraphy. Square A1 was placed at the top of the sand dune and Square A5 was placed downslope in the direction of the swamp area. The density of materials was not anticipated by Rowland and subsequently, strategic measures for the recovery of samples was undertaken (Michael Rowland pers. comm. 2016). This included the excavation of 5cm excavation units (XUs) in the upper layers and 10cm XUs in the lower layers (Michael Rowland pers. comm. 2016). Due to time and safety constraints, a 30cm auger core was carefully deployed in Square A5 (stratigraphic unit 8-9) to extract a sample of the deepest unexcavated materials. The auger core reached a depth of 3.44m (see Figure 3.15) (Rowland 1999a). pH tests for all stratigraphic units measured a broadly neutral range of 7-8 (Rowland 1999a). Materials recovered from the site were sieved through 1/8” (3.17mm) mesh, placed into clearly labelled bags and transported to the University of Queensland (Michael Rowland pers. comm. 2020).

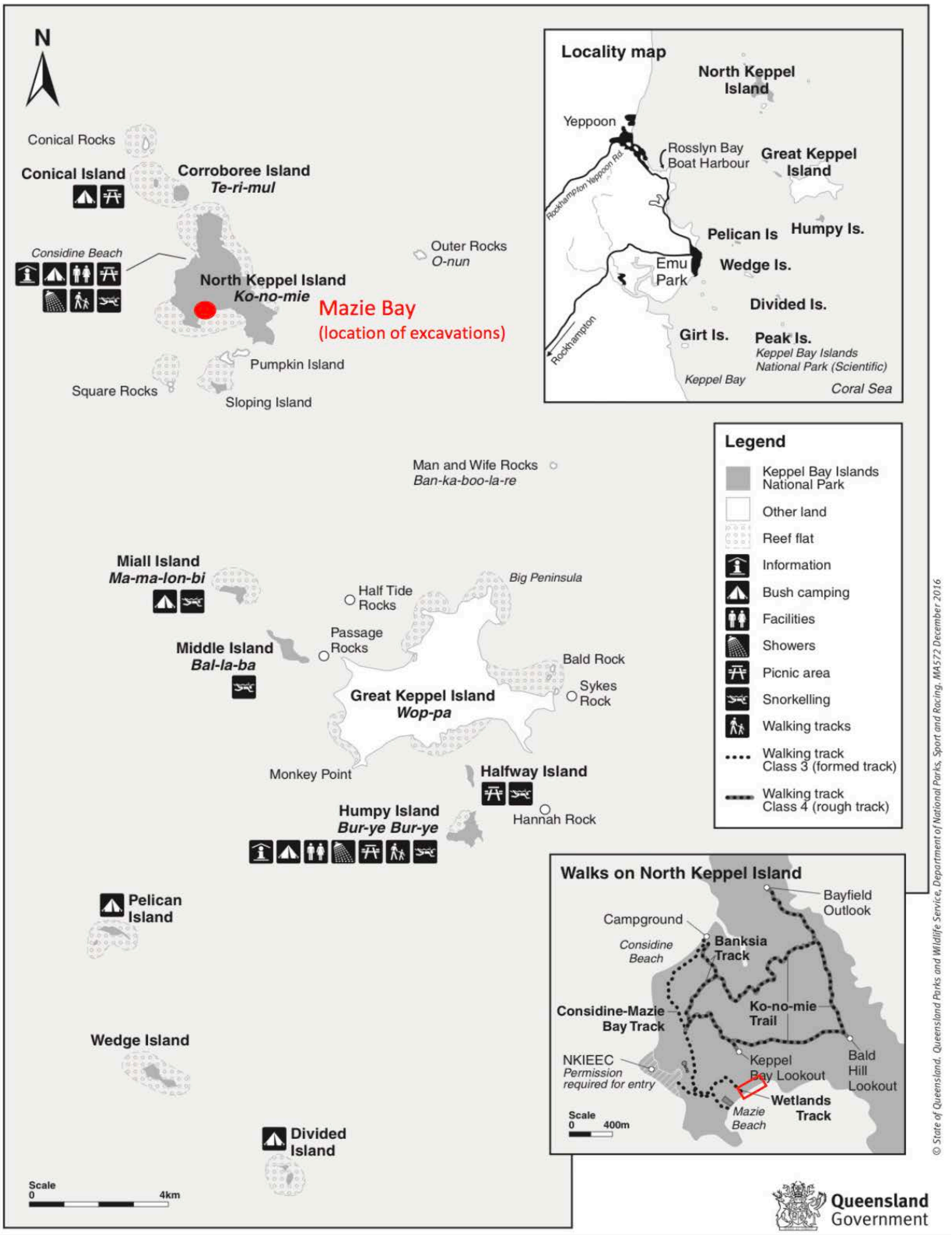


Figure 3.11 Keppel Bay Islands National Park map, showing the location of archaeological excavations at Mazie Bay by Rowland in 1979 and 1981 (after QPWS 2016).

Quantification Approach

Preliminary laboratory work conducted by Rowland and colleagues was completed at the University of Queensland, Brisbane. Mollusc, bone, and stone materials were sorted and weighed to the nearest 1g. Weight data for the molluscan materials arising from Rowland's 1979 laboratory analysis, and the rationale for taxonomic groupings can be consulted in Appendix B. All nomenclature appearing in these datasets has been updated as at December 2019, using the World Register of Marine Species (WoRMS editorial board 2019), except where noted otherwise. Weight summaries from Square A1 and Square A5 show Ostreidae (oysters) to be the most dominant with *Pinctada* spp. showing the second highest contribution (Figure 3.16). Chapter 5 uses these data in cooperation with findings arising from Hermes' (1984) fish bone analysis and radiocarbon dates to begin examining the socio-ecological trajectory at Mazie Bay.

Figures 3.12, 3.13, 3.14 Mazie Bay archaeological excavation, North Keppel Island, led by A/Prof. Mike Rowland 1979 (Photographs, courtesy Rowland). Left, Mazie Bay; middle, excavation of squares A1 to A5; right, Ian Walters excavating.

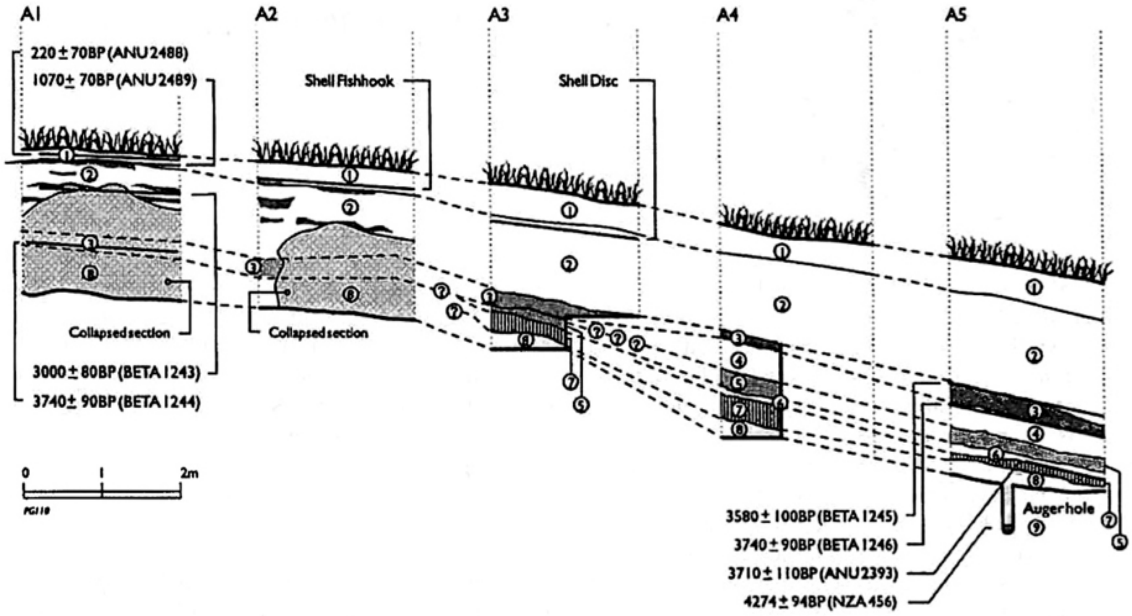


Figure 3.15 Section drawing of the Mazie Bay cultural site excavation, south section (from Rowland 1999a:142).

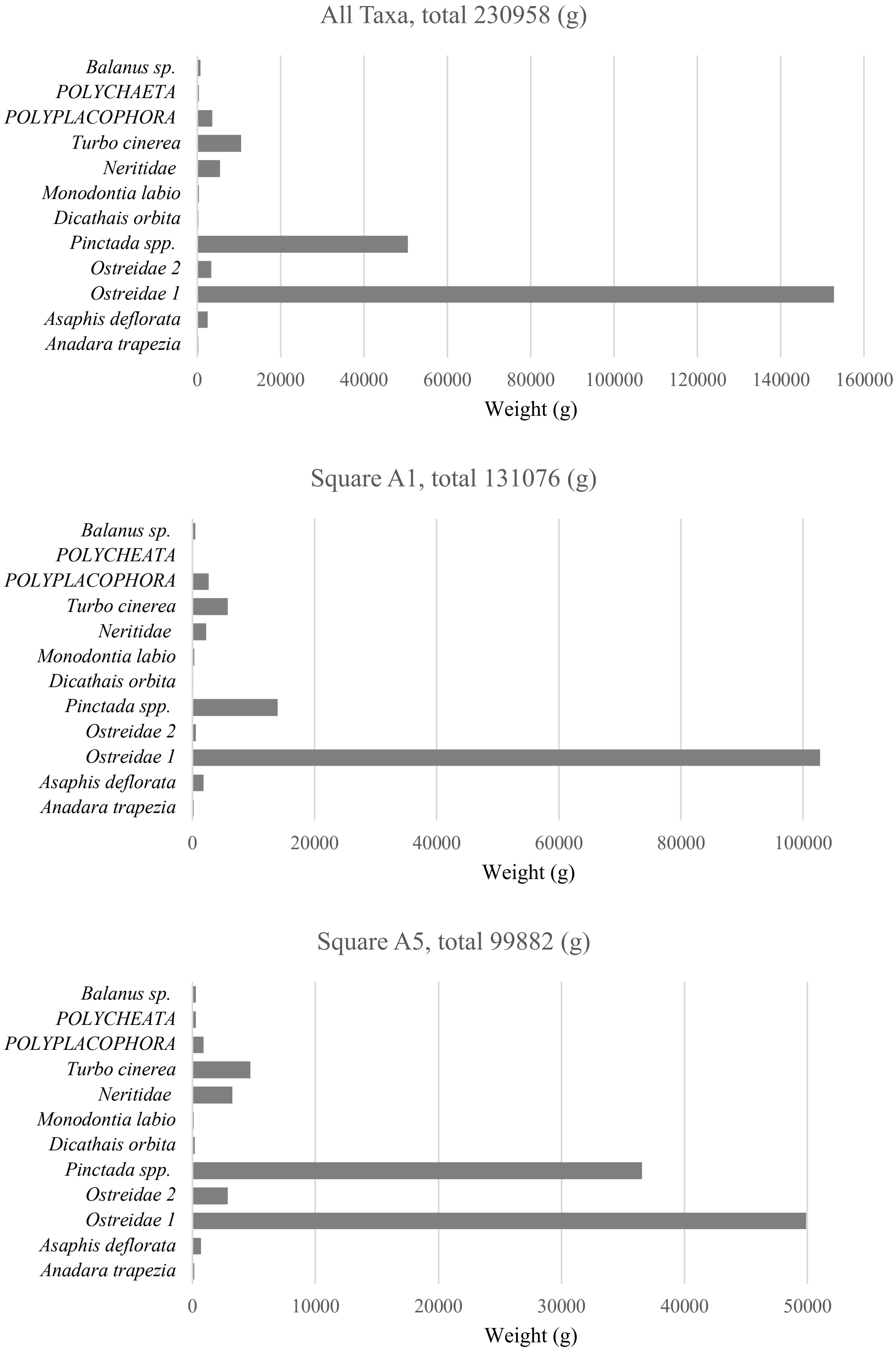


Figure 3.16 Total taxonomic weights for Square A1 and Square A5, Mazie Bay, from Rowland's 1979 laboratory analysis.

3.3.3 Other Deep Time Sites within the Keppel Bay Islands

Other deep time cultural sites were surveyed using archaeological methods by Rowland and others in 1978, 1979, 1980 and 1981, and by Hall and Barker in 1989, at North Keppel Island and South Keppel Island. At North Keppel Island, these included Monkey Point, Stockyards Beach and Considine Bay, however excavations of these sites were not undertaken (Rowland 1992:96-100). The Monkey Point rock shelter contained a cultural scatter of material comprised of sunset shells (*Asaphis violascens*), oysters (*Saccostrea cucullata*) and stone artefacts (Rowland 1992:96). Stockyards Beach revealed a shallow 5-10cm cultural deposit of *S. cuccullata* and quartz flakes from an auger sample (Rowland 1992:97-98). At Considine Bay, shell scatters and stone flakes were identified in the low sand dune system (Rowland 1992:98, 100). At North Keppel Island, Rowland (1992:104-105) identifies a higher diversity of botanical species (including the absence of the Cabbage Tree Palm, *L. decipiens*), landform features, and hydrological properties in comparison to South Keppel Island. Deep time sites at South Keppel Island were identified at Big Peninsula Quarry, The Clam Bay Ridgelands, Putneys Beach, Leeke's Beach, Little Svensden's and Svensden's Beaches, Big Sandhills Beach, Wreck Beach, Little Wreck Beach, Long Beach, Monkey Beach, Clam Bay, and Red Beach.

Putney's Beach, Leeke's Beach, Little Svensden's Beach, Svensden's Beach, and Long Beach revealed surface scatters of mollusc shell and stone artefacts, with the dominant components being *S. cuccullata* and quartz stone tools (Rowland 1992: 107, 109-111, 118-119). Red Beach is characterised by 6m high Pleistocene sediment, sand dunes, and an extensive scattering of stone tools (Rowland 1992:121-122). Rowland (1992:122) notes that Red Beach was a 'substantial campsite where substantial stone knapping was undertaken' and includes flakes, flake scrapers, hammer stones and firestones. Excavations of Big Peninsular Quarry, Little Wreck Beach, Wreck Beach, Big Sandhills Beach and Monkey Beach at South Keppel Island were undertaken in 1980 by Rowland. Big Peninsular Quarry is defined by Rowland (1992:105-106) as a 'stone working area' rather than a quarry. He recorded hammer-stones and flakes manufactured from a primary rock source at the site but noticed a limited scatter of oyster shells, concluding that it was not a main campsite (Rowland 1992:105-106). Two test trenches at Little Wreck Beach to 25cm depth recovered stone artefacts, including hammer-stones made from quartz, milky quartz, chert, rhyolite and sandstone (Rowland 1992:113-114). The dominant molluscan species is *S. cuccullata* (Rowland 1992:113-114). At the western end of the beach a fireplace and base of a hut, identified by a series of stones placed in a circle, was also uncovered (Rowland 1992:113-114).

The Wreck Beach excavation revealed stone flakes, anvils, scrapers and mollusc shell, primarily *S. cuccullata*, Neritidae and *Pinctada sugillata*. Big Sandhills was excavated in 2 x 1m^2 squares to a depth of 20cm (Rowland 1992:111-112). Stone artefacts included hammer stones, anvils and grindstones made from sandstone, quartz and rhyolite, with one *juan* knife made from silcrete (Rowland 1992:111-112). Marine species at the site included *S. cuccullata*, *A. violascens*, *P. sugillata*, Neritidae, turtle and fish (Rowland 1992:111-112). A test square at Monkey Beach was excavated to a depth of 40cm but materials were present in the top 5cm only, including *S. cuccullata*, *L. cinerea*, *A. violascens*, *Monodonta labio*, *P. sugillata*, and stone flakes made from quartz, quartzite and sandstone (Rowland 1992:118-119). In addition to these findings, a clay pipe and modern glass indicated that Monkey Beach was perhaps occupied during the historic period (Rowland 1992:118-119). A 50cm^2 test pit excavated at Clam Bay revealed *S. cuccullata* as the dominant taxon, with different species to those recorded at other South Keppel Island sites including, *Cypraea* sp., *Trichomya hirsuta* and *Chlamys* sp. (Rowland 1992:119).

The dominant shellfish species at the North Keppel and South Keppel Island cultural sites is the rock oyster, *S. cuccullata*. From Rowland's surveys and excavations in the late 1970s we understand the Mazie Bay cultural site to represent the earliest, largest, most diverse, and densest known cultural material assemblage. Other known sites within the Keppel Bay Islands date to within the last ~1500 years (Rowland 2007). These site locations may have been major camp or quarry sites in the past; however, as Rowland (1992) argues, erosion and oscillating sea-levels might have influenced the visibility and integrity of these deposits.

3.4 Discussion

Archaeological evidence, oral histories, and ethnographic accounts show how marine resources are a central component in the lives of the Woppaburra People. The Woppaburra seasonal calendar and Rowland's (1979) preliminary analyses of molluscan remains from Mazie Bay, reveal that intertidal zones were favoured to procure marine resources. The harvesting of marine resources in the recent past (i.e. extending to the maximum length of time living memory can serve) to modern times is explained by the Woppaburra People to agree with a cyclic seasonal patterns. Interestingly, Creighton (1984) suggests faunal resources have undergone extensive shifts in availability and abundance in recent times. This notion is based on early 1980s survey work undertaken within the Keppel Bay Island group. His findings propose *P. sugillata* populations decreased, macropod populations declined, and the local koala population went extinct since the arrival of European people in the region (Creighton 1984; and see Rowland 1985). Creighton's observations and Rowland's preliminary analyses speculate, rather than confirm, influences responsible for socio-ecological changes within the Keppel Bay Island group.

Existing scientific datasets describe the Holocene as a 'high energy window' where peak biodiversity occurred ~5500 years ago. After this time, the socio-ecological trajectory at Mazie Bay shows considerable variability. These changes might have been influenced by local site-specific changes or larger scaled mechanisms (e.g. altered harvesting patterns, climatic and environmental variations) or combinations of these factors. Resource use trends and the availability of faunal populations to the Woppaburra People might have been linear, ad-hoc, or cyclic during the Holocene, or, trends might have varied at key temporal intervals. In any case, high-resolution datasets are needed to tease out socio-ecological complexities that operated during the Holocene at Mazie Bay. The examination of materials extracted from deep time, using newly available techniques, presents the unique opportunity to assess a long-term socio-ecological record from the Keppel Bay Islands.

3.5 Summary

The GBR is a tremendously rich bioculturally diverse region of the world. The Keppel Bay Islands, home to the Woppaburra People, shows at least ~5000 years of marine resource use and deep cultural connection to sea Country. The context for the re-analyses of the Mazie Bay cultural resource materials, and factors potentially influencing change to Woppaburra resource use and to the availability of resource populations, has been introduced in this chapter. Due to the enormity, density, and cultural significance of marine resources Mazie Bay offers, it is an ideal case in which to examine socio-ecological dynamics. Chapter 4 identifies the variables influencing change and critiques newly available analytical techniques to the study.

4

Analytical Techniques

4.0 Introduction

This Chapter begins by identifying key variables potentially influencing Woppaburra resource use patterns and mollusc growth at Mazie Bay during the Holocene. Three analytical techniques to test Mazie Bay molluscan samples against key variables are then reviewed: biometrics, sclerochronology and stable isotope biogeochemistry. Although these analytical techniques have been applied to various taxa in zooarchaeology, this review is concerned with their application to the shells of molluscs only. Of the zooarchaeological studies that have examined molluscs using these techniques, most have focused on species from temperate Northern Hemisphere regions and seldom for species in tropical Southern Hemisphere regions. Only three zooarchaeological studies have employed metrics to some Great Barrier Reef (GBR) mollusc species, and no studies have made use of sclerochronology or biogeochemistry techniques. The potential for GBR mollusc shells derived from cultural contexts to provide insights into human resource use patterns and palaeoclimatic proxies has profound implications.

4.1 Mechanisms, Variables and Multi-Variable Analyses

While it is ideal to describe socio-ecological trajectories to be of one and the same phenomena, it is necessary to some extent, for the purposes of examination, to discriminate between different types of variables (but see discussion in Chapter 2, section 2.2). Single driving forces or multiple sets of variables operating under human, climatic, or environmental mechanisms, ultimately unite to define complexities in socio-ecological structures (see Crain et al. 2009). This view appreciates that humans and the environment should not be treated as ‘simplistic separations’ but as interrelated and ‘embedded’ (Head 2008). The Woppaburra Peoples’ long-term occupation at the Keppel Bay Islands is no exception. Multiple variables working prior to, during, and continuing throughout human occupation shape the cultural landscape. Table 4.1 summarises variables extrapolated from information reported in Chapter 3 for what the Mazie Bay intertidal and shoreline context might have looked like through time. A research analysis priority rank is assigned to each variable, based on the degree of variable intensity, as a way of identifying change and/or stability at Mazie Bay during the Holocene. Table 4.2 explores the analytical techniques appropriate for testing these variables.

Table 4.1 An evaluation of variables relevant to the Mazie Bay cultural site analyses. Priority 1 shows the highest significance to Mazie Bay cultural materials and priority 0 has the least importance. Note: variables that cannot be tested here but are assigned a rank 1 or 2 priority suggest further analysis is required beyond this project.

Mechanism	**Variable**	**Interpretation Example/Rationale**	**Examination Approach**	**Priority**
CLIMATIC AND ENVIRONMENTAL	Sea Surface Temperature (SST)	Changes in seasonal temperature patterns e.g. wet and dry months might affect trends in mollusc growth; can influence Woppaburra seasonal harvesting patterns.	Use shell chemistry to reconstruct SST values, build proxy dataset. Use dominant species for sampling from Woppaburra occupation phases. Compare to live-collected control samples.	1
	Sea Surface Salinity (SSS)	Changes in seasonal precipitation patterns including evaporation e.g. wet and dry months might influence trends in mollusc growth; can influence Woppaburra seasonal harvesting patterns.	Use shell chemistry to reconstruct SSS values, build proxy dataset. Use dominant species for sampling from Woppaburra occupation phases. Compare to live-collected control samples.	1
	Water Mixing	Changes in terrestrial run off or currents might influence growth patterns in mollusc species and/or signal seasonality; significant run-off and flood plume events recorded for the Fitzroy River adjacent to North Keppel Island; can change availability of resources to the Woppaburra People.	Test shell chemistry for terrestrial/marine values, build proxy dataset. Use dominant species for sampling from Woppaburra occupation phases. Compare to live-collected control samples.	1
	Sea-Level Oscillations	Changes in location of mollusc populations; could have influenced Woppaburra occupation locales and resource harvesting sites (e.g. prograding shorelines).	Record presence/absence data of species. Target rocky shore species with known vertical growth limits e.g. *Saccostrea cuccullata*.	1

Mechanism	Variable	Interpretation Example/Rationale	Examination Approach	Priority
	Tidal Cycles and Moon Phases	Changes in access to mollusc food and nutrients e.g. aerial exposure versus inundation and spawning patterns; can signal availability of resources to the Woppaburra People or timing of resource harvesting.	Record mollusc sclerochronologies and compare with seasonal growth indices. Assess species with intertidal habitat preferences. Consider aerial respiration capabilities with growth. Use available literature to understand spawning behaviours. Compare with live-collected control samples.	1
	Species Population Density	Changes to species population density due to environmental impacts e.g. competition for space.	Record size and shape differences in species with clustering abilities (e.g. *Saccostrea cuccullata*).	1
	Tropical Storm Events	Changes in mollusc growth due to impacts by tropical storms e.g. periodic sedimentation, turbidity, or freshwater flooding from cyclones; can signal availability of resources, infer occupation trends, or resource harvesting patterns by the Woppaburra People.	Observe seasonal tropical storm trends for the region using existing climate data. Examine disturbance to shell samples and make use of shell chemistry values. Build proxy dataset.	1
	Primary Productivity	Changes in eutrophication or hypoxia events e.g. due to algal bloom events, upwelling or toxicity from red tides; can signal availability of resources to the Woppaburra People.	Interpret mollusc shell chemistry. Record presence/absence data of species. Record size and shape differences across species assemblages and hypothesise extent of primary productivity role.	2
	Waves and Currents	Changes in turbid conditions might influence morphology of mollusc shells; can signal site locations of Woppaburra harvesting.	Record size and shape of mollusc shells, focus on morphological features.	2

Mechanism	Variable	Interpretation Example/Rationale	Examination Approach	Priority
	Geomorphological Events	Changes in habitat composition i.e. substrate such as sediments in intertidal zone or beach matrix such as sand dune formations (influences prograding shorelines) due to environmental events; can signal changes in Woppaburra occupation locales or resource harvesting sites.	Measure stratigraphic features at the cultural site. Record presence/absence of species. Examine morphological features of mollusc shells to deduce geomorphological characteristics of species habitats at the time of being harvested.	2
	Species Invasions	Changes to native fauna composition e.g. from pumice rafting; can signal opportunity for Woppaburra harvesting to include other species.	No immediate signal for species invasions from the Mazie Bay cultural site materials during Woppaburra occupation; however, this remains to be tested. Due to time constraints, species invasions potentially owing to natural causes will not be assessed here.	0
	pH Levels	Changes in the acidification of ocean water causing bleaching events and species deaths; can signal the availability of resources to the Woppaburra People.	Not available from Mazie Bay mollusc shell materials i.e. wet tissue components are absent.	0
ANTHROPOGENIC	Fishing/Harvesting (incl. bycatch)	Changes in species population densities and growth success; might signal changes in resource use patterns, changes in technologies for resource procurement, or Woppaburra population growth.	Record size and age data using biometric techniques.	1
	Geomorphological Events	Changes in site composition e.g. substrate such as sediments in intertidal zone or sand dune matrices could be signalled from human use of the landscape e.g. large-scale firing events; changes in Woppaburra occupation locales or resource harvesting sites.	General stratigraphic features as per Rowland (1999a) excavation notes.	1

Mechanism	Variable	Interpretation Example/Rationale	Examination Approach	Priority
	Disease and Foreign Contaminants	Changes in species growth success.	Disease or foreign contaminants potentially introduced at the time of human occupation.	1
	Ocean-Based Pollution (macro)	Changes to site use or resource habitats.	No signal for ocean-based pollution (i.e. plastics, metals) within the Mazie Bay cultural site.	0
	Ocean Mining (incl. dynamite fishing)	Changes to resource procurement and use.	No immediate signal for ocean mining or use of dynamite from the Mazie Bay cultural site materials. Potential use of toxic plants as an aid in fishing has not been assessed.	0
	Introduced Species	Changes to native fauna composition; can signal Woppaburra trade and exchange with other cultural groups or relocation trends.	No immediate signal for species invasions from the Mazie Bay cultural site materials during Woppaburra occupation.	0
	Climate Change	Changes in atmospheric pollution due to human events e.g. large-scale burning.	Not isolated to Woppaburra burning events but rather of a larger-scale magnitude, i.e. resolution of Mazie Bay cultural site does not allow for meaningful climate change interpretations in this context.	0

Table 4.2 Summary of variables assigned the highest priority rank and appropriate analytical methods to examine mollusc shell samples from Mazie Bay (references within this chapter). Preliminary assessments will be made on the available site stratigraphy and geomorphological interpretations.

Mechanism	Variable	Sample Availability Y/N	Analytical Method
CLIMATIC AND ENVIRONMENTAL	Sea Surface Temperature	Y	Stable Isotopes $^{18}O/^{16}O$ Trace Elements
	Sea Surface Salinity	Y	Stable Isotopes $^{18}O/^{16}O$ Trace Elements
	Water Mixing/Eutrophication/Primary Productivity	Y	Stable Isotopes ^{15}N, ^{13}C Trace Elements
	Sea-Level Oscillations	Y	Geomorphological Observations
	Tidal Cycles and Moon Phases	Y	Sclerochronology
	Species Population Density	Y	Biometry, Morphometrics
	Tropical Storm Events	Y	Sclerochronology Stable Isotopes ^{15}N, ^{13}C, $^{18}O/^{16}O$ Trace Elements
	Waves and Currents	Y	Biometry, Morphometrics
	Geomorphological Events	N	-
ANTHROPOGENIC	Fishing/Harvesting (incl. bycatch)	Y	Stable Isotopes $^{18}O/^{16}O$ Biometry Morphometrics
	Geomorphological Events	N	-
	Disease and Foreign Contaminants	Y	Trace Elements

A primary aim of this research is to define to what extent key variables influenced Woppaburra resource use and mollusc growth at Mazie Bay during the Holocene. In Australia, the employment of advanced analytical techniques to molluscan assemblages are in their infancy and yet to gain momentum as standard procedures for assessing socio-ecological dynamics. Several international zooarchaeological projects examining similar themes however, have had success in refining understandings about influencing variables through the application of biometrics, sclerochronology, and biogeochemistry techniques to faunal assemblages. The discussion below draws on international examples, detailing how and why these techniques are suitable for advancing interpretations in archaeomalacological research and palaeoenvironmental modelling. To understand basic applicability to molluscan assemblages, a brief introduction of the phylum is provided.

4.1.1 Molluscan Remains

The earliest molluscs derive from the Early Cambrian fossil record ~543 million years ago (Ponder and Lindberg 2008:1, 33). The phylum Mollusca is comprised of 9 classes: Bivalvia, Caudofeveata, Cephalopoda, Gastropoda, Monoplacophora, Polyplacophora, Rostronchia, Scaphopoda and Solenogastres (WoRMS 2019). Collectively, these invertebrate species form the second largest taxonomic group in the world and are morphologically defined as soft bodied organisms with usually, but not explicitly, an exoskeleton (Giribet et al. 2006:7723). Over millennia, molluscs have played important roles in human societies as food resources, as medicinal remedies, as important materials for tool and artefact manufacture, and in spiritual and cosmological contexts (e.g. Antzcak and Antzcak 2008). The earliest known human use of molluscs comes from a terrestrial site in the Rift Valley, Africa, where shell remains date between 2.5-1.7 million years ago (Erlandson 2001; Leakey 1971). In a marine context, the earliest evidence for the use of molluscs by *Homo sapiens* dates to ~164 thousand years ago from Pinnacle Point in South Africa (see reviews in Jerardino 2016a, 2016b). The high visibility of molluscs and volume of molluscan remains at cultural sites, particularly in coastal marine environments, is noted in many locations worldwide (Antzcak and Antzcak 2005:9; Buchanan 1985; Jerardino 2010). For instance, *Strombus gigas* shells at Los Roques Archipelago, Venezuela, exist in the thousands with each shell weighing ~2kg each (Antzcak and Antzcak 2005:9). In other cases, smaller molluscs have been the focus of human harvesting events (see Neritidae e.g. in Eichorst 2016). Differences in the use of larger or smaller mollusc species by human communities might have been influenced by a range of different factors, including a change in the availability of a species, totemic, spiritual or cosmological beliefs discouraging the use of certain species, needs or wants for artefact manufacture, preferences for taste or tenderness, ease of procurement and processing, protein or calorific return rates, or brain-selective nutrients (Broadhurst et al. 2002; Campbell 2008:113; Gaffney et al. 2018; Kyriacou 2017; Kyriacou et al. 2014, 2016; Marean et al. 2007; Meehan 1982; Szabó and Amesbury 2011).

When examining molluscan remains from deep time cultural contexts, approaches to the analysis of usually fragmented samples differ to routine approaches adopted in malacology. Further, the shells of molluscs derived from deep time contexts have usually been exposed to a range of taphonomic processes through time. These include breakage or fragmentation caused by environmental elements or trampling, wear from tool and artefact manufacture, damage from heat treatment or meat extraction, and demineralisation caused by leaching, among other reasons (and consider nested criteria in Lyman 1994:68 for mollusc shells). Recovery methods, such as excavation recording procedures, size of excavation units (XUs), identification of stratigraphic units (SUs), mesh sizes, sample sizes, and laboratory identification and quantification methods will depend on the research question, practicability within the project timeframe, and funding (Bonar et al. 2011:11; Woo et al. 2016). Mesh size is a key recovery method that is stressed across the zooarchaeological literature. Large mesh sizes might bias interpretations due to the loss of smaller fragments, loss of material evidence for an entire species, or loss of evidence for temporal periods (Boner et al. 2011:14; Woo et al. 2016; and see fishbone e.g. in Ross and Duffy 2000; Ross and Tomkins 2011). With intact or partially intact mollusc shells and appropriate application of analytical techniques, meaningful interpretations of datasets can provide information to assist in understanding long-term socio-ecological dynamics.

4.2 Biometrics in Archaeomalacology

In malacology, evolutionary history and phylogenetic relationships between molluscan classes, families and species has received considerable attention (e.g. see Hautman 2006 for Ostreidae; for *Lunella cinerea* see Williams 2007; Williams et al. 2011, 2012a). Historically, phylogenies were based on shell morphology using observations of surface features as well as soft tissue anatomy. More recently, DNA sequencing has become an available technique for identifying taxa to species level (see Lam and Morton 2006). The shape and size of individuals is largely, but not explicitly, influenced by behavioural qualities and availability of food (for e.g. see cases discussed in del Norte-Campos et al. 2005, Vermeij 1978, 1993). Examples illustrating this point are further discussed in section 4.2.3 and summarised in Table 4.3 below. In other cases, where certain species exhibit sexual dimorphism, biometrics can be used to determine the sex of an individual (e.g. for Strombidae see Halder and Paira 2019). For many species, however, the gonads of male or female individuals are needed to determine the sex of the individual. Analyses of hard-shell components are particularly well suited to archaeological inquiries, although somewhat difficult for reasons discussed below, and because the soft tissue parts of molluscan taxa are typically not preserved (Marelli and Arnold 2001:557). Metrical datasets are useful for understanding species ecology and population dynamics which can then be used to form understandings about predator-prey interactions and environmental and climatic conditions. Applications to *Rochia nilotica* (synonyms: *Tectus niloticus*, *Trochus niloticus*) or ‘commercial top shell’, shows how baseline metrical datasets in the biological sciences have been used to inform contemporary resource management initiatives.

Rochia nilotica is described as a highly visible marine gastropod that occurs in tropical waters across the Western Pacific and Indian Ocean (Carpenter and Niem 1998; Szabó 2007). Historically, the species has been targeted commercially due to its importance as a food resource and for manufacturing artefacts (e.g. buttons) (Amos 1997). Nash (1985) offers one of the earliest comprehensive accounts of *R. nilotica* biology and ecology. Others have continued work on *R. nilotica* in the South Pacific region in response to declining populations, and for commercial and restoration needs. This work has led to many *R. nilotica* fishing management strategies now implementing harvesting controls to improve population stocks, including no take zones, or catch limits of individuals based on size profiles (Amos 1997; Castell 1997; Gimin and Lee 1997a, 1997b; Lemouellic and Chauvet 2008; Purcell et al. 2003 for applications). The maximum basal diameter of the shell is routinely used in fisheries surveys (Lemouellic and Chauvet 2008). Biometric methods used in modern ecology are mostly transferrable to archaeomalacological research with a few fundamental differences. Given the traditional focus of archaeological inquiry, the human use of molluscs is emphasised in archaeomalacology. Secondly, archaeomalacology relies on the marine biology literature to understand species ecology, general growth trends, habitat preferences, behavioural traits and diets. Datasets are established from often-fragmented shells of molluscs which are derived from a series of discard events rather than on one or more modern live-collected mollusc shells that are intact or whole. Archaeomalacology studies typically utilise metrical datasets to examine mollusc shell assemblage increases or decreases for one or more human occupation phases and at one or more site locations.

Biometrics or linear morphometrics use point and line measurements to form two-dimensional (2D) or three-dimensional (3D) object size representations (Mitteroeker and Gunz 2009:237). Point and line landmark criteria rely on three main parameters: (1) scale, (2) orientation and (3) position – these should be kept consistent across a population of examinable objects (Mitteroeker and Gunz 2009:237). Metrical analysis is classed as a non-invasive or non-destructive technique, whereby potential damage to the object under investigation is avoided during the measuring process. Datasets are examined by statistical testing to predict size changes across an assemblage of a target taxon. Two-dimensional data representations are collected by digital or manual hand callipers achieved by distance and distance correlations (Mitteroeker and Gunz 2009:237). Three-dimensional data representations are comprised of a series of stitched images collected by digitizing or scanning (Mitteroeker and Gunz 2009:237). In archaeomalacology, 2D metrical data are usually sufficient for capturing and examining size changes (Glassow et al. 2016:33). Traditional biometric applications in archaeomalacology focus on size changes, which rely on standardised length, height, or width measurements taken from maximum distances across posterior and anterior shell margins (Randklev et al. 2009:205). Swadling (1972:42) critically observes, however, that metric datasets based on maximum size measurements, or commonly ‘length’ measurements, do not necessarily correlate well with establishing age profiles in some species.

4.2.1 Maximum Size Versus Age-At-Sexual-Maturity

An important consideration when recording maximum size values is the correlation with mollusc ontogenetic age and sexual maturity profiles. Socio-cultural, climatic or environmental variables, such as those described in Table 4.1 and access to food and nutrients, can influence species growth and therefore impact population structures. Shawcross (2011:43-44) explains:

> *... if, ... the oldest and largest sized age-classes are exterminated, their removal will probably give the younger classes increased opportunities for growth; consequently, the size of individuals involves an adjustment to competition for food and is not an absolute measure of age. But in a population dominated by senile individuals, on the other hand, the young are likely to be relatively stunted. Thus, selection of the individuals is likely to make the overall population progressively more juvenile, although with little obvious physical damage to the population as a whole.*

When maximum size does not correlate with sexual maturity profiles, other independent age identifying landmarks should be measured where available (Shawcross 2011:57). In strombids for instance, species typically exhibit lip thickening either at, or, just after the onset of sexual maturity (O'Dea et al. 2014; Poiner and Catterall 1988; Radermacher et al. 2009; Vermeij 1993). The key metric used to assess *S. gigas* from Los Roques Archipelago for instance, was measurement of apertural lip thickness (Antzcak and Antzcak 2005:9-10; Antzcak et al. 2008:54-55; Cipriani and Antzcak 2008; Schapira et al. 2009:788).

Strombus gigas is reported to be of high commercial value in modern Caribbean fisheries and was an important resource in early human occupation periods (Antzcak and Antzcak 2005; Antzcak et al. 2008; Cipriani and Antzcak 2008; Schapira et al. 2009). Indeed, Antzcak et al. (2008:55) estimate ~5 500 000 *S. gigas* shells from Amerindian phase cultural resource use sites and ~11 500 000 *S. gigas* shells from historic Hispanic phase cultural resource use sites. *S. gigas* can live for ~20 years but display a lip thickness of ~5cm at full maturity (Antzcak and Antzcak 2005:9-10). Maximum length can also be used as an indicator of age but only in individuals ≤ 3 years old (Antzcak and Antzcak 2005:9-10). Biometric datasets revealed stability in the reproductive success of *S. gigas* throughout early human occupation periods, but population declines are evident in historic and modern periods (Antzcak and Antzcak 2005; Antzcak et al. 2008; Cipriani and Antzcak 2008; Schapira et al. 2009). An increase of juvenile individuals in modern assemblages was attributed to intense overfishing which led to the protection of *S. gigas* across the Caribbean (Antzcak and Antzcak 2005:9-10; Antzcak et al. 2008:54-56; Cipriani and Antzcak 2008; Schapira et al. 2009:788, 790).

4.2.2 Linear Regression Modelling

A common challenge in the collection of metrical data on samples recovered from deep time is the often-fragmentary nature of shell materials (Glassow et al. 2016:32; Thangavelu et al. 2011). Capturing size data from fragmented shell samples has been attempted in the past by using nested sieving techniques to isolate variously sized diagnostic shell fragments, by assessing correlations between shell weight and shell length or shell length and meat weight, and by measuring diagnostic fragments against type-scale templates (Bell 2009; Singh and McKechnie 2015; see for review Glassow et al. 2016:33). Restricting analyses of deep time assemblages to whole or intact individuals has the potential to limit sample sizes and decrease the robustness of statistical analyses, therefore, fragmented samples should also be included in analyses where possible (Faulkner 2010; Woo et al. 2016). Linear regression modelling is a technique that is used to estimate shell size from fragments, using known relationships, and which also serves to increase assemblage sample sizes for statistical testing (Ashkenazi et al. 2005; Faulkner 2010; Jerardino and Navarro 2008; Szabó 1999). Routinely, linear regressions rely on bivariate values which can account for shell sizes but not shell shape (Rhoads and Lutz 1980:39). Therefore, other analyses such as those incorporating shell morphologies or use of multivariate measures to individuals is needed to explain shell shape across populations (e.g. see Peacock and Seltzer 2008). Linear regression models are based on independent datasets built from species assemblages consisting of whole or intact individuals - either live-collected from an area relevant to the assemblage of interest or from museum collections (Campbell and Braje 2015:168; Faulkner 2010).

Experimental metrics, used to examine correlations between a variety of landmarks on whole or intact individuals, is usually adopted to increase the number of opportunities to predict shell sizes from fragmented assemblages, and to understand possible preservation bias (Campbell and Braje 2015; Jerardino 1997; Jerardino and Navarro 2002, 2008:1028). For instance, Ashkenazi et al. (2005) examined the relationships of 22 landmarks on intact freshwater crabs to increase samples sizes of an early-middle Pleistocene Acheulian freshwater crab assemblage in the Jordan Valley, Israel. Experimental metrical data found significant statistical relationships between pincer size and maximum carapace size (Ashkenazi et al. 2005:680). Where the carapace height or width values on fragmented crabs were not available, pincer measurements were recorded, and then maximum carapace size was estimated using established linear regression equations (Ashkenazi et al. 2005:684). In another study, Jerardino and Navarro (2008:1026) examined nine landmarks to predict maximum length values established on live-collected intact *Cymbula granatina* and *Scutellastra granularis* (limpet), with application to individuals of these taxa recovered from Pancho's Kitchen Midden, South Africa. Linear regression equations predicted missing length values on 232 *C. granatina* shells, increasing the sample size to 367 statistically testable cases, and from 172 fragmented *S. granularis* shells to 412 statistically testable cases (Jerardino and Navarro 2008:1026). An increase in limpet size rather than a decrease in size through time was subsequently shown for these species (Jerardino and Navarro 2008).

Faulkner's (2010:1950) *Tegillarca granosa* (formerly *Anadara granosa*) (granular ark) metrical dataset, comprising two sites from Blue Mud Bay, northern Australia, was increased by ~25% using fragmented samples. In this case, *T. granosa* exhibited highly robust qualities demonstrating that linear regression modelling might not always be required for assessing size changes in species assemblages (due to large enough sample sizes of intact shells) (Faulkner 2010). As Faulkner (2010:1943) points out, however, complete species assemblages, regardless of whether they exhibit high or low fragmentation rates, are critical for characterising differences in site formation processes and resource use patterns across temporal and spatial phases, which should be assessed on taxon-specific, 'excavation unit-specific' and 'site specific' bases (Faulkner 2010:1948, 1950). Reasons for species size increases or decreases through time are complex but are central to the assessment of socio-ecological dynamics.

4.2.3 Species Ecology, Morphometry and Human Harvesting

Understanding species ecology, including habitat preferences and behavioural traits, is crucial for characterising faunal growth rates and structural differences between populations (Faulkner 2011:822). Shell morphology, which can be independent of species age or sexual maturity, is largely influenced by endogenous and exogenous dynamics (Glassow et al. 2016). Importantly, when individuals within a population reach size or age thresholds, habitat change could be triggered due to newly developed needs. For example, size or sex cohorts might migrate to different habitats based on particular food or space requirements. Migration from shallow reef habitats to subtidal reef habitats in *R. nilotica* is signalled by sexual maturity at ~2 years of age, at which time they reach a shell basal diameter of ~50mm (Carpenter and Niem 1998; Castell 1997:216; Lemouellic and Chauvet 2008; Magro 1997). Adult *R. nilotica* situate themselves on windward reefs where increased productivity delivers a heightened supply of food and nutrients (Carpenter and Niem 1998:405). In clustering oyster species which grow affixed to substrates, irregular shell shapes could indicate situations where individuals experienced competitiveness for space to grow (Winder 2017). Alternatively, oyster shells showing greater regularity in size and shape might indicate low level competitiveness for space (Winder 2017). Essentially, the physical and biological conditions of habitats will affect shell size and shape, and potentially population densities (Campbell 2010; Winder 2017:247-248).

Shell size and shell shape can reveal information about environmental or climatic changes, or human harvesting patterns, however these inferences must be considered carefully. An assemblage of mollusc shells recovered from a deep time and representative of a juvenile cohort for example, might be indicative of forager patch choice rather than a case of overexploitation. As Campbell (2008:111-112) argues, in taxa similar to mussels which grow in 'dense mats' or species that live buried under sediments (e.g. Donacidae), size selection by harvesters is not prioritised. He explains that harvesting strategies might include instances where:

> *… the typical size [of molluscs] seems 'good enough' (i.e. it corresponds reasonably closely to the mental template of an acceptable shellfish), rather than to survey the whole habitat for optimum shellfish size before harvesting* (Campbell 2008:112).

Campbell (2008) makes a good point - these instances are certainly possible and perhaps particularly so in circumstances where less visible species with sediment burrowing capabilities are targeted. Indeed, in oyster species, changes in the presence of 'clumped' shells and more regularity in shell shape, size, and age could indicate more consistent harvesting patterns or cultivation (i.e. creating space for remaining individuals to extend in shape and size) (Campbell 2010; Winder 2017:249). In cases of low intensity harvesting of oysters, Winder (2017:247) suggests that we would expect to see small numbers of individuals isolated to certain units in deep time sediment matrices, a variety of size and ages, and some shells 'clumped' together. At the most intense level of use, such as oyster farming or laboratory grown individuals, definitive trends across size, shape, and age should be observable (Winder 2017:249). Species behaviour in response to environmental or predator threats may also influence shell shape and size. For example, elongated shell features in bivalve species might be a cause of burrowing into sediments (and see del Norte-Campos et al. 2005 for species response behaviours and traditional ecological knowledge of species behaviours influencing harvesting strategies). Table 4.3 summarises variables which might affect mollusc shell shapes and sizes pre-mortem, and, at peri-mortem to post-mortem junctures.

Table 4.3 Variables contributing to various shell morphologies across bivalve or gastropod species (after Boekschoten 1966; Cabral and da Silva 2003; Campbell 2008, 2010, 2014; Carpenter and Niem 1998:4-8; Kirby 2001; Mannino et al. 2008; Mariani et al. 2002; Seed 1968; Stanley 1988; Vermeij 1993:94-112; Vermeij and Dudley 1988; Winder 2017; Yanes et al. 2012). Note that variations to shell shape and size can also be influenced by shell regrowth or 'remodelling' to a damaged area by surviving individuals (Vermeij 1993:32-35).

Variables	Morphological Feature Example
Behavioural	
Burrowing	Elongated valves (bivalves).
Crowding or clustering in populations	Varied sizes and shapes in species assemblage (competition for space and food).
Environmental	
Wind, turbidity, substrate, currents slow/fast (gastropods)	Conical shape differences, raised versus smooth shell sculpture.
Wind, turbidity, substrate, currents slow/fast (bivalves)	For e.g. in oysters: small-hinge, round, raised sculptural features/large-hinge, oval, smooth shell sculpture.
Primary productivity	Thickened shell due to heightened supply of food and nutrients.
Biotic	
Boring from cephalopods, worms, gastropods, sponges	Puncture wound through shell; or thick shells to deter drilling predators.
Cracks from fish or bird attacks	Shell breakage and scarring.
Infestation by organisms: e.g. worms, parasites	Additions to shell architecture.
Encrustation by living organisms: e.g. barnacles	Additions to shell architecture.
Predation	
Periodic human harvesting of natural populations	Varied size and shapes in species assemblage (incl. attachment of spat in oyster species),

Variables	Morphological Feature Example
	inclusion of encrusting organisms or infestations to shell.
Continuous human harvesting of natural populations either by hand or with the aid of technology	Limited sizes and shapes in species assemblage (incl. absence of attached spat in oyster species), inclusion of encrusting organisms or infestations to shell.
Collection of species from different locales	See behavioural and environmental morphological features (above).

Modifications to shell morphology, including alterations to sculptural and architectural features, can also occur post-mortem. Post-mortem features are usually caused by targeted interaction (e.g. hermitting by terrestrial crabs see Szabó 2012), taphonomic processes (e.g. beach rolling, weathering, trampling, vegetation), damage from meat extraction strategies, damage from processing foods like plants or seeds, or damage from artefact manufacture (Glassow et al. 2016:33; Szabó 2012). Distinguishing pre-mortem, peri-mortem and post-mortem features from each other is essential for confirming temporal use and spatial differences in mollusc assemblages. Comparison of molluscan remains between at least two species, from one or more cultural deposits, and from one or more habitats, is also advantageous for discriminating between variables influencing growth and availability of resources (Campbell 2008:115). Physical changes in mollusc populations caused by human harvesting patterns or environmental conditions can be inferred by metrical datasets; however, interpreting rates of growth, which can vary across habitats, (Campbell 2008:113) can be improved by using sclerochronological techniques.

4.3 Sclerochronology in Archaeomalacology

Incremental growth features in living organisms have long been recognised. They have been observed in trees (dendrochronology) (e.g. Hafner et al. 2015), in speleothems (e.g. Vanghi et al. 2018), and in fish otoliths (e.g. Cerrato 2000) among others. The term ‘sclerochronology’ was coined by Buddeimer et al. (1974) to define the assessment of internal growth features in $CaCO_3$ accreting organisms such as molluscs and corals. A simple explanation of the technique posits that the age-growth axis of an organism may be sectioned, and then visually assessed using a selection of methods (see section 4.3.3 for further detail) (Andrus 2011:2894). Internal shell features can be used to evaluate growing conditions during seasonal cycles, tidal sequences, moon phases, spawning events, or to assess the timing and impact of storms. Sclerochronology is a particularly useful technique when shell size, or external architectural features cannot be used to predict ontogenetic age (but see Andrus 2011:2894; Mirzaei et al. 2014; Richardson 2001:104; and see for e.g. Mannino and Thomas 2007); or, when a mollusc shell has been subjected to harsh environmental or taphonomic processes (Schöne and Krause 2016:231; and see for e.g. Lord 2012:53 for aging chiton species and Cardaso et al. 2013:94 for aging Baltic clams, *Macoma balthica*). It is a destructive technique but nonetheless necessary to assess mollusc growth more accurately.

In commercial contexts, sclerochronology has been widely applied to fin-fish species although, it is yet to gain traction as a standardised approach for assessing molluscs (Steinhardt et al. 2016:2). This is potentially due to time, analytical capabilities, practicability or financial constraints. Research based environmental monitoring projects have shown transferrable advantages in adopting sclerochronology techniques to long-lived molluscs (Schöne and Krause 2016; Steinhardt et al. 2016:9). Examples like the applications to shells in Mussel Watch programs for instance (Schöne and Krause 2016), are sorely needed to advance interpretations and improve environmental conservation efforts in other regions. *Arctica islandica* (ocean quahog) is a slow-growing bivalve that can live for >500 years (Ballesta-Artero et al. 2019:173; Begum et al. 2009; Butler et al. 2013; Schöne 2013). *A. islandica*'s long life-span and its ability to store annual and sub-annual growth, climatic, and environmental data has made the species an ideal candidate for recording proxy datasets; and since it is an important commercial food resource it has significant implications in environmental monitoring (Thorarinsdóttir and Jacobsen 2005:97). Absolute chronologies from the species have been used in several studies using dating methods, geochemical sampling and sclerochronology techniques (Schöne 2013). Reynolds et al. (2017) used a multi-species chronological approach, employing *A. islandica* and *Glycymeris glycymeris* (dog cockle) to reconstruct Northern Atlantic climate records. Data were used from samples collected over a 500km stretch of ocean, with findings confirming comparable yet varied broad-scale environmental and climatic drivers of growth (Reynolds et al. 2017:333). According to Ballesta-Artero et al. (2019) the availability of food to *A. islandica* in eight locations across the Northern Atlantic did not impact on the species' longevity, despite previous valve gaping (opening and closing of valves) studies suggesting this was the case (see Ballesta-Artero et al. 2017, 2018; and see for e.g. Schwartzmann et al. 2011 for sclerochronology and gaping study for the tropical giant clam *Hippopus hippopus*).

Few sclerochronological studies have considered the application of creating longer-time series datasets using molluscs (Butler et al. 2013). Butler et al. (2013) demonstrate 'the feasibility of annually-resolved and absolutely-dated shell-based chronologies for more than 1000 years' using eight *A. islandica* samples (live-collected articulated valves, dead articulated valves and dead single valves) and statistical methods derived from dendrochronology. In another assessment, museum derived samples have been used to take advantage of earlier chronological records (e.g. Schöne et al. 2005b). An *A. islandica* sample retrieved by Schöne et al. (2005b) from a museum archive, collected in July 1868 from somewhere 'near Iceland', shows the remarkable ability for just a single specimen to reveal significant climate and environmental data. This sample revealed 375 growth increments, a marker for the Tambora volcanic eruption in 1815, and variable growth during the Little Ice Age (between c. AD 1550 and 1620) (Schöne et al. 2005b). While long-lived species including *A. islandica* are ideal for establishing these types of records, as Schöne et al. (2005:131b) note, the data from shorter lived species can be 'strung together' to build longer time series datasets.

Constructing sclerochronologies using mollusc shell samples recovered from deep time can provide long-time series baselines. These datasets can be connected to historic and modern datasets for more holistic interpretations. Using sclerochronological datasets in conjunction with metrical datasets permits clearer depictions of the types of variables linked to socio-ecological changes through time (Andrus 2011:2897). Internal features of mollusc shells may confirm ontogenetic age, rates of growth, morphological life-history traits, and population age structures (Andrus 2011:2897; Deith 1983:432-433; Quitmyer et al. 1997:825). A main goal in the adoption of sclerochronological techniques within archaeology is to determine seasonal use of certain species. Mollusc growth rates might show peaks during climatic seasons, usually between summer and winter periods, or consistency in growth over annual cycles (Burchell et al. 2012). Importantly, Quitmyer et al. (1997:826) make the distinction that 'seasonal patterns of resource procurement' is a different interpretation to that of seasonal site use. Indeed, a human population may occupy a site continuously but adopt seasonal or periodic harvesting behaviours for certain species.

4.3.1 Mollusc Shell Growth and Microstructure

Several factors affecting mollusc growth must be considered during the examination of external shell architecture and internal shell growth-patterning when recording species life-histories. In general, molluscs grow in equilibrium with the environment, each having specific tolerances to influencing variables (Rhoads and Lutz 1980:35; Schöne 2008). Shell is built at the earliest stage of the mollusc's life, as a trochophore, and over its entire life-history (Marin et al. 2012:1108; Steinhardt et al. 2016:8). At the cellular level, calcified shell matrices are made of calcium carbonate ($CaCO_3$) and conchiolin or organic proteins, amino acids, trace elements, lipids, chitin, enzymes, peptides, and polysaccharide molecules; some of which can be present or absent in different species, in different structural layers, or at different shell forming stages during a molluscs life (i.e. for bivalves during the building of the prodissoconch or phase 1 as a trochophore, at the veliger larva prodissoconch phase 2 stage, and at the juvenile-adult dissoconch phase 3 stage; and for gastropods at the protoconch trochophore 1 phase, the protoconch veliger larva phase 2 stage, and the juvenile-adult teleconch phase 3 stage) (Checa 2018:4; Marin et al. 2012:1108; Marin and Luquet 2004:469, 473-474; Steinhardt et al. 2016:8; Suzuki and Nagasawa 2013; Trueman and Clarke 1988:11; Zhao et al. 2018:2752; and see Marin et al. 2008 for comprehensive review). For successful shell building to occur, some organic proteins (~5-10% total shell weight) are thought to be consistently represented across all stages and all conchiferan molluscs in succession with $CaCO_3$ (~90-99% total shell weight) (Almagro et al. 2016:2083; Checa 2018:2; Checa and Salas 2017:2; Marin et al. 2008:209-210, 211; Marin and Luquet 2004:472; Suzuki and Nagasawa 2013:349; Trueman and Clarke 1988:69; and see Zhao et al. 2018 for discussion). $CaCO_3$ and key molecules are absorbed by the mollusc through food, nutrients and water filtration, which collectively forms the Extra Pallial Fluid (EPF) situated in the extra pallial space between the outer mantle epithelium and the inner most shell layer (Figure 4.1).

The EPF interacts with $CaCO_3$ and other selected molecules which results in the formation of calcified shell layers (Crenshaw 1972:505; Checa and Salas 2017:2-4; Marin et al. 2008:217-219; Marin and Luquet 2004:475, 483; McConoughey 2008:288; Steinhardt et al. 2016:8; Taylor et al. 1969:9). Although the mantle is in contact with the ambient sea water and mantle epithelium in contact with the EPF, the EPF has a different composition to that of sea water (Crenshaw 1972). In some molluscs, the EPF has also been shown to have a different composition to that of blood (Crenshaw 1972). Microstructures are determined by physical and/or biological influences (Checa 2018:13, 16). These influences shape the interaction of $CaCO_3$ and other molecules within the internal 'biologically-controlled' environment of the mollusc which is 'not in direct contact with the environment' (Marin et al. 2012:1100). Molluscs that grow external hard shells typically but not explicitly have between 1 and 5 calcified layers, and sometimes 1 organic layer that grows longitudinally and incrementally toward the ventral margins of the animal (see Almagro et al. 2016:2083; Crenshaw 1972:505; Marin et al. 2012:1101; Marin and Luquet 2004:472; McConoughey 2008:288; Schöne and Surge 2014:20). In bivalves, shell structures in the left and right valves often, but not always, mirror each other (e.g. oyster species are commonly inequivalve) (Trueman and Clarke 1988:87). In other taxa, such as strombids and cowries, sexually mature individuals may undergo longitudinal as well as latitudinal deposition of $CaCO_3$ to selected parts of their shells (i.e. lip thickening); and senile individuals may only be subjected to latitudinal $CaCO_3$ deposition (Vermeij 1993:32). Metrical or observational data, identifying morphological changes to a mollusc's shell architecture throughout each growing stage, may be used to determine the size and/or age profile of the individual.

$CaCO_3$ layering in mollusc shells is complex. Typically 1, 2, or 3, combinations $CaCO_3$ polymorphs are present in microstructural shell layers: calcite, aragonite, or vaterite (Checa 2018:2; Checa and Salas 2017:2). During the first stages of growth in bivalves, Checa and Salas (2017:1) suggest aragonite structures dominate phase 1 and phase 2 growth stages, though sometimes 'traces of calcite' are also identifiable. As the mollusc grows, either calcite or aragonite, or combinations of aragonite and calcite, continue to form the shell throughout the dissoconch phase 3 stage. Vaterite is an anhydrous (containing no H_2O) $CaCO_3$ polymorph that rarely occurs in molluscs. In some taxa however, at shell repair sites and in pearls, vaterite has been identified but it has never been identified as a precursor for early shell development (Checa and Salas 2017:2; Marin and Luquet 2004:474). In bivalves, calcification also occurs at the site of the adductor muscle scar which is explicitly an aragonitic microstructure (Suzuki and Nagasawa 2013:353). A pallial line can sometimes follow through the adductor muscle scar site, effectively separating shell layers (commonly occurring in oyster species) (cf. pellucid line in Kobayashi 1969:665).

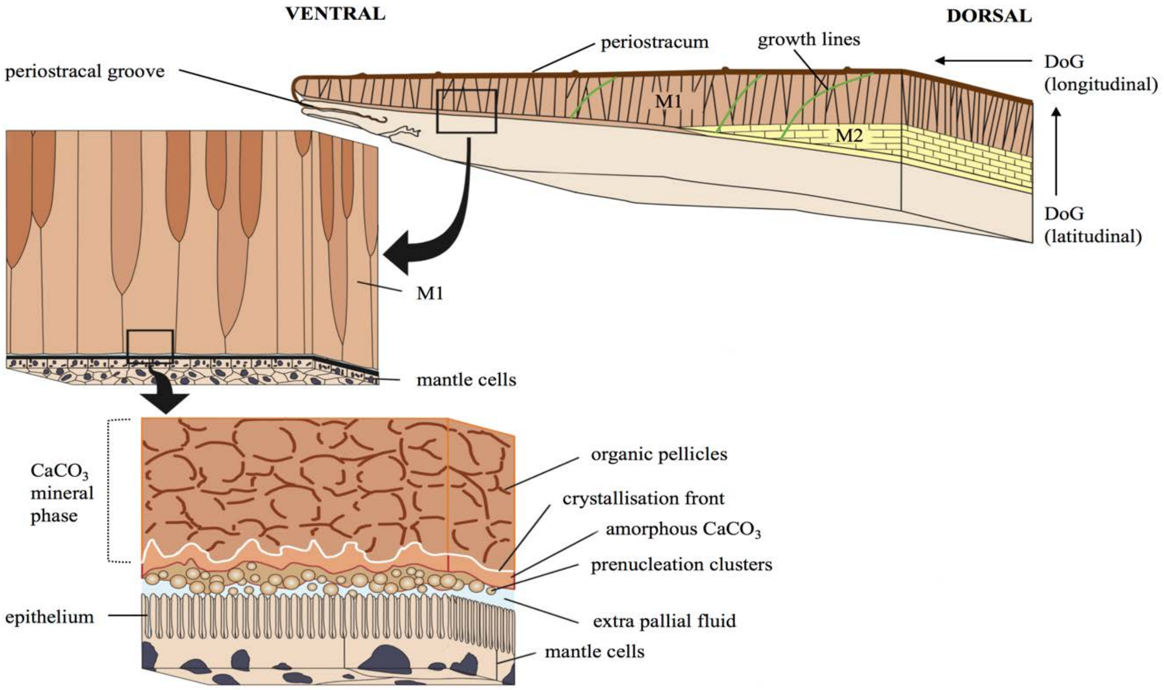


Figure 4.1 Diagram of the biomineralisation process in some bivalves from an amorphous precursor (after Checa and Salas 2017:32). This cross-section shows an example of shell layers and soft components within an upper bivalve valve including the periostracal groove and upper, middle and lower mantle folds (gastropods typically have only two mantle folds (Marin et al. 2008:217)); the periostracum with overlapping folds; the M1= microstructural prismatic shell layer and M2= microstructural nacreous shell layer. Note the Direction of growth (DoG) is longitudinal towards the ventral margin, and in some but not all molluscs, a latitudinal direction of growth may be employed in maturing or senile individuals (architectural and morphological examples not represented on diagram).

The microstructural layers in mollusc shells and their crystallographic configurations are observable in 3D under Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), or through use of other high-powered microscopic technologies (Checa 2018:1; Checa and Salas 2017:1; Marin et al. 2008:211). Staining solutions, or more specifically Feigl's solution, may expose types of CaCO$_3$ polymorphs but cannot be used to determine geometric crystallographic morphologies. Early descriptions of shell growth and microstructural properties were provided by Bøggild (1930) who described eight groups, Kobayashi (1969) who described 11 groups, Taylor et al. (1969, 1971) who described numerous groups, and then various taxonomic groups were published in a comprehensive review in the 'Skeletal Biomineralization' volumes edited by Carter (1990). More recently, and during the production of these reference publications, research has focused on refining understandings of shell growth at the species level and understanding the functional biochemical relationships between crystallographic structures from fossil and living examples. A brief description of some microstructural layers and CaCO$_3$ polymorphs found in extant mollusc species is provided below. Figure 4.2 illustrates some crystallographic morphologies found in these layers. Concise descriptions of these crystallographic morphologies are summarised well in Marin et al. (2012:1102) using Carter and Clark's (1985) classifications (and see also Carter 1990 and earlier reference publications listed above).

The periostracal layer is a thin multi-fold organic waterproofing film that covers the outer calcified shell layer (Marin et al. 2008:217). It is comprised of ions, lipids, amino acids and proteins, which are reflective of the mollusc's habitat and surrounding temperature (Checa and Salas 2017:3-12; Trueman and Clarke 1988:69-70). A periostracum occurs in some but not all bivalve and gastropod species. It serves as a protective film for the soft and hard shell components of the mollusc from predators and exposure to dissolution; and to aid in osmoregulation, to store food, and in some instances to carry eggs (Checa and Salas 2017:4-12; Trueman and Clarke 1988:11). The periostracum, including the section protruding into the periostracal groove, is the first layer to be formed, ultimately allowing the accretion of $CaCO_3$ polymorphs in other layers (Checa 2018:3-4; Kobayashi 1969:663; Suzuki and Nagasawa 2013:350; Taylor et al. 1969:11).

The prismatic layer can be made from calcite or aragonite and is positioned underneath the periostracal layer (i.e. in species comprising a periostracum) but is the outermost or 'external' calcified shell layer (Almagro et al. 2016:2083; Checa and Salas 2017:1; Marin and Luquet 2004:486; Szabó 2017:315-316). The organic and protein content in prismatic shell layers is comparatively high (Currey 1988; Szabó 2017:316). Species in the Turbinidae family often comprise of a prismatic outer layer and inner nacreous layer (Szabó 2017:315).

The nacreous layer, also called the lamellar or laminar layer, inner lustrous layer, or mother-of-pearl, is often the innermost shell layer in Turbinidae and Trochidae species (Marin and Luquet 2004:486; Szabó 2017:315). It is always comprised of aragonite and is known as one of the 'strongest of all molluscan microstructures in live shells (i.e. in dead shells, organic components dissipate making the structure significantly weaker) (Checa 2018:13; Checa and Salas 2017:1; Currey 1988; Marin et al. 2012:1102-1106; Suzuki and Nagasawa 2013:352-353; Szabó 2017:314). Nacre is a metastable polymorph comprising orthorhombic crystal structures which occur as columnar nacre in gastropods and sheet nacre in bivalves (Checa and Salas 2017:2; Marin and Luquet 2004:486; and see Szabó 2017:316).

Foliate or laminae layers in shells are predominantly found within Ostreidae or more generally within the shells of some bivalve species (Szabó 2017:315; Taylor et al. 1969). This microstructure made of calcite and is sometimes found in association with fibrous calcite or 'chalk' (see Checa et al. 2018 and references within; and see Ullmann et al. 2013). Both foliated calcite and fibrous calcite are mechanically weak disordered structures and appear as either smooth thinly layered sheaths (foliated calcite) or as a collection of splintered needles (fibrous calcite) (Checa et al. 2018; Szabó 2017:315).

Crossed-lamellar shell layers consist of aragonite and are found in gastropods, in bivalves, and in some species of chiton (Salinas et al. 2017; Szabó 2017:315; Peebles et al. 2017). This structure is mechanically tough, allowing shell species comprising this microstructure good protection from external forces (for e.g. *S. gigas* predator attacks, see Salinas et al. 2017:58). Crossed-lamellar structures have low organic content and appear as blocks of tightly arranged stacked rods (Szabó 2017:315). Each block of stacked rods are successively connected but each of them are 'angled in different directions' (Szabó 2017:315; and see additional figure in Salinas et al. 2017:59 for *S. gigas*).

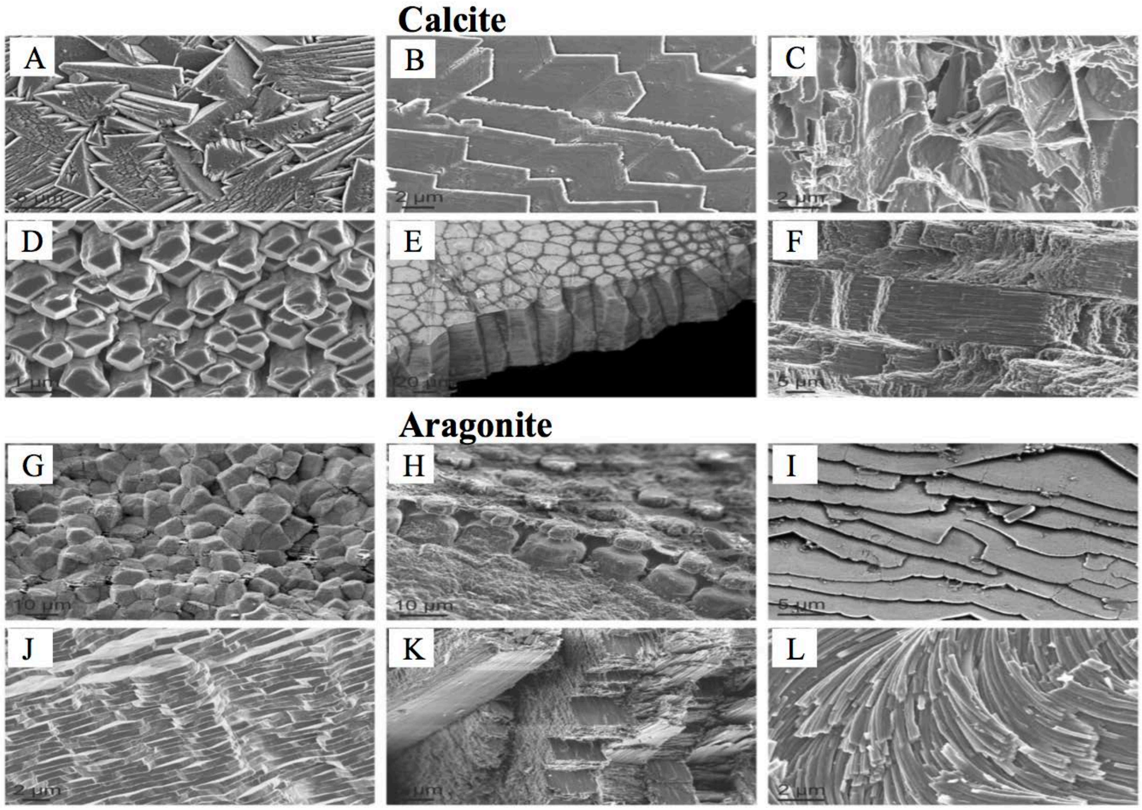


Figure 4.2 Examples of calcite and aragonite crystallographic structures from Checa (2018:3). A) 'Granular '(rhombohedral) calcite', limpet *Cellana toreuma*. B) 'Foliated calcite', jingle shell *Anomia ephippium*. C) 'Chalk', oyster *Crassostrea angulata.* D) 'Fibrous calcite', mussel *Mytilus chilensis*. E) 'Columnar prismatic calcite', pinctada *Pinctada margaritifera*. F) 'Crossed foliated', limpet *Scutellastra tabularis*. G) 'Granular prismatic aragonite', rock clam *Entodesma navicula*. H) 'Columnar prismatic aragonite', brooch clam *Neotrigonia lamarckii*. I) 'Foliated aragonite', limpet *Veleropilina euglypta*. J) 'Nacre', limpet *Neotrigonia bednalli*. K) 'Crossed lamellar', scotch bonnet *Semicassis granulata*. L) 'Helical fibrous aragonite', unidentified sea slug (Opisthobranchia). Note: vaterite (not shown) has hexagonal shaped crystals (Checa and Salas 2017:2).

Determining growth features in the microstructural layers of mollusc shells to identify ontogenetic age using growth lines (GLs) and growth increments (GIs) can be challenging (see Table 4.4 for terminology). Indeed, growth hiatuses depicted as disturbance lines (DLs), appearing as inconsistent anomalies in a growth profile, can complicate interpretations (Burchell et al. 2012; Goewert and Surge 2008; Richardson 2001:105; and see Schöne 2008). When molluscs experience a growth hiatus, $CaCO_3$ stops being accreted at the ventral margin or growing edge after which time a sudden onset of growth commences (Deith 1983:433; Schöne 2008). Growth hiatus anomalies can be represented differently across calcite and aragonite layers in a single individual (Richardson 2001:110). There are numerous reasons why growth hiatuses can occur, some of which are presented in Table 4.5.

Table 4.4 Sclerochronology terminology adopted in this study (after Richardson 2001).

Term	Definition
Growth Line (GL)	Tightly spaced or loosely spaced lines, bands, or rings representing either annual, monthly, weekly, daily or sub-daily periods of growth.
Growth Increment (GI)	Represents the time interval between growth lines.
Disturbance Line (DL)	A hiatus, anomaly, or interruption in shell growth.

Table 4.5 Examples for how growth stoppages can occur in mollusc species, consequently influencing the morphology of growth features across one or more microstructural layers.

Short Descriptor	Description	Comments
Ontogenetic Age	Senile individuals can experience a slow-down in growth that can be represented across one or more polymorphic layers in a single specimen and/or in the external shell architecture.	Richardson (2001) provides an example for this in the nacreous layer of some mussel species (see also Rhoads and Lutz 1980:35; Schöne 2008; Vermeij 1993:27-28).
Climate (ambient seawater)	Temperature changes.	An important consideration by Henkes et al. (2013) are the potential differences in stable isotope signatures, ^{13}C and ^{18}O, comprising temperature information between the 'mineral and precipitating fluid' and differences between prismatic and nacreous layers in a single specimen. Calibrations correcting these signatures can be difficult (Dombrosky 2020; Henkes et al. 2013). Also, noted here is the potential for growth stoppages to occur when an individual is submerged in non-ambient water (i.e. rock pools) where thermo-shock/s might be delivered (McConoughey 2008).
Climate (ambient air)	Unwanted exposure or varying exposures to air (e.g. between tides) and/or air temperature changes.	McConoughey (2008) provides an example for an aerial respirating oyster species. Ambient air temperatures can have a different isotopic signature to that of ambient seawater temperatures. Also noted is the potential for growth stops to occur from to exposure to non-ambient air (i.e. stagnant air). For example, in individuals that might be subjected to thermo-shock situations, such as in a collecting bucket with an airtight lid (and see also Dombrosky 2020 for the Suess Effect).
Environment (physiological)	Sedimentation or other physical impacts.	Can retard mollusc growth or, in severe cases, cause premature death (see Schöne 2008).
Environment (Marine and Fluvial Water)	Run-off from terrestrial or brackish water sources, or precipitation.	Can retard mollusc growth.

4.3.2 Growth Variability and Season-of-Death

Line and increment measurements and growth feature morphologies are important in the assessment of seasonal mollusc growth changes. Most studies rely on measuring the GI widths between GLs to record growth rates. Observations and measurements of disturbance anomalies (DLs) are used to record phases of stunted or slowed growth, or to identify growth stoppages. Internal growth features are routinely noted as being opaque (light shade) or translucent (dark shade, representing organic materials) (Jones and Quitmyer 1996; Schöne 2008). For example, in a species population GLs might be characteristically translucent and GIs opaque; however, inverse representations are rarely explained. Even fewer studies adopt comprehensive observations of line and increment morphologies (but see Milner 2001 and Deith 1983). Inverse representations of opaque and translucent features and/or altered morphologies could reflect latitudinal differences, where accelerated growth or stunted growth is influenced by warmer or cooler temperatures or other physiological stressors (Andrus 2011:2895; Deith 1983:432-433; Richardson 2001:109; Schöne 2008). In latitudes where seasons are well defined, usually in temperate locales, growth signals might be stronger than in intermediate latitudes or tropical areas where only 2 seasons are typically acknowledged (the wet season and the dry season) and therefore displaying more 'complex patterns' (Andrus 2011:2895; Jones and Quitmyer 1996).

Insightfully, Arkhipkin et al. (2014) caution that each species population responds to localised climatic variability, localised seasonal cues, and localised habitat conditions differently regardless of their geographical range. Indeed, some taxa display differences in GL and GI characteristics across habitats due to variability in species ranges or environmental change (for e.g. *Crassostrea virginica* populations see Andrus 2011:2895; and intertidal versus subtidal *T. granosa* populations see Mirzaei et al. 2014:459). Kirby (2001) demonstrates why some variations might occur in shell morphologies across species populations. Movement into new substrates for instance, could be in response to needing higher food intake to grow thicker shells, and thereby reducing predator attacks (Kirby 2001:99). Internal growth feature observations were not included in Kirby's (2001) assessments, nevertheless this example emphasises the necessity of considering a wide range of approaches to isolate reasons for variability in shell growth.

Table 4.6 reviews how interpretations might be developed using measurement, morphology, and pigmentation patterns in the internal skeletal hard parts of mollusc shells. Note that the terms pigment and pigmentation refer to the differences in mineral/organic material densities (opaque/light shade and translucent/dark shade) within the internal microstructures of shells in this context (rather than referring to external pigmentation or shell colourations). Figure 4.3 shows examples of some of these features using a gastropod and bivalve species.

Table 4.6 Observations in the variability of growth features and potential interpretations (after Andrus 2011; Ballesta-Artero et al. 2019; Deith 1983; Gaspar et al. 1994; Jones and Quitmyer 1996; Lord 2012:52; Milner 2001; Richardson 2001:105).

Data Type	Growth Feature Characteristic	Interpretation Potential
METRICS	Thin-banded growth lines.	Sub-annual resolution.
	Thick-banded growth lines.	Annual resolution.
	Widely dispersed lines.	Fewer seasonal differences in growth.
	Tightly dispersed lines.	More seasonal differences in growth.
	Relative growth of different microstructural layers.	Occurs in some senile individuals or as a response to seasonal temperature changes.
MORPHOLOGY	Highly defined growth lines or poorly defined growth lines.	Either heightened or limited supply of food and nutrients; or, constant or periodic submersion (e.g. aerial respiration).
	Poorly defined growth lines.	Taphonomic processes or, the feature can represent older or senile individuals.
	Growth features change orientation to steeper or gradual slopes.	Shell morphology changes in response to environmental conditions (e.g. tight clustering in oyster species).
	Growth lines fade away at the shell posterior and anterior margins.	Disturbance anomaly.
	Steep-sided notches or grooves in outer shell layer.	Growth stop from environmental or climatic disturbance or spawned individuals.
	Notch/es aligned with growth lines.	Seasonal growth lines.
	Sediments lodged in growth features.	Disturbance from high sediment turbidity (e.g. storms).
	Raised or uneven shell cover at site of disturbance.	Shell regrowth repair response at the growing edge.
PIGMENTATION	Inverse opaque/translucent features.	Latitudinal variability or other physiological stressors (e.g. heat).
	Differences in timing of precipitation of opaque/translucent features.	Latitudinal variability.
	Tight accumulation of translucent features.	Slow-down in growth prevalent in mature individuals but can also occur in juveniles.

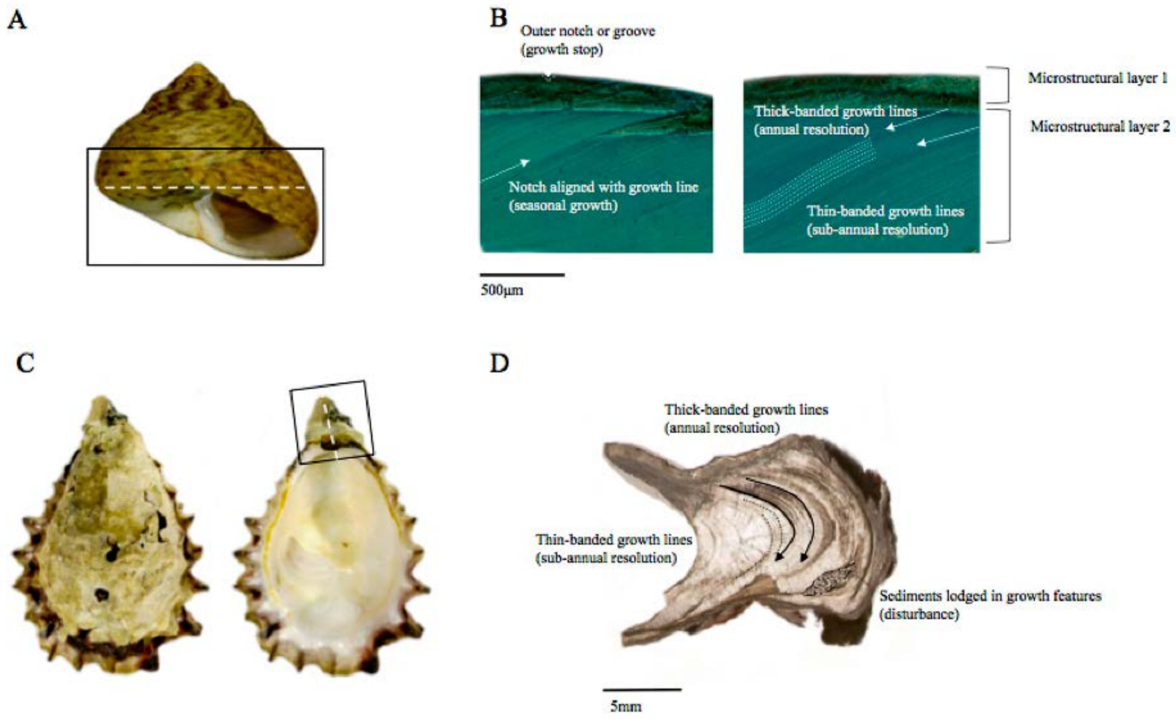


Figure 4.3 A) *Phorcus lineatus* (commonly topshell) showing axis of cross-section in the aperture area (specimen from WoRMS 2019), B) Stained *Phorcus lineatus* cross-sections showing growth features, collected alive from Langre Beach, Cantabria, Spain (after García-Escárzaga et al. 2019). Note highly defined widely dispersed annual lines and highly defined tightly dispersed sub-annual lines. Note: the 'outer notch or groove' representing a growth stop does not appear in the original image. C) *Saccostrea glomerata* (commonly Sydney rock oyster) showing the dorsal and ventral views of the left valve and axis of the cross-section in the hinge area (specimen from WoRMS 2019), D) Unstained *Saccostrea glomerata* cross-section showing growth features. This sample, SSPSg005 (dated to ~1600 BP), was excavated by Nolan in 1985 from Sandstone Point, southeast Queensland, Australia, and cross-sectioned by Tynan (2017:168-169). Note the poorly defined growth lines due to taphonomic processes with potentially less visibility of growth features due to the section being unstained. The area representing lodged sediments, does not appear in the original image.

4.3.3 Methods, Interpretations and Limitations

When seasonal growth trends are not known, as is often the case when factoring in temporal and spatial variability, it is sensible to include assessments of control samples (Deith 1983, Milner 2001:861). To stop the accretion of $CaCO_3$ at the time of collection, control samples are often boiled in the field (e.g. Milner 2001:862; García-Escárzaga et al. 2019). Several studies have shown however, that boiling, or heating mollusc shells can change shell chemistry (Milano et al. 2018b and see review in section 4.4.3). Freezing samples is a better solution to stop $CaCO_3$ accretion. After euthanizing, the outer shell surface is embedded or painted with epoxy resin to assist in keeping the integrity of the sample during the cutting process. Shell cross-sections are obtained by cutting across the growth axis diagnostic of age (e.g. in strombids the lip thickness is used, Radermacher et al. 2009). The position of the saw and orientation of the cut is critical, as some growth features might not be observable if there is any misalignment (Deith 1983:433). Several methods for enhancing growth features in cross-section for observation have been applied in the past. These methods play key roles in how growth feature data might be interpreted and recorded. Depending on the sample and its state of preservation, growth features can be directly observed in cross-section with or without the aid of a high-powered microscope (Richardson 2001:107), by visually enhancing growth features via etching in hydrochloric acid or bleach (Mirzaei et al. 2014:462; Richardson 2001:107), by using acetate peels (Deith 1983; Milner 2001:864; Richardson 2001:107; Schöne 2013), or by using staining techniques. Mirzaei et al. (2014:462) trialled Alizarin Red stain, although Mutvei's Solution has been shown to achieve superior results (for e.g. see Burchell et al. 2012, Hallmann et al. 2009 for applications on *Saxidomus gigantea* (butter clam), Colonese et al. 2017 for *Anomalocardia flexuosa* (Venus clam), Gutiérrez-Zugasti et al. 2017 for *Patella vulgata* (limpet) and Prendergast and Schöne 2017 for *Patella caerulea* (limpet). Schöne et al. (2005a) offer the best review of Mutvei's Solution.

Growth feature data can show single mode or polymodal peaks which might correspond with seasonal growth (Campbell 2008:113; García-Escárzaga et al. 2019). If local seasonal growth trends of a species are known, the season-of-death may be assessed by observing characteristics in the last growth increment. These data can be used to extrapolate human harvesting patterns related to season of harvest (i.e. season-of-collection), which are best interpreted in combination with other analytical applications like stable isotope analyses (e.g. Andrus 2011:2893; Butler and Schöne 2017; Burchell et al. 2012; Deith 1983; Milner et al. 2001:861; Prendergast and Schöne 2017; Quitmyer et al. 1997). As outlined above, distinguishing growth features from each other can be challenging. A common finding in sclerochronological datasets is that ontogenetic age is often overestimated, and growth rates underestimated (Goewert and Surge 2008; Jones and Quitmyer 1996). These discrepancies have implications for interpreting 'population dynamics, and the utility of specimens for paleoecologic and paleoclimatic study' (Goewert and Surge 2008:334; and see Jones and Quitmyer 1996). An important study by Goewert and Surge (2008) shows inaccuracy in the interpretation of growth features can be overcome by deploying isotopic analysis on samples (see also Cardaso et al. 2013; Gutiérrez-Zugasti et al. 2017:56; Jones et al. 2004:708; Roussel et al. 2011). In their example, sclerochronology was used as a preparatory stage for examining chemical signatures in the growth features of the bivalve *Chesapecten madisonius* (scallop). Results confirmed different seasonal growth trends between warm summer months and cool winter months, and that *C. madisonius* growth was predominantly influenced by changing ocean current conditions (Goewert and Surge 2008).

4.4 Biogeochemistry in Archaeomalacology

To improve the interpretation of climatic and environmental signatures derived from mollusc growth increments, sclerochronological studies are routinely coupled with isotopic and trace elemental analyses (Andrus 2011:289; Gröcke and Gillikin 2008:266; Kirby 2000). Sclerochemistry is a term Gröcke and Gillikin (2008:266) use to define the combined application of sclerochronology and geochemistry to 'the hard tissues of organisms'. Most mollusc species grow in close equilibrium with their environment, recording ambient environmental signatures in their shell microstructures (Butler et al. 2013; Gutierrez-

Zugasti et al. 2017; Schöne and Surge 2014). Sclerochemistry is therefore a method that can be used to examine environmental and climatic variability, captured as geochemical properties from within shell microstructures to determine variability in annual or seasonal mollusc growth (Burchell et al. 2012; Mannino et al. 2016:197; Schöne and Surge 2014). High-resolution datasets resembling these are employed to understand (1) if certain species can be used as recorders of palaeoenvironmental and palaeoclimatic changes - useful for building palaeoenvironmental datasets, and (2) to map seasonal resource use patterns by humans – useful for understanding socio-ecological dynamics.

4.4.1 Stable Isotope Analysis

When applying geochemical techniques to mollusc shell, it is important to have first identified the microstructural properties within growth features. Calcite and aragonite features have slightly different isotopic ratios which must be accounted for to alleviate skewed interpretations (see Grossman and Ku 1986). The alternate side of shell cross-sections used for sclerochronological assessments (i.e. unstained sections) are routinely used to analyse minerology: calcite, aragonite, or combinations of both. This step, important for calibrating isotopic values, is achieved by analysis of shell microstructures with Raman spectroscopy, SEM Fourier Transform Infrared Spectrometry or by using staining techniques such as Fiegl's Solution (Lindauer et al. 2018:50; Mannino et al. 2003:670, 2007:122, 2008; and see Prendergast and Schöne 2017 for applications of Fiegl's solution). Powdered samples for stable isotope analysis are extracted by either micro-drilling or micro-milling into the shell carbonate material at known growth feature areas. Powder samples can then be related to mollusc age and environmental/climatic conditions at that time. Only a small powder sample (<1g) is required for processing, however the precise amount will depend on the requirements of the mass spectrometer instrument. Conventional stable isotopes are routinely used in archaeomalacological research because they provide adequate high-resolution results. Clumped isotopes require larger powder samples by weight and are costlier but provide 'isotopologues' which report on a series of isotope signatures present in a carbonate sample, allowing direct reconstructions of seawater temperature (Eiler 2011; Henkes et al. 2013; Milano et al. 2017b:396). Table 4.7 summarises the isotopes commonly used in archaeomalacological research and their potential proxy interpretations from shell material.

Temperature and salinity are recognised as the primary variables influencing mollusc growth and are most commonly identified using oxygen and carbon isotopes (Gosling 2015:44, 178). Nitrogen isotopes are often used to collect information from modern collected mollusc shells, but have not been widely used on samples derived from deep time (for e.g. see Gillikin et al. 2017 and Graniero et al. 2016). At present, nitrogen isotopes might be considered supplementary to baseline archaeomalacological datasets derived from oxygen and carbon isotopes but are still important nonetheless (see challenges using nitrogen isotopes in archaeomalacology studies in Darrow et al. 2017:40-41).

Table 4.7 Summary of isotope and trace elements commonly used in archaeomalacology research.

Element		Potential Proxy Interpretation	Examples
Stable Isotopes			
Carbon dissolved inorganic carbon (DIC)	^{13}C	Feeding or diet trends (deposit feeding, filter feeding) Primary productivity Salinity Water mixing (freshwater versus brackish)	Andrus and Crowe 2000; Andrus and Thompson 2012; Colonese et al. 2017; Hausmann et al. 2017a; McConnaughey 2008; and see also Layman et al. 2012.
Oxygen	$^{18}\text{O}/^{16}\text{O}$	Temperature or salinity (SST, SSS, incl. precipitation)	Andrus and Crowe 2000; Bar-Yosef Mayer et al. 2012; Bosch et al. 2018; Burchell et al. 2012; Colonese et al. 2009; Culleton et al. 2009; Galimberti et al. 2017; García-Escárzaga et al. 2019; Hausmann et al. 2017a; Jones et al. 2004; Mannino et al. 2003; Mannino et al. 2007; Mannino et al. 2011; Milano et al. 2016, 2017b; 2018a; Prendergast and Schöne 2017; Prendergast et al. 2013.
Nitrogen dissolved organic nitrogen (DON)	^{15}N	Water mixing or eutrophication (freshwater versus estuarine) Food web dynamics (trophic level) Pollution	Black et al. 2017; Darrow et al. 2017.
Radiogenic Isotope			
Carbon	^{14}C	Used in radiocarbon dating determinations	Numerous case studies.
Trace Element		Metabolic changes	Cahyarini et al. 2008; Hausmann et al. 2017b; see discussion in Gutiérrez-Zugasti et al. 2017:57 for use of Mg/Ca ratios in SST estimates;
Magnesium/Calcium	Mg/Ca	Temperature	Marali et al. 2017.
Strontium/Calcium	Sr/Ca		
Manganese	Mn/Ca		
Barium	Ba/Ca		
Lithium	Li/Ca		

Trace element ratios can be used to verify geochemical changes in species growth and across habitats (e.g. Hausmann et al. 2017b; and see Surge and Walker 2006 application to microstructural layers of the clam, *Mercenaria campechiensis*). Few applications have isolated trace element and oxygen isotope analyses for provenance studies (but see Eerkens et al. 2005 and Mouchi et al. 2018). In any application, it is stressed that modern control samples should be used to compare with deep time samples for a range of reasons. Most agree that control samples collected local to the deep time cultural site are ideal candidates to test if species 'encode an annual pattern of temperature change' (Campbell 2008:113; Colonese et al. 2009, 2017; Goodwin et al. 2003; Gutiérrez-Zugasti et al. 2017; Hausmann et al. 2017a; Jones et al. 2004; Lartaud et al. 2010; Mannino et al. 2007:124, 2008; Parker et al. 2017; Prendergast et al. 2013, 2016; Surge and Walker 2006). Testing control samples from non-local areas may show contradictory growth trends. These types of findings may be reflective of distinctive geological foundations unique to a location or reflect changing environmental conditions during different temporal sequences in the same or alternate locations (e.g. see Radermacher et al.'s 2009:315 Puerto Rico and Bermuda *S. gigas* study, and see discussion in Mannino et al. 2003:669). Testing at least 2 species is also good practice to isolate geochemical signatures that might arise concurrently across multi-species assemblages, thereby eliminating other suspected variables (e.g. food or nutrient intake).

High-resolution intra-sampling or long-edge micro-drilling, defined as continuous powder sampling from the complete growth profile of a shell in cross-section, provides comprehensive growth history records (e.g. *Arctica islandica* see Schöne 2013). These datasets are useful for reconstructing environmental and climatic proxies and for identifying seasonal growth trends in modern and deep time samples. Temperature reconstructions require $\delta^{18}O_{shell}$ signatures and $\delta^{18}O_{water/salinity}$ ratios derived from either water samples collected *in situ*, or from modelled SST and SSS data from where the modern mollusc grew (e.g. Andrus and Crowe 2000; Colonese et al. 2017; Goodwin et al. 2003; Hausmann et al. 2017a; Mannino et al. 2003, 2008; Milano et al. 2017b; Quitmyer 1997). The standard procedures for palaeotemperature equations for aragonite and calcite can be found in Grossman and Ku (1986). Roberts et al. (2017) provide standard reporting procedures for isotopic analysis and suggestions for statistical examination of datasets in archaeology. In Gutiérrez-Zugasti et al.'s (2017:49) example, live-collected *P. vulgata* samples collected from northern Iberia, Spain, and modern sea temperature data showed good correlation between measured and shell-reconstructed SSTs. Their results indicated a ±2.7 error range. Poor correlation may be indicative of isotopic disequilibrium. Disequilibrium might be triggered by food sources, stored or expelled energy, or other kinetic or metabolic effects (Gutiérrez-Zugasti et al. 2017:49; Mannino et al. 2003:668).

Advantages of extracting and examining isotopic values from shell growth structures includes the ability to construct palaeoclimate proxies and the opportunity to document human resource use patterns (see discussion in Twaddle 2016b). Shackleton (1973) introduced the idea of using mollusc shells to identify the season-of-collection of resources by humans. Short-edge micro-drilled powder samples taken from the last few GIs at the shell edge can be used to reveal the season-of-death or season-of-collection of a mollusc. When several shells' isotopic values are examined (routinely <5 per study), a reconstruction of seasonal human harvesting patterns may be drawn (Milano et al. 2016; Mannino et al. 2003:669, 2007; Prendergast et al. 2016). Alternatively, isotopic values from short-edge micro-drilled samples might be indicative of a seasonal event where a population has undergone mass mortality (e.g. tropical storms). A sensible approach, particularly when accessing samples from a range of temporal periods from within deep time contexts, is to anticipate changing palaeoenvironmental conditions: isolated or cyclic climatic events (i.e. a tropical cyclone storm versus routine seasonal cycles), non-linear resource use patterns, and indeed patterns showing equifinal effects (see discussion in Chapter 2, section 2.3).

4.4.2 Palaeothermometers, Palaeosalinometers and Palaeoseasonality

Key studies exemplify the significance of deriving isotopic data from cultural shell remains. Data may show distinct trends for the season-of-collection for one or several species, although, these trends may change across different spatial and temporal scales (e.g. continuous seasonal resource use versus periodic seasonal resource use). Coupling isotopic datasets from two or more taxonomic assemblages can be used to derive a more holistic picture of site use and human resource use patterns. Isotopic analyses on molluscan shells coupled with stable isotopic analyses on human teeth for instance, can inform of both human resource use patterns and diet (see Prendergast et al. 2018 for overview). Calibrated isotope values, either derived from ^{18}O, ^{13}C, or ^{15}N, inferring seasonal harvesting patterns might be achieved by dividing data into quartiles (four seasons) and by observing the upper and lower bounds of those values (e.g. see Mannino et al. 2007). Four distinct seasons are usually acknowledged to occur in temperate regions (summer, autumn, winter, spring) but for tropical regions, it is typical for Western scientific datasets to be examined using only 2 seasons (the wet season and the dry season) (e.g. see Hinton 2012 and Twaddle 2016).

Selected studies have used alternate measures to extract seasonal environmental and climatic data from mollusc shells, with some of these proving advantageous in teasing out complex relationships found exclusively in isotope datasets. Milano et al. (2017b:404) demonstrate water temperature (± 1.7°C of error) can be identified by recording morphological changes (size and elongation) of crystals within live-collected *Cerastoderma edule* (cockle) microstructures. In another study, Milano et al. (2017a:1578) found similar results for laboratory reared *A. islandica*, suggesting crystallographic morphologies can assist in defining 'conditions … [in] estuaries or restricted basins'. Additionally, Kirby (2001:85) suggests recording encrusting organisms on mollusc shells, as these have their own temperature and salinity tolerances. Using samples from Grand Bahama Island, Yanes et al. (2012) take this idea a step further by combining morphometric and isotope analyses to deduce seasonal mollusc predation from drilling predators (e.g. cephalopods or other molluscs). Although these innovative techniques have not yet become standardised in zooarchaeology, they demonstrate the usefulness of adopting multi-variable approaches to account for key indicative changes during a mollusc's life cycle.

4.4.3 Shell Chemistry and Taphonomic Complexities

Several taphonomic processes operating on molluscs at pre-mortem, peri-mortem and post-mortem stages can influence shell morphology. In some cases, impacting variables can also affect the chemical properties of mollusc shells. During the life of a mollusc, biomineralising processes form morphological features within the $CaCO_3$ tissue structure of the shell (Milano et al. 2017a:1577-1578). Where this occurs, configurations of organic and inorganic biominerals form crystal microstructures which are predominantly calcite, aragonite, or combinations of both (Milano and Nehrke 2018:1; Milano et al. 2017a:1578; Schöne and Krause 2016; Suzuki and Nagasawa 2013). Diagenesis, or diagenetic alteration, either developing gradually throughout 'geological timespans' or instantaneously after death, occurs when impacting variables alter the geochemical and mineralogical properties of the shell structure (Lindauer et al. 2018:530; Milano and Nehrke 2018:2). Diagenetic alterations can result in the dissolution of microstructural properties causing recrystallisation or cementation, or manifest as partial or complete 'irreversible' mineralogical conversions (Andrus 2011:2893; Andrus and Crowe 2000; Lindauer et al. 2018:532; Milano and Nehrke 2018:2). Exposure to processes of thermal alteration, involving wet heating (boiling in water over a fire) or dry heating (roasting in an underground oven or over an open fire), are examples of when diagenesis can occur (Andrus 2011:2893; Andrus and Crowe 2000; Lindauer et al. 2018:528-529; Milano et al. 2018b; Milano and Nehrke 2018; Milano et al. 2016; Oertle 2019).

Experimental work exposing mollusc shells to extreme heat, and using data from Raman spectroscopy and SEM images, reports on partial or complete aragonite to calcite transformations in some species. These species include: *Anadara uropigimelana* and *Terebralia palustris*, from Khor Kalba (United Arab Emirates) at ≥ 500°C (Lindauer et al. 2018), *Phorcus turbinatus* from Haua Fteah (eastern Libya) at ≥ 300°C (Milano et al. 2018b), and *P. turbinatus* from Sousa (Libya) at ≥ 300°C and at various time-heat exposures (Milano et al. 2016). Further, structural differences between prismatic, nacreous, and cross-lamellar layers following exposure to high temperatures (≥ 250°C) in *P. turbinatus, Monodonta turbinata* and *Trochocochlea turbinata* (see Milano and Nehrke 2018), and in *Geloina expansa*, *T. granosa, Pinctada maxima*, *Turbo setosus* and *Saccostrea glomerata* (see Oertle 2019) is probably due to the amount of organic content within shell microstructures (Milano and Nehrke 2018; Oertle 2019; and see Currey 1988). Importantly, Milano et al. (2016) and Milano et al. (2018b) determined that in some species $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values can alter when exposed to temperatures >300°C. These alterations can have significant implications for reconstructing and interpreting environmental and climatic proxy datasets such as temperature and salinity (usually resulting in decreased $\delta^{18}O_{shell}$ and therefore overestimations in $\delta^{18}O_{water}$), and radiocarbon dating determinations (Andrus and Crowe 2000;

Lindauer et al. 2018; Milano et al. 2018b, 2016:15; Milano and Nehrke 2018:1; Twaddle et al. 2016a, 2016b, 2017). Mollusc shells exposed to temperatures <300°C are not significantly altered and therefore deemed appropriate to use in environmental and climatic reconstructions - although this should be confirmed with each species and different microstructural types (Milano et al. 2016, 2018b; and see Oertle 2019 for complexities in samples specific to tropical contexts).

4.5 Applications to Great Barrier Reef Cultural Mollusc Shell Assemblages

Global climate modelling is based on the collation of datasets extracted from the deep past, historic, and modern temporal periods (Butler and Schöne 2017:295). Contributions of Northern Hemisphere datasets are well advanced and therefore contribute to much of our global climate understandings (Butler and Schöne 2017:295). Southern Hemisphere datasets, particularly those from sub-tropical and tropical climate regions by comparison, make less of a contribution to our knowledge due to fewer studies (Parker et al. 2017:252). Deep time cultural deposits are ideal repositories to assess and record past resource use patterns and for building palaeoclimate proxies. For the GBR, climate research is well underway but sorely lacks integration of socio-ecological datasets extracted from the deep past. Only 3 archaeological studies have deployed metric assessments to mollusc taxa from deep time GBR cultural sites. These studies are included in the review below.

The earliest known evidence for use of molluscs on GBR islands and adjacent mainland comes from the Whitsunday Island Group, dating to ~9000 years ago (Barker 2004). Barker's (2004) assessment included 4 sites in the Whitsunday Island Group, central GBR: Nara Inlet, Nara Inlet Art Site, Border Island and Hill Inlet. His work amassed metrical data to identify changes in mollusc shell size, and to extrapolate meat yields for two main phases of Ngaro occupation. Maximum length measurements were used to record shell sizes for gastropods *Nerita undata*, *Monodonta labio*, *Lunella cinerea* (operculum only), *Thais kieneri*, bivalve *Saccostrea cuccullata* and chiton *Acanthopleura gemmata* (Barker 2004:59-60). Similar conclusions for all sites were presented by Barker (2004) from these data, arguing that marine resources were continuously available throughout the Holocene and were 'largely unaffected by documented environmental changes' (Barker 2004:146). He notes that discard rates of mollusc shell, charcoal, and bone increased after 3000 BP (Barker 2004:146). The most abundant species throughout all spatial and temporal phases includes *S. cuccullata* and *A. gemmata*. Although meat yields were high for all species, *N. undata* showed a decrease in shell size (Barker 2004:86, 146). Barker attributed this change to human predation pressures (Barker 2004:86).

Forde (2014) collected abundance indices and metrical data for *Pinctada* sp., *Nerita* sp., *Turbo* sp. and *S. cuccullata* from Woppaburra's Mazie Bay site, North Keppel Island. The analysis aimed to understand differences in taxonomic discard and changes in mean mollusc shell size (using maximum length measurements) over a 3500-year human occupation period (Forde 2014:27-29). Samples were derived from Square A1 units but not from other contiguous squares (i.e. Squares A2, A3, A4 and A5). These data were used to argue for consistent representation of *S. cuccullata* and *Pinctada* sp. throughout the deposit, with statistically significant differences evident in mean shell sizes for *S. cuccullata* and *Turbo* sp. (Forde 2014:43). Forde (2014:47) infers changes in mollusc abundance, mollusc size, and human occupation phases at the site to be a result of fluctuating sea-levels and intensified El Niño-Southern Oscillation (ENSO) events ~3500 years ago. In the northern GBR region, Aird (2014) collected metric datasets for *R. nilotica* and *Conomurex luhuanus* (strawberry conch) from the Mangrove Beach Headland site, Lizard Island. Dingaal occupation at the site spanned at least ~4000 years during the Holocene (Aird 2014). This dataset did not reconstruct meat weights, but rather looked at size and sexual maturity profiles of each population to understand predation pressures (Aird 2014). Results indicated no human over-predation on *R. nilotica* or *C. luhuanus* (Aird 2014). Potential environmental impacts affecting species growth were not evaluated in the study (see also Lentfer et al. 2013; and Ash et al. 2013 and Carter 2004 for applications to Torres Strait cultural shell assemblages).

The GBR case studies discussed above acknowledge human, climatic, and environmental mechanisms driving changes in human resource use and species populations to some degree. Barker (2004) used a socio-cultural framework to address metrical results from the Whitsunday Island dataset, Forde (2014) compared available ENSO data to the Keppel Islands metrical dataset, and Aird (2014) used an Optimal Foraging Theory (OFT) framework for the Lizard Island biometric dataset. Although each of these cases use metrics to directly examine samples derived from their respective local sites, they rely on broad-scale regional analogies to explain changes. In these exchanges, important information such as site-specific or habitat-specific conditions risk being misinterpreted. For example, mollusc shell size could be unique to certain conditions at a particular site (e.g. temperature changes) but are not necessarily reflective of regionally scaled climatic oscillations. As discussed in Chapter 2, Douglass and Zinke's (2015:270) explanation that 'correlation does not necessarily imply causation' is important here. Direct evidence for socio-ecological interactions can be cross-checked in these instances using advanced analytical techniques such as biometrics, sclerochronology and biogeochemistry. A few studies situated within Australia and elsewhere have made use of some or all of these techniques. Importantly, these studies showcase that sclerochronology and biogeochemistry techniques in particular, can be applied to tropical mollusc species.

Despite the consensus that sclerochronological and geochemical techniques are best applied to temperate species due to seemingly more distinct seasons of growth, 1 study from the Northern Territory (western corner of the Gulf of Carpentaria) and 2 studies from northern Queensland (eastern corner of the Gulf of Carpentaria) examined mollusc samples that show specific wet and dry season growth characteristics. Brockwell et al. (2013) compiled molluscan samples from 3 cultural sites situated across the Northern Territory for analysis; Hope Inlet (Darwin region), Blyth River (north-central Arnhem

Land) and Blue Mud Bay (eastern Arnhem Land). Two oxygen isotope datasets (30 powder samples each) were derived from cultural and modern *T. granosa* and *Dosinia laminata*, both sand-mud flat bivalve species (Brockwell et al. 2013:24). Results suggested a reduced pattern of precipitation and increased aridity between 2000 to 500 cal BP (Brockwell et al. 2013:29). As Brockwell et al.'s (2013) research was initiated as a pilot study, broad palaeoclimate trends could be inferred, and to some degree human behavioural responses to changed palaeoclimatic conditions during the late Holocene (and see key metric datasets for Blue Mud Bay in Faulkner 2009, 2010, 2011 and 2013).

On the eastern side of the Gulf of Carpentaria, Hinton (2012) investigated the mangrove dwelling mud cockle *Geloina erosa* (synonym: *Polymesoda erosa*), from Bentinck Island. Hinton's (2012) study deployed sclerochronology and stable oxygen and carbon isotope analyses to cultural and modern *G. erosa* valves collected near Mirdidingki Creek. Results showed *G. erosa* growth was broadly consistent between the wet and dry seasons (Hinton 2012). Twaddle (2016) continued sclerochronological and isotopic analyses of *G. erosa* for Bentinck Island, but added examinations of *Marcia hiantina* and *Gafrarium pectinatum* (sand-mud flat bivalve species). His findings also showed broad trends in mollusc growth between wet and dry seasons; however, closer inspection of *G. erosa* and *G. pectinatum* shell chemistry determined high growth variability (Twaddle 2016; Twaddle et al. 2016a, 2017). Hydrological shifts, including precipitation and tidal patterns, showed *G. erosa* and *G. pectinatum* from Bentinck Island to be unsuitable for palaeoenvironmental proxy reconstructions or for use in radiocarbon dating (Twaddle 2016; Twaddle et al. 2016a, 2017). *M. hiantina*, however, exhibited appropriate qualities for palaeoenvironmental modelling (Twaddle 2016; Twaddle et al. 2016a, 2017).

Durand's (2002) project on freshwater mussel species, *Alathyria pertexta* and *Velesunio wilsonii*, from the Barkly Karst region in northwest Queensland (near the Gulf of Carpentaria), Australia, also recognised the complexities in seasonal hydrological patterns. Although many significant cultural sites exist near Durand's study site, consideration of the human use of these species was not included. Instead, Durand's (2002) research focused solely on the suitability of these species as potential palaeoclimatic indicators. Her sampling strategy included non-cultural live-collected and dead collected *A. pertexta* and *V. wilsonii* valves from riverbanks, and from at least two non-cultural Quaternary sites (Durand 2002). The methodology adopted for the separation of carbonate shell layers in *A. pertexta* might also be transferrable to other species. Indeed, several studies report on the difficulty of distinguishing GIs from GLs and vice versa (see complexities in Tables 4.5 and 4.6). Durand's (2002:52-55) strategy of submerging sample cross-sections in a 5% sodium hypochlorite solution at repeated intervals over <10 days each showed successful separation of these features. Carbon and oxygen isotope sampling, and trace element analyses followed sclerochronological techniques. Results reported the unsuitability of *V. wilsonii*, but suitability of *A. pertexta* as palaeoclimatic indicators.

A recent Australian study, by Tynan (2017), concentrated on 2 oyster species, *S. glomerata* and *Ostrea angasi*, and 1 mussel species *Mytilus galloprovincialis*. Observation of oyster growth was examined *in situ* from 3 locations over a period of 1 year at Little Swanport in Tasmania, Pambula Lake in New South Wales, and Moreton Bay in southeast Queensland (Tynan 2017, Tynan et al. 2014). Tynan's (2017) aim, like Durand's (2002) was to test the suitability of these species for palaeoclimatic reconstructions (and see Tynan et al. 2014, 2017a, 2017b). An additional examination of just 2 cultural *O. angasi* shells derived from the Severs Beach Midden, Pambula River, southeast coast of New South Wales, was also incorporated (Tynan et al. 2017a). Although Tynan et al. (2017a) acknowledge the small sample size of cultural *O. angasi*, they posit cultural mollusc shells are valuable for constructing palaeotemperature proxies using biogeochemical techniques. In this study, cultural and modern *O. angasi* samples indicated slightly cooler temperatures (~2°C) at ~1850 years BP (Tynan et al. 2014, 2017a). As Twaddle (2016) and Durand (2002) also found, Tynan et al. (2014:207) recognised the complexities associated with saltwater and freshwater mixing (e.g. from precipitation or freshwater river plumes), input of plant detritus, and sedimentation, when thinking through impacts upon mollusc growth. They concluded oxygen isotope signatures alone could not characterise mollusc growth appropriately. Subsequently, Tynan (2017) employed trace element analyses to test modern *S. glomerata* samples from Pambula Lake and Moreton Bay. Trace elements, Mg and Ca, showed that *S. glomerata* do depend on temperature for growth, but salinity also plays a vital role and may vary between locations (Tynan et al. 2017:85). In their publication, Tynan and colleagues argue '[t]his is an extremely important finding, as it calls into question the prevailing paradigm that bivalve shell Mg/Ca offers a temperature tracer that is independent of salinity' (Tynan et al. 2017:87).

4.6 Analytical Techniques for the Mazie Bay Mollusc Shell Samples

Only a handful of archaeomalacological studies have consecutively employed biometrics, sclerochronology and geochemical techniques to cultural mollusc shell assemblages. Studies that have employed some or all of these techniques have focused on temperate bivalve species (e.g. see Prendergast et al. 2013:77). The application of these techniques to Australian case study samples is limited but now gaining momentum due to newly informed research needs, improved specialist training, and accessibility to instrumental equipment. Tropical mollusc species, typical of northern Australian coasts, are generally understudied due to suspected 'minimal seasonal changes' and difficulties with interpreting other complex variables owing to socio-ecological changes. Strategic examination and careful interpretation of datasets, however, is achievable and worthwhile for tropical locations. As Faulkner (2009:831-832) explains, long-term resource use patterns derived from these types of datasets provide an adequate resolution through which to identify key changes in human resource use. At present, only broad scale socio-ecological understandings exist for the Keppel Bay Island region. These generalisations can be refined by explicitly informing on how resource populations and humans operated within the 'high nutrients coastal strip' (GBRMPA 2018) over a 5000-year period. Long-term human resource use patterns, seasonal growth indices, species growth tolerances, preferred habitat/s, and food and nutrient requirements, are examples of where fisheries management initiatives could be informed (Radermacher et al. 2009; and see Roussel et al. 2011 for applications to an abalone species, *Haliotis tuberculata*).

Explanations posit that most fauna, including molluscs, experienced exponential growth in the GBR during the Holocene which is described by Hopley (1984) as the 'high energy window'. From this review, variables prompting the most change in faunal growth at Mazie Bay are predicted to include socio-cultural harvesting trends, SST, SSS, and availability of food and nutrients. In some cases, mollusc shell size might be a good indicator of ontogenetic age, which could shed light on relative growth rates. Temporal growth sequences, or the length of time for each GI to be laid down, are best measured by analysing internal growth features of the shell using sclerochronology techniques. Seasonal inferences may be made from sclerochronological datasets; however, each variable's 'value' is best targeted using stable isotope analysis. At Mazie Bay, mollusc shells recovered from Woppaburra's cultural resource use site might signal seasonal trends in species growth and/or seasonal use of resources by humans. Indeed, Woppaburra's resource use calendar depicts harvesting patterns according to 7 overlapping seasons. To my knowledge, no geochemical datasets comprising seasonality studies have attempted to define the seasonal use of resources with traditional ecological knowledge (TEK). This type of inclusion of both scientific data and TEK has enormous potential to cross-culturally inform resource management initiatives about long-term socio-ecological dynamics. A breakdown of the explicit aims using each analytical technique under the Keppel Bay Islands Historical Ecology framework is provided below:

Biometrics

(1) Identify any changes in species shell sizes and age profiles through time.
(2) Determine if maximum shell sizes is a good proxy for ontogenetic age.

Sclerochronology

(3) Isolate growth feature characteristics in shell species, including any features that might be indicative of seasonal change.
(4) Determine ontogenetic ages.

Stable Isotopes

(5) Understand how mollusc growth is influenced by sea temperatures by assessing $\delta^{18}O$ values.
(6) Detect potential trends in Woppaburra harvesting patterns (i.e. seasonal harvesting).

Overall Aims

(7) Foster a translation of the Woppaburra seasonal resource use calendar knowledge together with scientific explanations for using marine resources at Mazie Bay, including key changes.

(8) Improve understandings of the growth and cultural use of tropical mollusc species (using the nominated techniques).

(9) Provide new baseline data for the growth of selected mollusc species in the Keppel Bay Island region useful to modern fisheries management (e.g. species specific tolerances to seasonal variables could be used to model future responses to climate scenarios).

(10) Make the analytical datasets available for comparative analyses in future research (i.e. comparisons to other temporal periods and for local, regional, international projects).

4.7 Summary

This review has emphasised the importance of applying multi-variable approaches, in the assessment of molluscan assemblages derived from deep time contexts. Analytical techniques that are newly available to the project and advantageous for deriving refined insights into socio-ecological dynamics at Mazie Bay include: biometrics, sclerochronology, and biogeochemistry. Seasonality studies aiming to construct palaeoenvironmental and palaeoclimate proxy datasets with TEK are tremendously beneficial for informing management initiatives. The following chapters report on the application of these analytical techniques to key mollusc species deriving from the deep time site at Mazie Bay and subsequent results.

5

Biometrics

5.0 Introduction

This chapter applies biometric analyses to key molluscan species recovered from the Mazie Bay cultural resource use site. A review of Rowland's preliminary findings is summarised before refining chronological understandings of Woppaburra occupation using newly obtained Accelerator Mass Spectrometer (AMS) radiocarbon dates. Quantification summaries for the Pacific asaphis (*Asaphis violascens*), rock oyster (*Saccostrea cuccullata*), Pinctada (*Pinctada sugillata)*, moon turban (*Lunella cinerea*), chamaeleon nerite (*Nerita chamaeleon*) and the black jewelled chiton (*Acanthopleura gemmata*) are presented before size assessments are undertaken. Linear regression analyses used landmark attributes on shell fragments to estimate the maximum size of intact shells. These findings are detailed before biometric results are discussed and summarised at the end of the chapter.

5.1 Early Characterisation of the Mazie Bay Cultural Site

Based on early radiocarbon dates, Rowland (1999a) infers continuous occupation at Mazie Bay by the Woppaburra People from at least 5000 years ago. Earlier evidence for Woppaburra occupation probably exists but these details have not yet been recorded. This is owing to Rowland's 1979 excavation at Mazie Bay ceasing at a depth of 4.2m (due to safety concerns), and potentially other sites existing but not having been located. The earliest radiocarbon result obtained from a charcoal sample was recovered from a depth of between 314-344cm. This sample provided a date of 4274±94 BP (NZA 456) (Rowland 1999a:143). The complete size and depth of the Mazie Bay cultural site has not been fully determined but is regarded as extensive with dense accumulations of cultural materials (see Rowland 1992 and Rowland 1999a). Rowland (1999a) summarises the first characterisation of molluscan materials derived from Woppaburra's cultural site at Mazie Bay.

The density of shell materials discovered during Rowland's excavation of Mazie Bay in 1979 was not anticipated, therefore a sub-sampling retrieval method was adopted (Michael Rowland pers. comm. 2016). Sample selection consisted of unbiased collection of cultural material samples, with these being placed into clearly labelled laboratory bags at the site and transported to the University of Queensland for quantitative analysis (Michael Rowland pers. comm. 2016). Remaining cultural materials were carefully placed back into the excavation squares as backfill (Michael Rowland pers. comm. 2016).

Preliminary preparation of mollusc materials for quantification (i.e. dry sieving through 3.17mm mesh) was prepared by Rowland in 1979 (summary weight data for the molluscan assemblage and Rowland's 1999a Mazie Bay section drawing is provided in Chapter 3, section 3.3.2).

After careful consideration of findings, Rowland (1999a) suggested the occurrence of a distinct depositional event. This event is characterised as a 'buried soil' event, representing a sand dune formation hiatus period occurring at ~3500 BP in stratigraphic unit (SU) 3 (Rowland 1999a:141-142). Although, accumulation rates and deflation patterns of aeolian sands has not yet been confirmed, other characteristics distinguishing broad trends before and after the '~3500 BP buried soil event' is suggested by Rowland (1999a:141-143; and see Rowland 1981:67). These distinctions include changes to the direction of sand dune apexes, changes in the density of cultural materials, and changes in the representation of key taxa (Rowland 1999a). Figure 5.1 provides a visualisation of broad changes in the abundances of selected Mollusca, Osteichthyes (bony fishes), Testudines (turtles), and Crustacea taxa before and after the proposed 3500 BP buried soil event using observations from Rowland (1999a) and Hermes (1984). Hermes (1984) models the types of fishing technologies likely to have been used per taxa, suggesting that hook and line fishing was prevalent in the post-3500 BP phase (evidenced by the appearance of bony fish species and a fishhook recovered from the site, see Hermes 1984 and Rowland 1981). Horsfall (1982) reports on changes in pre- and post-3500 BP, lithic assemblages and argues for a 'small tool tradition' in the post-3500 BP phase (see Darvill 2009 for definition of the Australian Small Tool Tradition). Limited evidence also suggests contact with the mainland, or trade of mainland lithic materials to the Woppaburra People (e.g. appearance of silcrete flakes – silcrete is not locally available on the Keppel Bay Islands) (see also Chapter 3, section 3.3.1 discussion).

Rowland (1999a; and see Rowland 1999b) speculated complex socio-ecological processes contributed to geomorphological and resource use changes at Mazie Bay. In his discussions, Rowland acknowledges how socio-cultural changes like population demographics and shifts in the use of technologies could have influenced change; although, in pursuit of holistically characterising the socio-ecological trajectory of the Keppel Bay Islands during the Holocene, available sea-level models and other 'globally synchronous' climatic cycles such as the El Niño- Southern Oscillation (ENSO) are included in his explanations (Rowland 1999a; and see Rowland 1999b). To refine understandings about changes occurring within different temporal phases at Mazie Bay, 5 additional AMS radiocarbon dates were first obtained from shell samples and evaluated with Rowland's (1999a) conventional radiocarbon dates. In an attempt to bracket the time period coinciding with the '3500 BP buried soil event' in SU3, 3 AMS radiocarbon samples were obtained from this unit. A single AMS radiocarbon date was taken from SU1 and another from SU7.

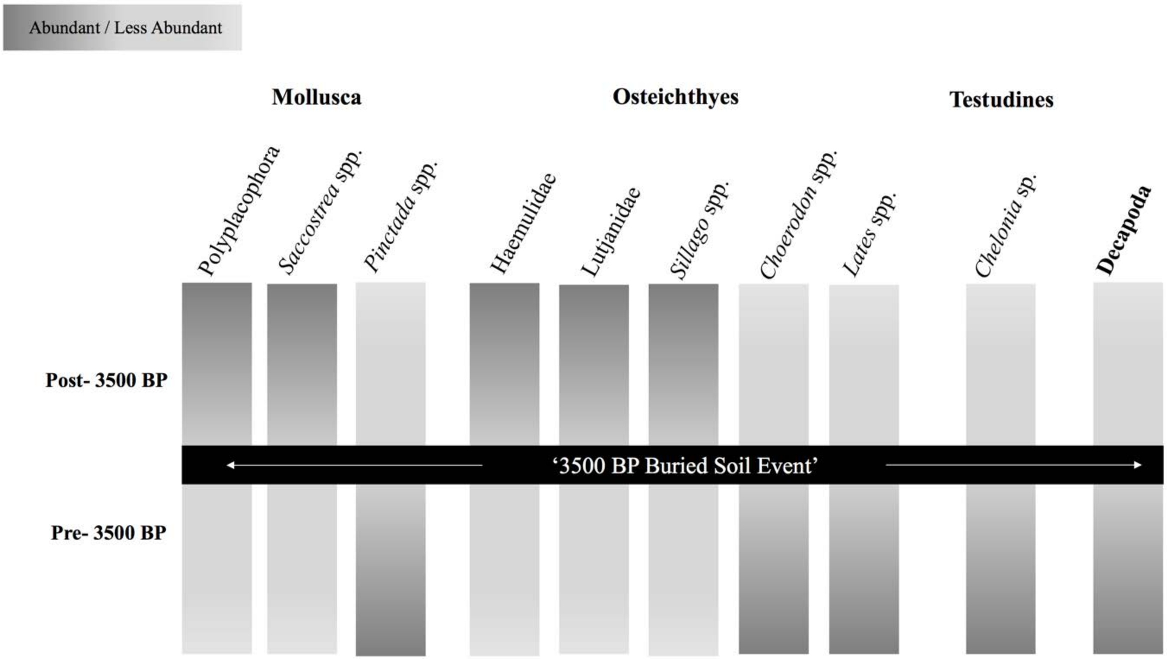


Figure 5.1 Broad representation of observable differences between taxa, pre- and post-3500 BP. Shading indicates relative abundance: darker = more abundant, lighter = less abundant. Polyplacophora = chiton, *Saccostrea* sp. = rock oyster, *Pinctada* spp. = pearl oyster, Haemulidae = sweetlip (cf. termed 'slatey' in Hermes 1984:33), Lutjanidae = snapper, *Choerodon* spp. = tuskfish, *Lates* spp. = barramundi, *Chelonia* sp. = turtle (probably green turtle *Chelonia mydas* as noted by Hermes 1984:41), Decapoda = unidentified crab. Please note that other important marine and terrestrial fauna and flora resources were used by the Woppaburra People but are not represented here.

5.1.1 AMS Radiocarbon Dating

Rowland (1999a) reported 8 conventional radiocarbon dates from 7 mollusc shell samples and 1 charcoal sample recovered from the Mazie Bay cultural site. These dates were originally corrected using Gillespie and Polach's (1979) 'environmental effect' calibration which has since been superseded. These conventional radiocarbon dates, compiled from data extracted from primary radiocarbon date reports and other sources (i.e. the Australian National University (ANU) database, a copy of the 1980 report (BETA- values), 1983 report (ANU-2488 and ANU-2489), and 1984 report (NZA-456) held by Rowland) are summarised in Table 5.1 and are calibrated using newly applicable corrections. Minor discrepancies between information appearing in the original radiocarbon date reports, laboratory databases, and earlier publications are apparent. For example, the ANU-2393 sample is recorded in the ANU database as *Pinctada facata/alibina sugillata* [sic] rather than *Crassostrea* sp. as noted in Rowland's publications (e.g. Rowland 1999a). This sample, along with other conventional radiocarbon dates determined from shell reported in Rowland (1999a), appear in Table 5.1 as Ostreidae. Provenance of radiocarbon samples according to excavation units (XUs) and stratigraphic units (SUs) were confirmed by Rowland (Michael Rowland pers. comm. 2016-2019). In addition to the corrections made to Rowland's (1999a) conventional radiocarbon dates, Table 5.1 presents 5 newly reported AMS radiocarbon date determinations from *L. cinerea* shells. These samples were retrieved from selected Mazie Bay excavation units (XUs) that were recovered by Rowland in 1979. AMS radiocarbon dating of these samples was completed at the University of Waikato Radiocarbon Dating Laboratory, New Zealand. Each sample (~2g each) was extracted from interior cross sections of each *L. cinerea* shell and tested for recrystallisation.

AMS radiocarbon date determinations broadly coincide with the newly calibrated conventional radiocarbon date results reported in Rowland (1999a). Differences in results might be a product of in-house laboratory preparations or calibration methods used for each species (i.e. between *L. cinerea* using AMS radiocarbon dating methods versus *Crassostrea* sp. using conventional radiocarbon methods). Importantly, using the AMS radiocarbon date determinations, SU3 is bracketed between ~3800-3700 cal BP and ~2700-2500 cal BP (WK-49316 and WK-49318). Samples BETA-1244 and BETA-1246 as explained by Rowland (1999a:141), have identical basal dates in Squares A1 and A5 (appearing as contiguous sequences). These results, as well as the BETA-1245 basal date formed Rowland's interpretations for when the 3500 BP buried soil event occurred. New AMS radiocarbon dates from closely related units suggest the height of this event might have occurred between ~3800-3500 cal BP (WK-48317 and WK-49318). To re-evaluate possible changes in the Mazie Bay molluscan assemblage throughout the Holocene, 4 phases were determined using selected radiocarbon dates. These phases were constructed using AMS radiocarbon dates (at 2 sigma) and sample NZA-456 (at 2 sigma), and informed by SU descriptions appearing in Rowland (1999a) (see Table 5.2).

Table 5.3 summarises the 4 phases alongside a summary of observations made by Rowland (1999a). An evaluation of mollusc shell quantifications using weight, minimum number of individuals (MNI) and number of individual specimens (NISP) data can refine interpretations about species abundances. Key to these interpretations is how molluscs are represented across each phase, and if harvesting trends followed a similar trajectory to that of observed events (e.g. an hiatus in sand dune formation proposed for Phase 2 might correspond to either minimal or increased mollusc shell deposition). Further, changes to the representation of molluscan taxa habitats might infer changes to Woppaburra harvesting localities and/or changes directly applicable to the Mazie Bay environmental setting. As a consequence of possible harvesting intensities or environmental changes in species habitats, shell sizes might show linear increases, linear decreases, or fluctuating size trends though time. Mollusc taxa flagged as 'dominant' in Rowland's preliminary analyses (Rowland 1999a) are used in the following assessments and according to current nomenclature specifications (as determined in Chapter 3, section 3.3.2). These species include: *A. violascens*, *P. sugillata*, *S. cuccullata*, *L. cinerea*, *N. chamaeleon*, and *A. gemmata*. Other faunal taxa are represented in the Mazie Bay assemblage but are not included in these assessments due to time constraints and potential bias in early excavation sampling strategies and/or taphonomic impacts (and see discussion in Chapter 4, section 4.1.1).

Table 5.1 Summary of radiocarbon date determinations for the Mazie Bay cultural site, Square A1 and Square A5. *denotes AMS radiocarbon dates collected from *Lunella cinerea* samples in this study. Conventional radiocarbon dates sampled from Ostreidae shells, originally reported in Rowland (1999a) and new AMS radiocarbon determinations were calibrated using Calib 7.1 software with a Marine13 (Reimer et al. 2013) curve (11±13) (regional Delta R average provided by Petchey, University of Waikato Radiocarbon Dating Laboratory). Charcoal sample (NZA-456) was calibrated in Calib 7.1 software with a SHcal13 curve (Hogg et al. 2013). Note: samples BETA-1244, Square A1 and BETA-1246 Square A5, are thought to be a location where Squares A1 and A5 overlap in stratigraphic unit 3.

Sample Code	**Square**	**SU**	**Depth (cm)**	**Material/Species**	**14C date (BP)**	**Cal age BP 1σ (probability distribution)**	**Cal age BP 2σ (probability distribution)**
*WK- 49315	A1	1	5-10	Shell/*L. cinerea*	467±18	0-78 (1.000)	0-129 (1.000)
ANU- 2488	A1	1	5-10	Shell/Ostreidae	670±50	259-376 (1.000)	147-164 (0.016) 188-436 (0.984)
ANU- 2489	A1	2	15-20	Shell/Ostreidae	1520±50	993-1131 (1.000)	932-1181 (1.000)
BETA- 1243	A1	3	55-60	Shell/Ostreidae	3450±70	3216-3393 (1.000)	3118-3484 (1.000)
*WK- 49316	A1	3	55-60	Shell/*L. cinerea*	2856±18	2576-2584 (0.043) 2586-2691 (0.957)	2502-2704 (1.000)
*WK- 49317	A1	3	105-110	Shell/*L. cinerea*	3582±18	3416-3502 (1.000)	3384-3543 (1.000)
BETA- 1244	A1	3	125-130	Shell/Ostreidae	4190±80	4150-4378 (1.000)	4018-4022 (0.001) 4028-4491 (0.999)
BETA- 1245	A5	3	165-170	Shell/Ostreidae	4030±90	3896-4155 (1.000)	3799-4325 (1.000)
*WK- 49318	A5	3	170-180	Shell/*L. cinerea*	3856±18	3755-3850 (1.00)	3703-3882 (1.000)
BETA- 1246	A5	3	180-190	Shell/Ostreidae	4190±80	4150-4378 (1.000)	4018-4022 (0.001) 4028-4491 (0.999)
ANU- 2393	A5	7	240-250	Shell/Ostreidae	4160±100	4084-4367 (1.000)	3834-4492 (1.000)
*WK- 49319	A5	7	255-265	Shell/*L. cinerea*	4148±18	4145-4240 (1.000)	4092-4297 (1.000)
NZA- 456	Auger	9	314-344	Charcoal	4274±94	4584-4599 (0.042) 4609-4768 (0.603) 4782-4870 (0.355)	4448-4467 (0.010) 4517-5040 (0.990)

Table 5.2 Each phase by depositional unit using AMS radiocarbon date determinations (and sample NZA-456), and stratigraphic units as defined by Rowland (1999a) for Square A1 and Square A5. Note: Square A1 does not contain stratigraphic units 4, 5, 6, or 7; and, Square A5 does not contain stratigraphic unit 1.

Phase	Stratigraphic Unit	Square A1 Depth	Square A5 Depth	cal BP
Phase 4	1	5-15cm	-	~200 to ~500
Phase 3	2	15-55cm	140-165cm	~500 to ~2500
Phase 2	3	55-130cm	165-190cm	~2500 to ~3800
Phase 1	4, 5, 6, 7, 8 + 9 (auger sample, NZA-456)	130-190cm -	190-314cm 314-344cm	~3800 to ~5000

Table 5.3 Summary of phases determined in Table 4.2 with coinciding phase descriptions appearing in Rowland (1999a).

Phase/s	Date Range (cal BP)	Coinciding Phase (Rowland 1999a)	Coinciding Observations (Rowland 1999a)
Phase 3 and Phase 4	~200 to ~2500	Post-3500 BP buried soil event	scattered cultural remains appear 'less clearly defined' chitons and oysters become more abundant hook and line fishing is introduced 3 fish species (representative of sand-flat habitats) become more abundant stone artefacts representative of a 'small tool tradition' appear
Phase 2	~2500 to ~3800	At-3500 BP buried soil event	hiatus in sediment deposition, likely an isolated event sand dune apex changes direction to be 'seaward facing'
Phase 1	~3800 to ~5000	Pre-3500 BP buried soil event	sand dune apex is 'landward facing' densely compacted' 20cm thick mollusc shell lenses pearl shell, 2 species of fish, crab and sea turtle remains more abundant

5.2 Mollusc Ecology and Biology

Species selected for this study are derived from the following molluscan classes: Bivalvia, Gastropoda and Polyplacophora. Characteristics typical of molluscs in these families is provided before details are given for each species of interest. Where information is available in the malacology literature for Great Barrier Reef (GBR) species populations, it is provided here. In most cases however, details for GBR species do not exist (for e.g. size-at-age indices), and therefore information from other regions is used. Detailed phylogeny, evolutionary, and physiological descriptions can be found in Ponder and Lindberg (2008) and Ruppert et al. (2004). Table 5.4 summarises the ecological and biological information for each species including their major habitats (described in Chapter 3, section 3.1.4) and Figure 5.8 shows their tidal zones. While basic molluscan ecological and biological information provided here, the subsequent chapters detail growth trends and other behavioural traits for each species.

Bivalvia

Bivalves, meaning 'two valves', or commonly 'clams' can be either equivalve (e.g. Veneridae) or inequivalve (e.g. Ostreidae) (Ruppert et al. 2004:368). Their shells are held together by a muscle ligament and hinge, with muscle expansion and contraction allowing a bivalve to open and close (Ruppert et al. 2004:368). Ocelli, or pallial eyes, are located on the mantle margin of most bivalves (Ruppert et al. 2004:397). Ranging from a few to several thousand, bivalve ocelli are photoreceptors that manage a bivalve's opportunity to respond to food capture or protection from predators (Ruppert et al. 2004:397). Bivalves can be sessile - affixed onto substrates (e.g. Ostreidae and Tridacninae), be free-swimming (e.g. Pectinidae), or have locomotion abilities (e.g. Arcidae and Tellinidae). Bivalves that achieve locomotion by moving over substrates, use a 'blade like' foot that extends and retracts from an inner pulsating muscle to outside the ventral margin (Ruppert et al. 2004:371).

The ages-at-sexual-maturity and lifespans for the common bivalves recovered from Mazie Bay, *A. violascens*, *P. sugillata* and *S. cuccullata*, are unknown for the Keppel Bay Island region and for the GBR region more generally. On the Western Australian coast, *S. cuccullata* reach sexual maturity at ~1 year (AVC 2016:15) (Table 5.4). Age estimates of Atlantic individuals suggest lifespans may be more than 10 years. For instance, Arkhipkin et al. (2014:3) measured an Ascension Island (central-east Atlantic) *S. cuccullata* individual to be 11 years-old and another to be 10 years-old. The general anatomy of species in the Psammobiidae, Margaritidae, and Ostreidae families is provided below (Figures 5.2, 5.3, 5.4).

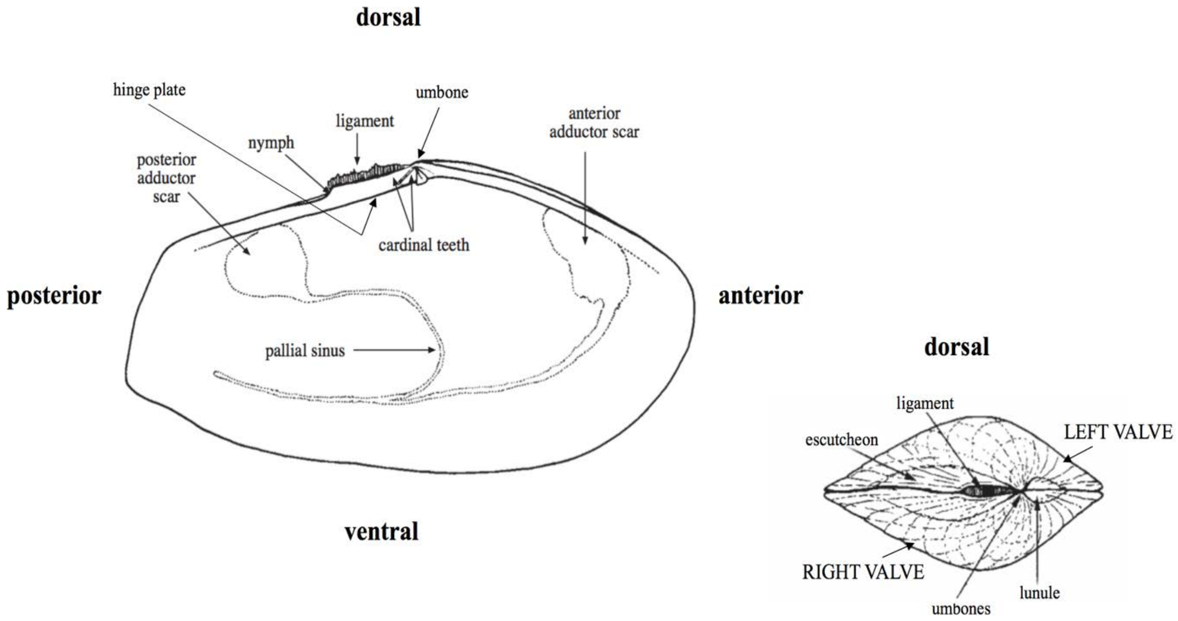


Figure 5.2 Anatomical diagram of a generalised Psammobiidae, showing the interior left valve and dorsal view of articulated valves (after Carpenter and Niem 1998:124, 305).

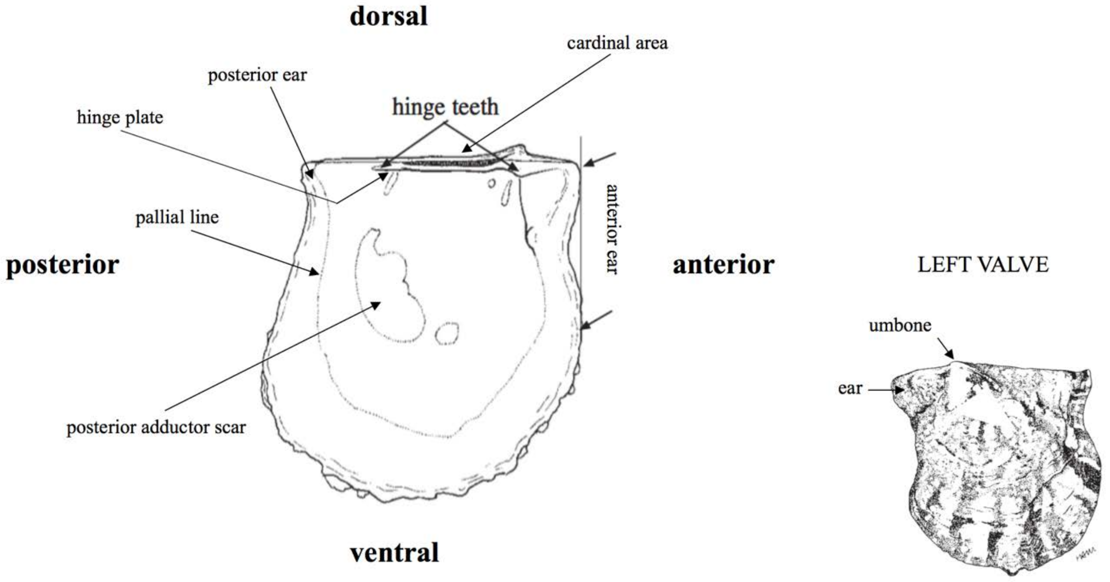


Figure 5.3 Anatomical diagram of a generalised Margaritidae, showing the interior left valve and exterior left valve (Carpenter and Niem 1998:124, 181, 182, 184 [after Kira, 1962]).

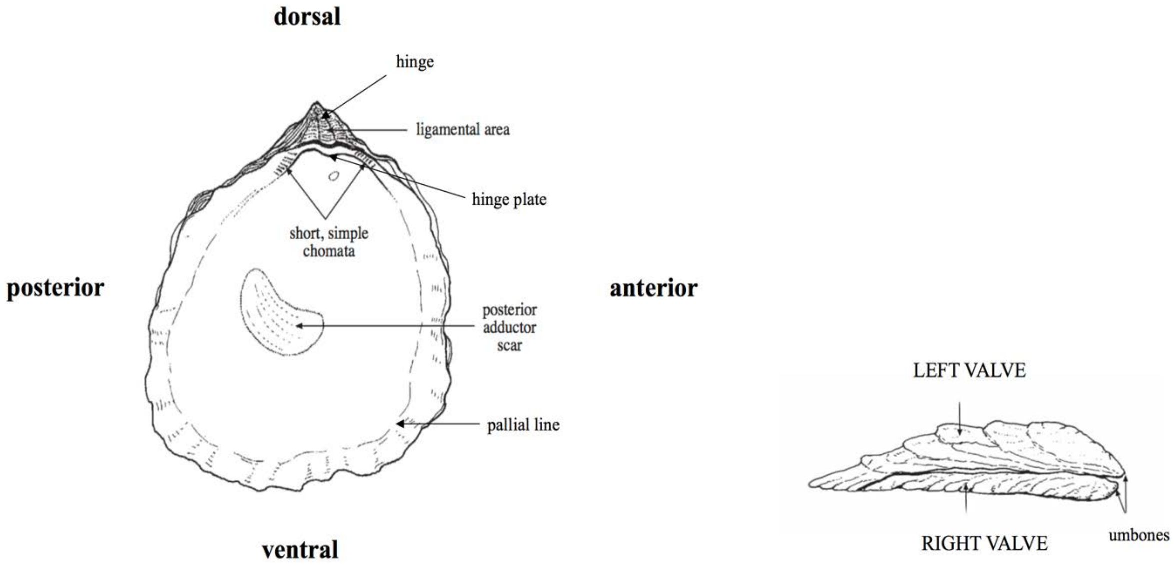


Figure 5.4 Anatomical diagram of a generalised Ostreidae, showing the interior left valve and articulated valves (after Carpenter and Niem 1998:124, 224).

Gastropoda

Gastropod, meaning ‘stomach foot’, or commonly ‘snail’, can be either coiled (e.g. Trochidae) or uncoiled (e.g. Patellidae) (Ruppert et al. 2004:300-304). Their exoskeleton or single outer shell houses the animal inside. In some species, an operculum fits into the apertural space, allowing the gastropod to open and close at the discretion of muscle expansion and contraction (e.g. *L. cinerea*) (Ruppert et al. 2004:300-304). Gastropods are mobile, achieving locomotion with a muscular foot which allows the animal to glide (e.g. Turbinidae) or hop (e.g. Strombidae) over substrates (Ruppert et al. 2004:313-314). Eyestalks can protrude from the aperture near the siphonal canal of some species (Ruppert et al. 2004:332). Fitted as a pair, gastropod ocelli are photoreceptors, that manage a gastropod’s opportunity to respond to food capture or protection from predators (Ruppert et al. 2004:332). Neritids tend to cluster in small or large populations, doing so as protection from the heat (see Eichhorst 2016:79) in the intertidal zone at high tide, which also acts as a haven from fish, octopus and other mollusc predators (Eichhorst 2016:73). Their ‘dry survival time’ as aerial respirators can extend over a few days (Eichhorst 2016:73, 80-81). Locomotion is achieved by foot, moving a slow ~2.5cm per hour on favourable surfaces (Eichhorst 2016:82).

The age-at-sexual maturity and lifespan for the gastropods in the Mazie Bay assemblage, *L. cinerea* and *N. chamaeleon,* are unknown for the Keppel Bay Island region (Table 5.4). The general anatomy of species in the Neritidae and Turbinidae families is provided below (Figures 5.5 and 5.6).

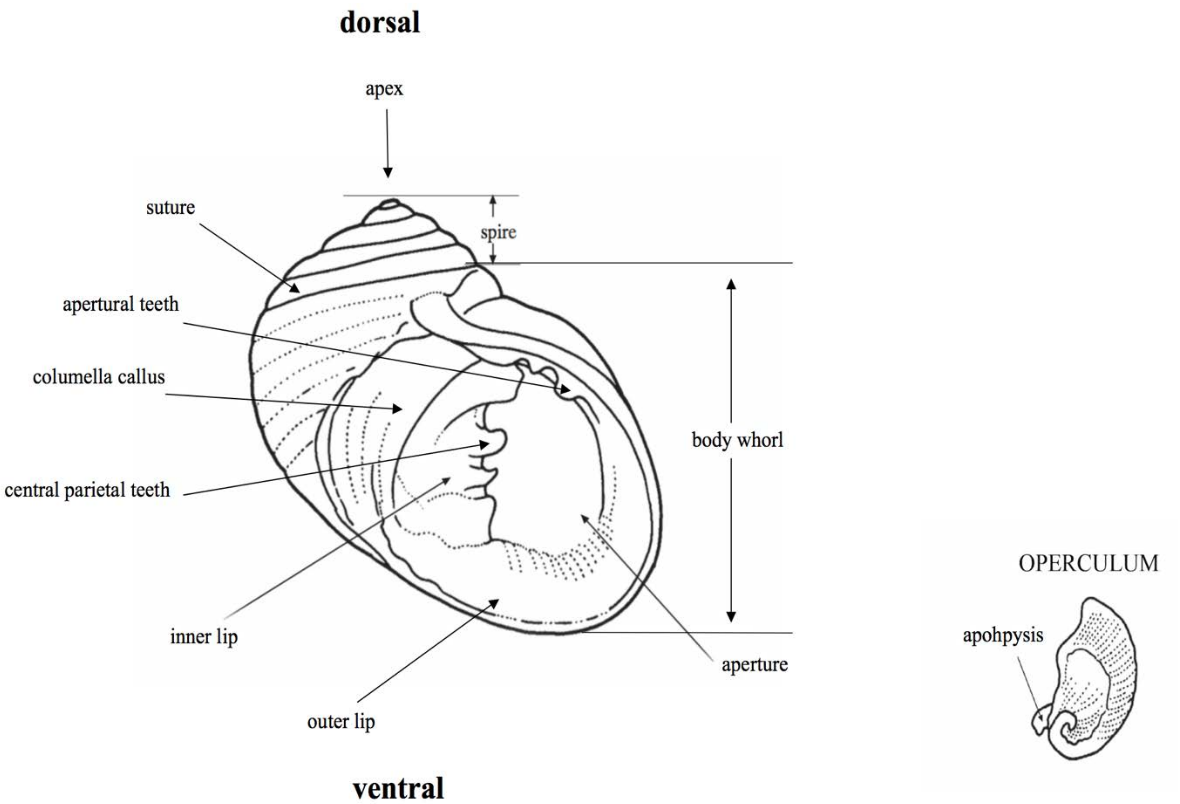


Figure 5.5 Anatomical diagram of a generalised Neritidae, dorsal view of operculum (after Carpenter and Niem 1998:420; Eichhorst 2016:113).

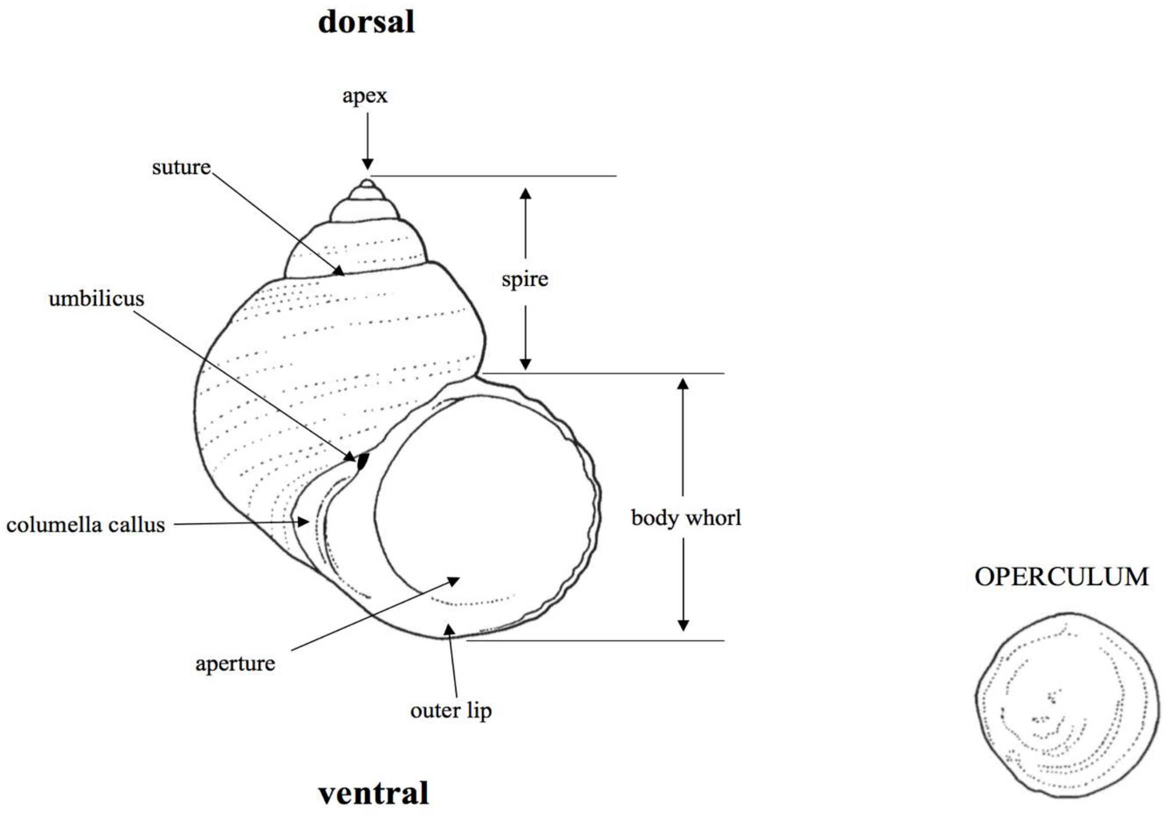


Figure 5.6 Anatomical diagram of a generalised Turbinidae, dorsal view of operculum (after Carpenter and Niem 1998:409).

Polyplacophora

Polyplacophora, meaning 'bearer of many plates', or commonly 'chitons', are elongate with 8 interlocking shell valves extending from the anterior to the posterior end of the animal (Giribet et al. 2006:7724). A dorsal exoskeleton and bordering soft tissue girdle can house the animal underneath (e.g. in *A. gemmata*) (Ruppert et al. 2004:292) or, in some species the plates can be hidden by soft tissue (e.g. *Cryptoplax* spp.). Muscular reflexes and interlocking shell valves enable the animal to form into a ball as protection from predators (Ruppert et al. 2004:292-294). Polyplacophora, like some bivalves, may contain thousands of ocelli photoreceptors, but these are situated on the anterior valves (Ruppert et al. 2004:296). Polyplacophora are mobile, their large suction foot covering most of the ventral exterior is used for locomotion to glide over rocky surfaces (Ruppert et al. 2004:294-295). In *A. gemmata*, age-at-sexual maturity is ~2 years and the estimated lifespan is ~12 years (Soliman et al. 1996) (Table 5.4). The general anatomy of species in the Chitonidae family is provided below (Figure 5.7).

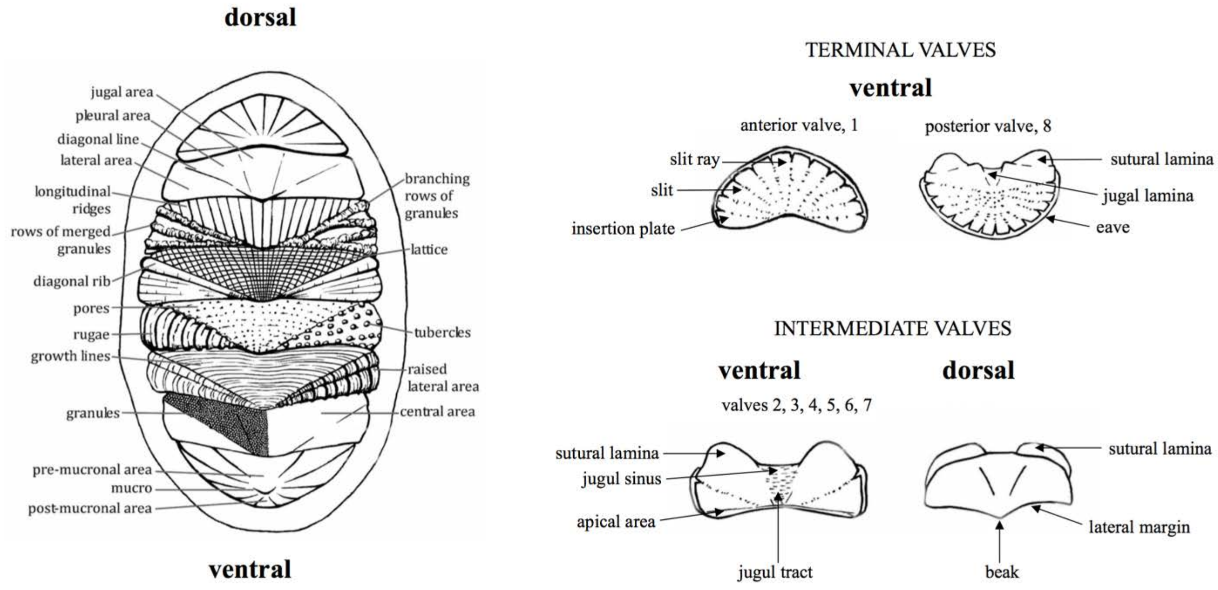


Figure 5.7 Anatomical diagram of a generalised Chitonidae, showing terminal valves (convex, concave or straight in shape) and intermediate valves (rounded or carinated in shape) (after Schwabe 2010; and Vendrasco et al. 2012:20).

Table 5.4 Ecological information for each species. The age-at-sexual maturity and lifespan for each species within the Keppel Island region is largely unknown. Age-at-sexual maturity and lifespan data that are included are estimates only and not necessarily specific to the Keppel Bay Islands or Great Barrier Reef region (from AFD 2017; AVC 2016; Barbosa et al. 2009; Beesley 1998; Carpenter and Niem 1998; Eichhorst 2016; Lamprell and Healy 1998; Sleiker 2000; Soliman et al. 1996; Stephenson and Stephenson 1972; Waikato 2017; Witney et al. 1988; WoRMS 2019).

Family	Species	Australian/ Sahulian Distribution	Habitat Type	Tidal Zone	Depth (m)	Feeding Trend	Size/Maturity
Psammobiidae	*Asaphis violascens*	Tropical north eastern and north western coasts/ Torres Strait, Papua New Guinea	Sand-Mud Flats	Subtidal	20	Deposit feeder	-
Margaritidae	*Pinctada sugillata*	Tropical central eastern and north eastern coasts/ Torres Strait	Coral Reefs/ Rocky Shores	Subtidal	-	Suspension feeder	-
Ostreidae	*Saccostrea cuccullata*	Southern subtropical and northern tropical coasts/ Torres Strait and Papua New Guinea	Rocky Shores/ Mangroves and Estuaries	Intertidal	5	Suspension feeder	1
Turbinidae	*Lunella cinerea*	Tropical north eastern and north western coasts/ Torres Strait and Papua New Guinea	Rocky Shores	Intertidal	-	Herbivorous grazers	-
Neritidae	*Nerita chamaeleon*	Tropical north eastern coast/ Torres Straight and Papua New Guinea	Rocky Shores/ Mangroves and Estuaries/ Sand-Mud Flats	Intertidal	-	Herbivorous grazers	-
Chitonidae	*Acanthopleura gemmata*	Subtropical eastern and tropical north eastern coasts/ Papua New Guinea	Rocky Shores	Intertidal	2	Omnivorous grazers	~2yrs 4th valve width ~17mm, lifespan ~12 years

Inshore Species Habitats by Tidal Zone, Mazie Bay

Figure 5.8 Representation of dominant mollusc species by tidal zone at Mazie Bay, North Keppel Island, depicting landward facing setting at low spring tide. The extreme high water spring tide mark (EHWS) is depicted with red dotted line, the extreme low water spring tide mark (ELWS) exists outside the parameters of the image. Species habitats correspond to colour coded tidal zones and fringes. Background shows cabbage palm lined swamp positioned behind casuarina trees on the beach (dry during site visit) (Photograph: Aird, September 2018).

5.3 Mazie Bay Cultural Mollusc Shell Quantifications

Re-quantification of molluscan remains (species determined 'dominant' in Rowland's preliminary dataset) from the Mazie Bay excavation squares A1 and A5 (housed at the Queensland Museum), was undertaken at the James Cook University ARC Centre of Excellence for Coral Reef Studies, Townsville (Queensland Museum outward loan agreement no: AAR1137). Where possible, whole and fragmented shell materials were identified to the lowest taxonomic level by consulting comparative physical reference samples held at the Australian Museum and Queensland Museum malacology collections, as well as published identification guides (e.g. Carpenter and Niem 1998; Eichhorst 2016). Dr John Healy, Queensland Museum Malacology department, assisted in the confirmation of *S. cuccullata* and *P. sugillata* identifications. All nomenclature was updated using the World Register of Marine Species as at 1 August 2019 (WoRMS 2019 Editorial Board). MNI, NISP and weight (g) counts were recorded following Szabó (2009). MNI counts were calculated for each XU, summed per phase and then for the total assemblage. The same Non- Repetitive Element (NRE) was used for each XU (as per Szabó 2009). These counts were based on 60% or more of diagnostic features present per fragment. For *A. violascens* the left or right umbo was used; for *S. cuccullata* this was the hinge area on either the left or right valve, or the adductor muscle scar on the right valve; for *P. sugillata* this was the hinge or ear on either the left or right valves; for *L. cinerea* and *N. chamaeleon* this was the apex or aperture; and for *A. gemmata* this was either the anterior or posterior valve. Fragments that could not be identified to species level using diagnostic features were assigned to genus, family or unidentified categories. Gently rinsing chiton remains in fresh water assisted in the identification of *A. gemmata*. This species has a distinct black diamond on the dorsal surface of each valve which becomes highly visible while damp. Fragments that presented evidence of hermitting (Szabó 2012) were noted and separated out from cultural materials. Table 5.5 summarises the quantification results for squares A1 and A5.

Table 5.5 Summary of Minimum Number of Individuals (MNI), Number of Identified Specimens (NISP), and weights (g) of the dominant mollusc species recovered from the Mazie Bay cultural site, Square A1 and Square A5 (as per sub-sampled assemblage recovered by Rowland, 1979).

Species	MNI	%	NISP	%	Wt (g)	%
Asaphis violascens	149	2.2%	1535	3.0%	2500	4.6%
Pinctada sugillata	883	13.1%	4068	8.0%	10098	18.5%
Saccostrea cuccullata	1313	19.5%	29432	58.2%	21343	39.2%
Lunella cinerea	2196	32.6%	3288	6.5%	10698	19.6%
Nerita chamaeleon	1740	25.8%	-	-	-	-
Nerita spp.	-	-	7602	15.0%	6333	11.6%
Acanthopleura gemmata	453	6.7%	4625	9.1%	3503	6.4%
Total	**6734**		**50550**		**54475**	

Lunella cinerea contributed the highest overall MNI (n=2196) from all XUs across squares A1 and A5, with a total NISP of 50550 and total weight of 54475g. In XU 170-190cm, *N. chamaeleon* has the highest MNI n=331. The highest contribution of shell by weight overall and per XU was by *S. cuccullata*. In XU 10-15cm, *S. cuccullata* produced the highest weight of shell material (XU 10-15cm 1775g, and overall 21343g). Appendix C details the quantification data per XU. Table 5.6 ranks each species assemblage per phase (based on MNI counts). When species MNIs are considered for all phases (Phases 1-4), *L. cinerea* ranks 1st (32.6%), *N. chamaeleon* 2nd (25.8%), *S. cuccullata* 3rd (19.3%), *P. sugillata* 4th (13.1%), *A. gemmata* 5th (6.7%) and *A. violascens* 6th (2.2%). When comparing species rank orders for each phase and per pooled phases (i.e. for pooled phases 1 and 2, and pooled phases 3 and 4), *A. violascens* has the lowest ranking (5th/6th rank order). The rank order of other species per phase and per pooled phases, fluctuates.

The highest MNIs for *A. violascens*, *P. sugillata*, *S. cuccullata*, *L. cinerea*, and *N. chamaeleon* occur in Phase 2. A decreasing MNI trend into Phase 3 and Phase 4 then follows for these species. For all species, Phase 1 shows higher MNI counts in comparison to Phase 4, except in *N. chamaeleon* (and excluding *A. gemmata*). For *A. gemmata*, the highest MNI count occurs in Phase 3. Either side of Phase 3, Phase 2 and Phase 4 show almost equal MNI counts, whereas Phase 1 shows the lowest MNI count. When considering how MNI trends might appear using the template provided in Table 5.3 which is more reflective of phases coinciding with Rowland's (1999a) observations (i.e. pooling phases 3 and 4, but treating Phase 2 and Phase 1 as separate sequences), Phase 2 shows the highest MNIs in all species except *A. gemmata*. For *A. gemmata*, pooled phases 3 and 4, shows the highest MNIs in comparison to Phases 1 and 2.

Summary

Although there is limited information available for testing sediment accumulation rates at the Mazie Bay cultural site, weight, NISP, and MNI quantifications for dominant mollusc species show some interesting trends (NB mollusc shell samples were recovered by Rowland during the 1989 excavation using unbiased techniques). Despite *S. cuccullata* being the most fragmented assemblage but most dominant by shell weight overall, *L. cinerea* has the highest overall MNI count. Rank order comparisons, based on MNI counts, showed a high degree of variability between phases. For all species however, except *A. gemmata*, the highest MNIs occur in Phase 2. This trend is consistent when all phases are treated separately, and when species MNIs from phases 3 and 4 are pooled as a single unit. Strikingly, for all species except *A. gemmata*, species MNIs decrease by ~50% between pooled phases 3 and 4, and Phase 2. If a 'buried soil' event did occur, this finding shows that the Woppaburra People increased rather than decreased their use of these taxa during this time. To determine where interspecies comparisons could further inform of any changes during the Holocene, MNI counts were used to tally the major habitat zones for each species and per phase.

Table 5.6 Summary of rank orders of the dominant mollusc species recovered from the Mazie Bay cultural site, Square A1 and Square A5. Phase 3 and phase 1 values are highlighted in grey for ease of interpretation.

			Phase 4						Phase 3					
Taxon	**Rank Order (MNI) Phase 4/Phase 3**	**Rank Order (MNI) pooled phases 4 and 3**	**MNI**	**%**	**NISP**	**%**	**Wt (g)**	**%**	**MNI**	**%**	**NISP**	**%**	**Wt (g)**	**%**
Asaphis violascens	5th/6th	6th	5	1.2%	108	4.9%	109	2.9%	43	2.9%	626	5.1%	928	6.7%
Pinctada sugillata	6th/4th	4th	4	0.9%	643	29.5%	26	0.7%	232	15.6%	953	7.8%	2942	21.1%
Saccostrea cucculata	1st/2nd	2nd	200	46.4%	120	5.5%	2471	66.3%	364	24.5%	6828	55.8%	5486	39.4%
Lunella cinerea	3rd/1st	1st	96	22.3%	86	3.9%	403	10.8%	484	32.5%	666	5.4%	1895	13.6%
Nerita chamaeleon	4th/5th	5th	20	4.6%					129	8.7%				
Nerita spp.					94	4.3%	62	1.7%			811	6.6%	699	5.0%
Acanthopleura gemmata	2nd/3rd	3rd	106	24.6%	1132	51.9%	655	17.6%	235	15.8%	2358	19.3%	1968	14.1%
Totals			**431**	**100**	**2183**	**100**	**3726**	**100**	**1487**	**100**	**12242**	**100**	**13918**	**100**

			Phase 2						Phase 1					
Taxon	**Rank Order (MNI) Phase 2/Phase 1**	**Rank Order (MNI) pooled phases 2 and 1**	**MNI**	**%**	**NISP**	**%**	**Wt (g)**	**%**	**MNI**	**%**	**NISP**	**%**	**Wt (g)**	**%**
Asaphis violascens	6th/5th	6th	85	2.2%	726	2.6%	1210	4.0%	16	1.8%	75	1.1%	253	4.0%
Pinctada sugillata	4th/4th	4th	497	12.7%	1478	5.2%	5561	18.2%	150	16.8%	994	14.0%	1569	24.7%
Saccostrea cucculata	3rd/3rd	3rd	591	15.1%	18235	64.2%	10690	35.1%	158	17.7%	4249	59.8%	2696	42.5%
Lunella cinerea	1st/2nd	1st	1392	35.5%	2099	7.4%	7578	24.9%	224	25.0%	437	6.2%	822	13.0%
Nerita chamaeleon	2nd/1st	2nd	1256	32.0%					335	37.4%	1214	17.1%		
Nerita spp.					4853	17.1%	4665	15.3%					907	14.3%
Acanthopleura gemmata	5th/6th	5th	100	2.6%	1002	3.5%	786	2.6%	12	1.3%	133	1.9%	94	1.5%
Totals			**3921**	**100**	**28393**	**100**	**30490**	**100**	**895**	**100**	**7102**	**100**	**6341**	**100**

5.3.1 Major Habitat Representations

The major habitat types for each mollusc species, which are common along coastal GBR site locations, were identified using key reference sources (see Chapter 3, section 3.1.4 for habitat descriptions, and Table 5.4 this chapter). MNI data were used to assign a score to each habitat type. In some cases, mollusc species are known to live across more than one habitat category. For instance, *S. cuccullata* can live attached to rocky substrates or mangrove roots in the intertidal zone. Where species are recorded to live across more than one habitat, and to account for potentially changing habitat conditions or Woppaburra habitat harvesting preferences through time, MNI data was equally divided and allocated to each of those habitat types. Tidal zonation and micro-substratum preferences for taxa at different life-cycle stages, for example sexually mature individuals versus juvenile individuals, were not included here.

Over the total assemblage and by MNI, taxa residing on rocky shores (*P. sugillata*, *S. cuccullata*, *L. cinerea*, *N. chamaeleon* and *A. gemmata*) contributed 64% of the dominant mollusc species analysed from the Mazie Bay cultural site. Mangroves and estuaries (*S. cuccullata* and *N. chamaeleon*) contributed 18%, sand-mud flats (*A. violascens* and *N. chamaeleon*) 11%, and coral reefs (*P. sugillata*) 7% (Figure 5.9). Figure 5.10 presents habitats per phase. Rocky shores are the most targeted habitat across phases 4, 3, 2, and 1. Mangrove and estuaries are consistently represented as the second most targeted zone. Interestingly, between Phase 1 and Phase 4 there is a 16% increase in the procurement of rocky shore species and a 4% increase in the use of species from mangroves and estuaries. Conversely, we see a decline in the procurement of sand-mud flat species by 11% between Phase 1 and Phase 4. During phases 1, 2, and 3 coral reef species represent only 8% of the assemblage, with no individuals represented in sandy seagrass meadow habitats in any phase.

Summary

Some degree of variation in the harvesting of dominant mollusc species from habitat types at Mazie Bay existed throughout the Holocene. Some species are known to occupy more than a single habitat type and therefore these inclusions were afforded in these assessments. Identifying exactly which habitat each species assemblage was derived from through time would require morphological assessments of each molluscan shell and/or trace element analyses. As morphological and trace element assessments were not undertaken here, an unbiased approach to assigning species to each habitat type was made.

The major habitat types for the assessed species includes rocky shores, mangroves and estuaries, sand-mud flats, and coral reefs. Sandy seagrass meadow habitats are not represented in any phase. This finding does not indicate that sandy seagrass meadow species were not available or harvested by the Woppaburra People, but rather that the dominant molluscan taxa (assessed here) did not derive from this habitat type. Indeed, other fauna that occupy sandy seagrass meadows such as turtles, are represented in the broader faunal assemblage. Results for the major habitat types for each dominant mollusc species shows an inverse trend between the use of sand-mud flat species (decreasing harvesting trend) and, rocky shore and mangrove and estuary species (increasing harvesting trend), through time. This trend persists through time despite MNI rank order comparisons between species showing some variability (as concluded in section 5.3 above). Mollusc shell sizes might provide further insight into species growth trends and Woppaburra harvesting patterns. These analyses are undertaken next.

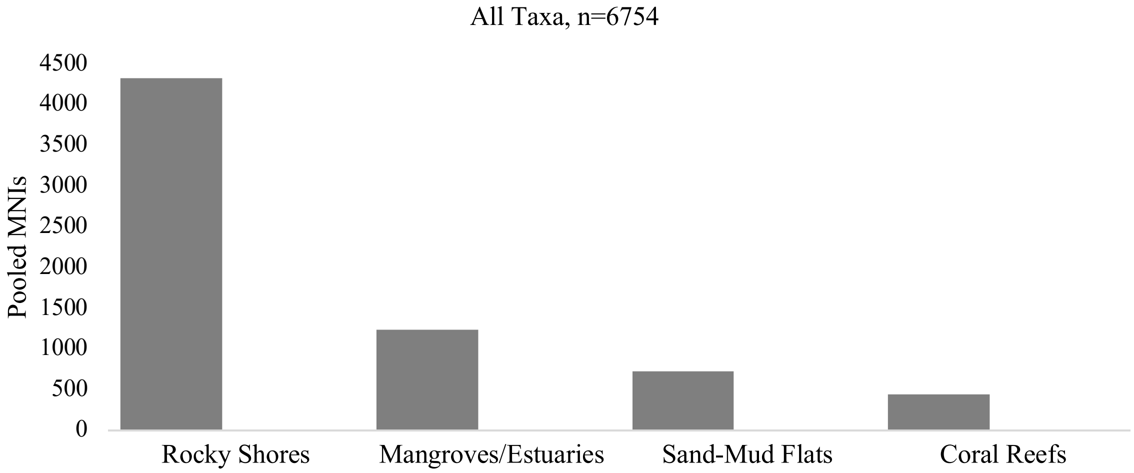


Figure 5.9 Major habitat representations across all phases, Square A1 and Square A5, Mazie Bay (n=total MNI count).

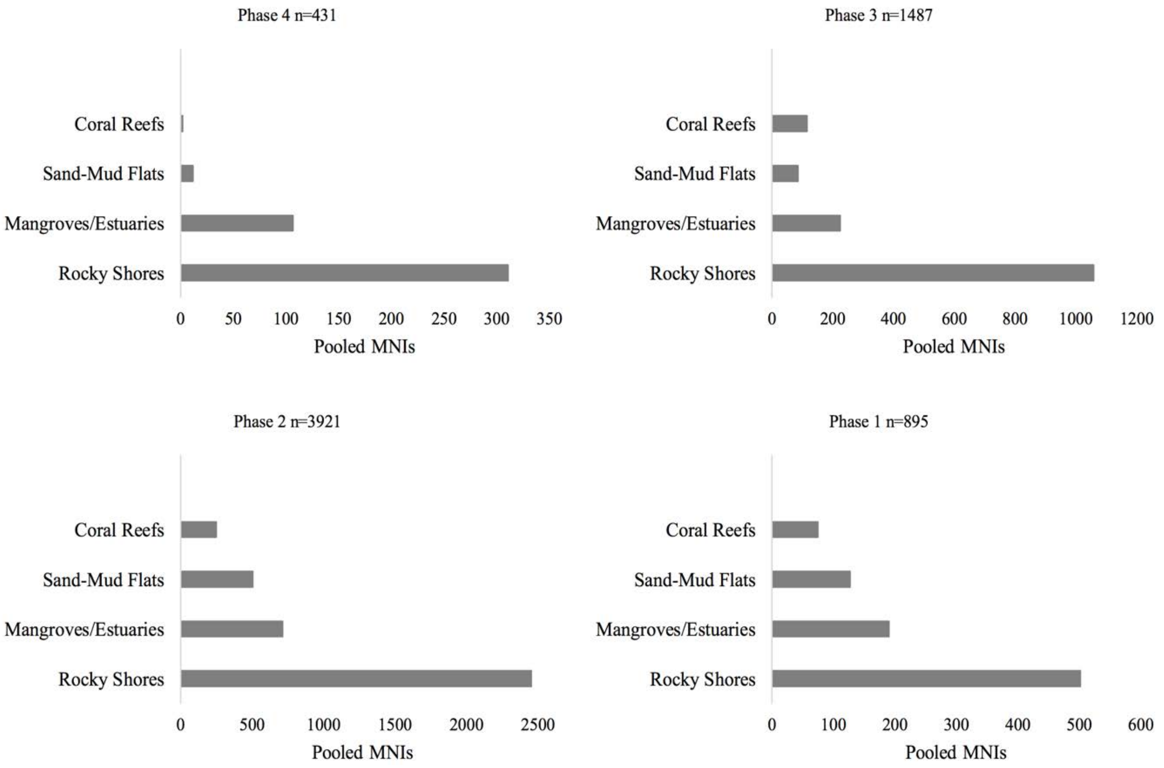


Figure 5.10 Major Habitat representations per phase (n=total MNI count per phase).

5.4 Biometric Techniques

Biometric analyses were employed to identify changes is species size profiles through time. At this time, potential size-at-age criteria for these species is not clear for GBR populations. Despite this being the case, assessing maximum size classes of species assemblages can reveal important information about population growth conditions and human harvesting preferences. For example, an assemblage of small *S. cuccullata* size profiles might indicate the Woppaburra harvested individuals from tightly clustered populations on rocky substrata; or, size selectivity potentially related to mariculture practices – where *S. cuccullata* individuals were repeatedly but strategically harvested from less compacted populations on rocky substrata. Owing to high fragmentation of mollusc samples, linear regression analysis was employed following assessment of independent taxonomic samples derived from museum assemblages to allow the size of individuals to be estimated from shell fragments, thereby increasing sample sizes of statistically testable cases.

5.4.1 Increasing Testable Cases: Linear Regression Results

When producing linear regression models for size predictions, it is important to use largely complete specimens. Time and permit requirements to collect adequate sample sizes of intact and live specimens from the GBR posed limitations (e.g. *P. sugillata* collection restrictions). Live-collected specimens housed in the Queensland Museum, Brisbane, and Australian Museum, Sydney, malacology collections were therefore used as independent samples to build linear regression equations. From the museum collections, wet and dry species samples were analysed from across the GBR region, including those collected from the Keppel Bay Island group. This approach allowed for metrical data to include the potential range of species growth trends which might best reflect the range of conditions present at Mazie Bay trough time (see Singh and McKechnie 2015:176; and Singh et al. 2015). Individual specimens from the museum collections were used only where provenance information (i.e. specimen labels) and identifications could be confirmed. Malacology staff were consulted in cases where there was uncertainty about species identification. Metrical data were collected from a range of shell features per species to the nearest 0.1mm using Mitutoyo Digimatic callipers. Measured attributes were chosen based on a review of biometric literature in addition to a consideration of shell taphonomy and preservation of key features (see literature cited in Chapter 4 and see Glassow et al. 2016 and Randklev et al. 2009 for application of adductor muscle scar measurement to bivalves). Morphological differences and taphonomic impacts to samples observed on the shell were noted to improve understandings about growth trends and to eliminate unsuitable attribute measurement data (i.e. attributes with scarring from predator-prey impacts).

Cases showing isometric relationships or positive allometry between two attributes providing an $r^2 \geq 0.85$ or higher, were considered appropriate to predict the size of individuals from fragmented materials (see threshold rationale, section 5.5). To account for variation in shell shape, data were log-transformed (base-10), using equation (1) to establish linear relationships between measured attributes:

$$\log(y) = \log(A) + b\log(x) \qquad (1)$$

Depending on the species, maximum length or maximum height values were plotted as the dependant variable and measured against a series of independent variables. Histograms and P-P plots versus residual plots indicated normally distributed data and therefore satisfied the conditions required for regression analyses. Log-transformed data estimated shell lengths or shell heights per species using equation (2):

$$y = 10^{a}\,(x^{\mathrm{b}}) \qquad (2)$$

Figures 5.11 to 5.16 illustrate the measured attributes of each species. Table 5.7 summarises the descriptive statistics for the combined independent Queensland Museum and Australian Museum sample assemblages. *A. violascens* left and right valve values were pooled together as this species is equivalve. For *P. sugillata* and *S. cuccullata* left and right valves were tested separately as these species are inequivalve. Due to concavity in left *S. cuccullata* valves, some attributes could not be measured (i.e. pallial line height, pallial line width, anterior adductor muscle scar height 'a' and 'b') but were measured for the right valves. To offer an equation useful to compare *A. gemmata* specimens from modern fisheries contexts and deep time contexts, maximum length including the girdle (MLG) and maximum length (ML) were both tested. This offers a standardised approach for determining maximum sizes for chiton species and, where appropriate, interspecies comparisons from samples derived from deep time or modern archives in the future. Doing this for the bivalve and gastropod taxa present in the Mazie Bay assemblage was not necessary because the soft tissue components are not externally present on the shell in live individuals of those species. Table 5.8 summarises the linear regression analyses performed on the measurable attributes for each mollusc species using independent museum samples. Appendix D provides additional reporting information for these analyses. Table 5.8 gives the linear regression equations for log shell length/log shell height and each log-transformed attribute measurement providing an $r^2 \geq 0.85$.

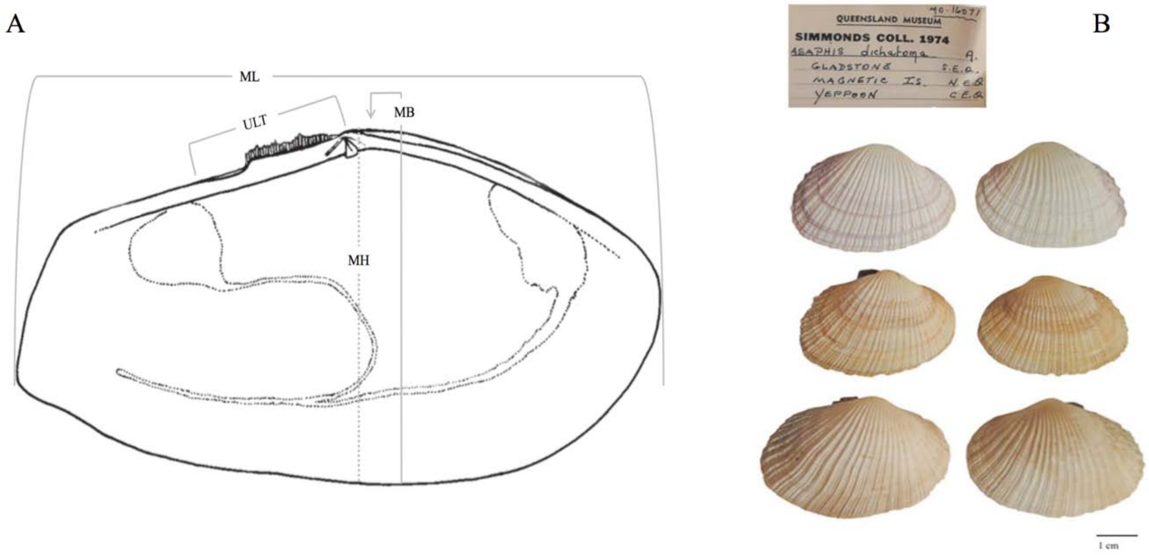


Figure 5.11 A) Measured attributes of *Asaphis violascens*. MH= maximum height, ML= maximum length, MB= maximum breadth, ULT= umbo to lateral tooth. Line drawing from Carpenter and Niem (1998). B) *Asaphis violascens* or commonly 'Pacific asaphis' example specimens from the Queensland Museum, Brisbane (Photograph: Aird 2016). Note colour variation across each set of conjoining valves (3 in total). Queensland Museum label '*Asaphis dichotoma*', is a synonym of *Asaphis violascens* (WoRMS 2019).

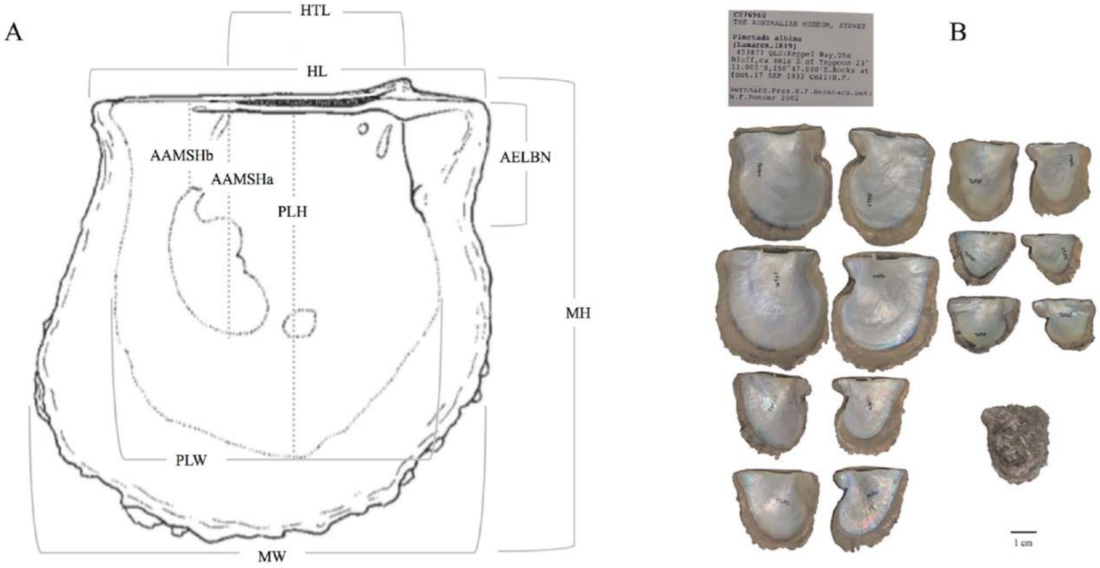


Figure 5.12 A) Measured attributes of *Pinctada sugillata*. MH= maximum height, MW= maximum width, PLW= pallial line width, PLH= pallial line height, HTL= hinge teeth length, HL= hinge length, AELBN= anterior ear length to byssal notch, AAMSHa= anterior adductor muscle scar a, AAMSHb= anterior adductor muscle scar b. Line drawing from Carpenter and Niem (1998). B) *Pinctada sugillata* or commonly 'pinctada' example specimens from the Australian Museum, Sydney (Photograph: Aird 2016). Note fragility in outer perimeter of shells evidenced by chipping along the ventral margins. Australian Museum label '*Pinctada albina*' is corrected in this research to *Pinctada sugillata* as the eastern Australian species. *Pinctada albina* is now identified as the Western Australian species (see distribution maps AFD 2019).

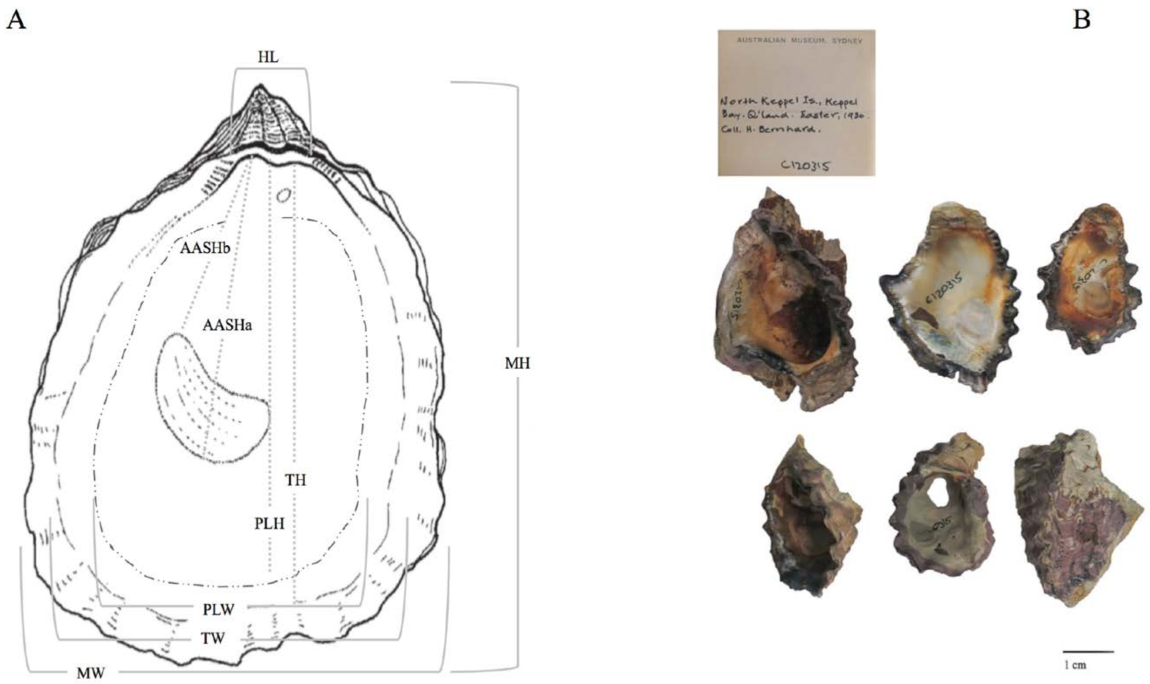


Figure 5.13 A) Measured attributes of *Saccostrea cuccullata*. MH= maximum height, TH= teeth height, PLH= pallial line height, MW= maximum width, TW= teeth width, PLW= pallial line width, HL= hinge length, AASHa= anterior adductor scar a, AASHb= anterior adductor scar b. Line drawing from Carpenter and Niem (1998). B) *Saccostrea cuccullata* or commonly 'rock oyster' example specimens from the Australian Museum, Sydney (Photograph: Aird 2016). Note non-uniform shape and random chipping along ventral margins.

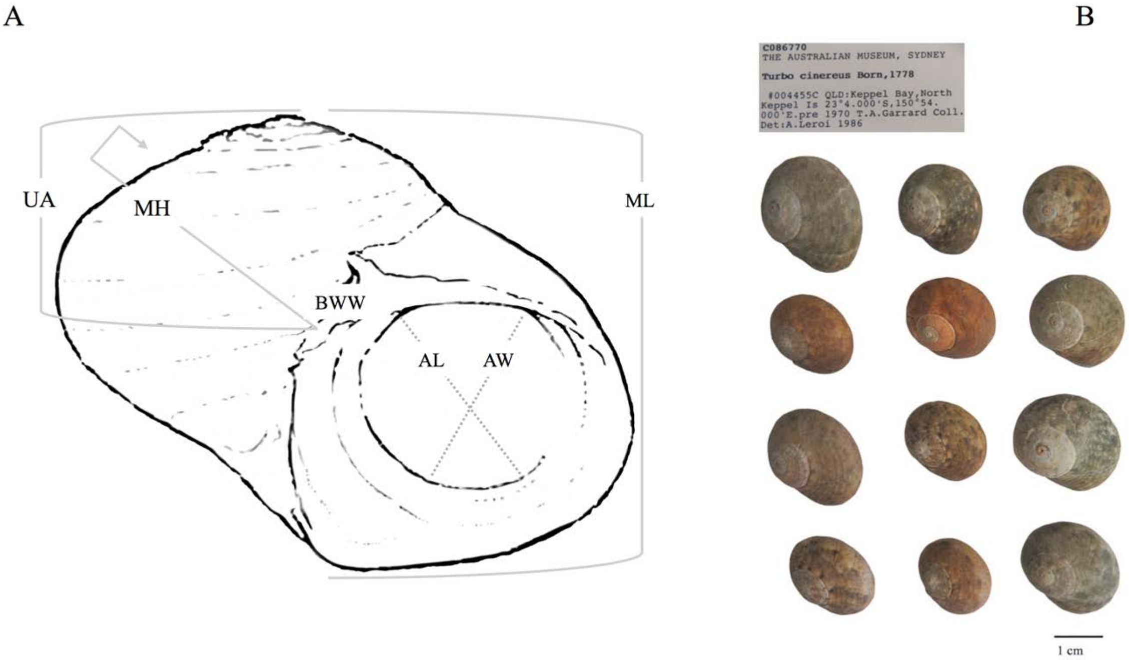


Figure 5.14 A) Measured attributes of *Lunella cinerea*. ML= maximum length, MH= maximum height, BWW= body whorl width, AL= aperture length, AW= aperture width, UA= umbilicus to apex. Line drawing redrawn from image (WoRMS 2019). B) *Lunella cinerea* or commonly 'moon turban' example specimens from the Australian Museum, Sydney (Photograph: Aird 2016). Note variation in colour across all samples. Australian Museum label '*Turbo cinereus*' is a synonym for *Lunella cinerea* (WoRMS 2019).

Figure 5.15 A) Measured attributes of *Nerita chamaeleon*. MH= maximum height, ML= maximum length, TW= tongue width, AW= aperture width, ATL= aperture to tongue length. Line drawing from Carpenter and Niem (1998). B) *Nerita chamaeleon* or commonly 'chamaeleon nerite' example specimens from the Queensland Museum, Brisbane (Photograph: Aird 2016). Samples appear beach rolled and note damage to sample shell in bottom left.

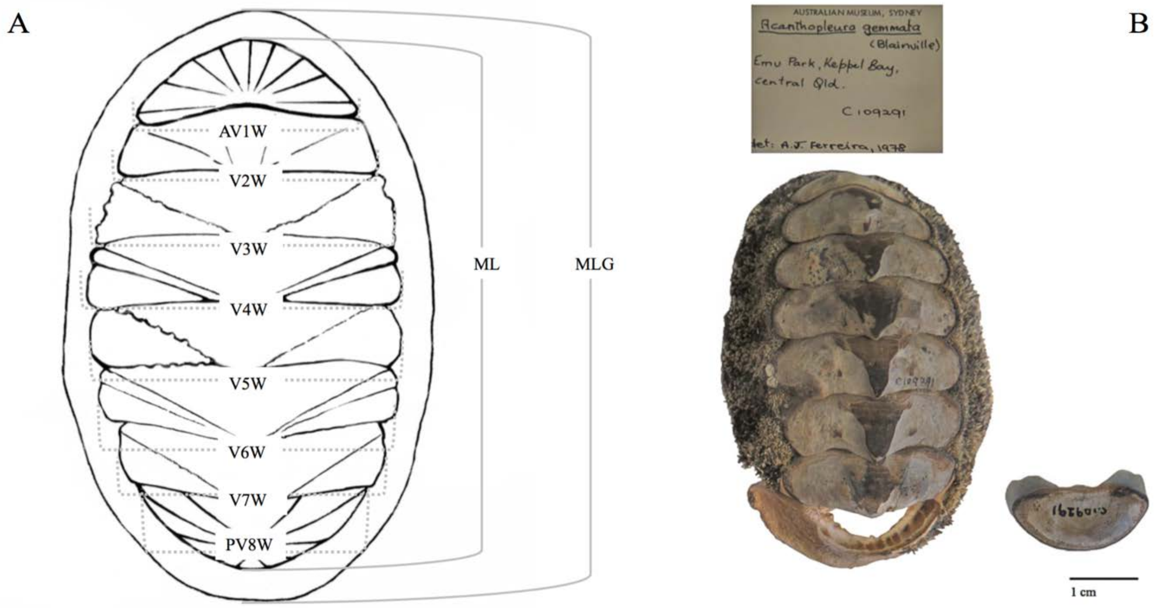


Figure 5.16 A) Measured attributes of *Acanthopleura gemmata*. MLG= maximum length with girdle, ML= maximum length, AV1W= anterior valve 1 width, V2W= valve 2 width, V3W= valve 3 width, V4W= valve 4 width, V5W= valve 5 width, V6W= valve 6 width, V7W= valve 7 width, PV8W= posterior valve 8 width. Line drawing from Vendrasco et al. (2012). B) *Acanthopleura gemmata* or commonly 'jewelled chiton' example specimen from the Australian Museum, Sydney (Photograph: Aird 2016). Note raised black diamond in centre of valves 2 to 7. The anterior valve, 2nd valve, and posterior valve (bottom right) show evidence of abrasion and/or weathering in this area. Eave sockets in the posterior girdle area can be observed.

Table 5.7 Summary of descriptive statistics for independent museum samples. Unit of measure = mm.

Species	n=	Mean	SD	Min	Max	Skew	Kurtosis
BIVALVES							
Asaphis violascens							
ML	111	46.09	13.08	20.96	71.77	0.03	-0.68
MH	111	31.76	9.47	13.69	51.51	0.09	-0.63
MB	111	10.75	3.32	4.47	18.76	0.14	-0.44
ULT	107	17.52	5.76	7.34	31.55	0.11	-0.64
Pinctada sugillata (right valves)							
MH	51	42.81	14.09	24.4	82.21	1.13	0.83
PLH	61	33.65	11.47	17.22	65.28	1.13	0.86
HL	59	34.38	10.22	16.64	60.39	0.57	0.18
HTL	54	10.27	3.53	4.52	21.42	0.93	1.79
AELBN	59	10.39	3.53	4.92	21.86	0.99	1.85
MW	47	42.64	14.15	24.04	77.53	0.94	0.12
PLW	61	31.80	10.88	15.21	57.03	0.99	0.23
AAMSHa	60	22.28	8.45	8.84	41.26	0.72	-0.2
AAMSHb	59	8.50	3.30	3.9	17.15	1.07	0.75
Pinctada sugillata (left valves)							
MH	49	43.90	14.08	28.1	73.96	1.09	0.33
PLH	60	36.67	13.10	18.78	66.74	1.17	0.92
HL	58	35.7	12.57	17.17	65.17	0.78	0.66
HTL	49	10.76	3.90	5.12	20.51	0.85	1.30
AELBN	26	8.95	3.36	4.59	18.43	1.48	3.44
MW	40	45.45	13.66	29.41	75.55	1.02	0.39
PLW	58	35.38	12.01	18.68	60.88	1	0.31
AAMSHa	52	23.23	9.03	7.45	41.4	0.62	0.27
AAMSHb	52	8.62	3.00	3.44	15.7	0.59	0.80
Saccostrea cuccullata (right valves)							
MH	116	34.49	13.45	13.53	91.41	1.44	3.29
HL	115	11.25	4.42	3.94	29.92	1.31	2.93
PLH	116	28.14	11.81	9.94	80.53	1.54	3.90
PLW	116	14.24	5.71	4.82	38.18	1.17	2.79
MW	116	26.91	9.46	9.99	64.14	1.01	1.95
TW	116	20.93	7.62	7.59	55.43	1.09	3.17
TH	116	31.50	12.72	11.35	86.99	1.49	3.66
AASHa	116	24.58	9.97	8.13	62.65	1.21	2.33
AASHb	116	14.61	7.31	2.84	42.22	1.44	2.95
Saccostrea cuccullata (left valves)							
MH	61	34.96	11.09	11.84	71.82	0.61	1.68
HL	62	11.57	3.76	4.57	23.13	0.64	0.66
MW	62	29.22	9.07	13.34	64.39	1.04	3.97
TW	62	20.61	6.78	7.46	49.77	1.58	6.96
TH	44	31.26	10.51	10.05	68.38	0.82	2.42

Species	n=	Mean	SD	Min	Max	Skew	Kurtosis
GASTROPODS							
Lunella cinerea							
ML	199	27.25	6.33	8.63	42.46	-0.29	0.54
MH	199	22.23	5.36	6.73	35.93	-0.2	0.49
BWW	199	22.78	5.21	6.67	35.63	-0.38	0.74
UA	199	10.83	2.86	2.92	18.91	-0.16	0.56
AW	199	17.95	3.82	6.58	26.25	-0.3	0.31
AL	199	13.38	3.34	4.21	21.56	-0.21	0.26
Nerita chamaeleon							
ML	157	20.22	4.91	8.98	28.31	-0.17	-0.99
MH	158	11.82	3.11	4.82	17.22	-0.14	-1.02
ATL	157	12.73	2.99	6.25	18.4	-0.04	-1.05
AL	158	5.50	1.45	2.48	11.79	0.42	1.06
AW	158	9.91	2.15	4.54	15.66	-0.10	-0.47
TW	158	15.41	3.36	7.86	20.93	-0.19	-1.00
POLYPLACOPHORA							
Acanthopleura gemmata							
ML	95	52.62	27.21	12	139	0.87	0.41
MLG	94	61.94	32.56	14	170	0.89	0.39
AV1W	101	13.34	6.01	4.15	29.55	0.57	-0.40
V2W	100	15.38	7.03	5.02	34.97	0.61	-0.32
V3W	100	16.90	7.99	5.02	39.23	0.63	-0.29
V4W	100	17.74	8.48	6.19	41.9	0.66	-0.18
V5W	100	18.02	8.82	5.19	43.58	0.65	-0.24
V6W	100	17.80	8.69	4.91	42.95	0.64	-0.26
V7W	100	16.50	8.04	4.25	39.87	0.60	-0.35
PV8W	103	13.03	6.64	2.96	33.3	0.72	-0.11

Table 5.8 Regression and significance test results for predicting log shell length (*Asaphis violascens*, *Nerita chamaeleon*, *Lunella cinerea*, *Acanthopleura gemmata*) or log shell height (*Pinctada sugillata*, *Saccostrea cucculata*) from the independent sample log-transformed biometric data. Predictions are listed from the strongest to weakest relationships with tests showing r^2 values ≥0.85 highlighted in grey (see threshold rationale, section 5.5). Note: *A. violascens* length versus ULT showed normal distribution and was therefore not log transformed.

	Pearson Correlation			**Linear Regression**		**ANOVA**		
Asaphis violascens	***r***	***p***	r^2	***A***	***b***	***F***	**df**	***p***
log MH	0.992	<0.001	0.984	0.248	0.943	6880.272	1	<0.001
log MB	0.981	<0.001	0.962	0.727	0.911	2719.669	1	<0.001
ULT	0.955	<0.001	0.912	8.105	2.167	1092.336	1	<0.001
Pinctada sugillata (right valves)	***r***	***p***	r^2	***A***	***b***	***F***	**df**	***p***
log PLH	0.972	<0.001	0.945	0.192	0.941	838.46	1	<0.001
log PLW	0.963	<0.001	0.927	0.213	0.939	621.805	1	<0.001
Pinctada sugillata (right valves)	***r***	***p***	r^2	***A***	***b***	***F***	**df**	***p***

log MW	0.96	<0.001	0.921	0.086	0.947	488.493	1	<0.001
log AAMSHa	0.933	<0.001	0.871	0.556	0.796	323.228	1	<0.001
log HL	0.912	<0.001	0.833	0.066	1.014	233.721	1	<0.001
log AELBN	0.872	<0.001	0.761	0.734	0.874	146.447	1	<0.001
log AAMSHb	0.885	<0.001	0.783	0.902	0.786	169.696	1	<0.001
log HTL	0.881	<0.001	0.776	0.807	0.811	152.544	1	<0.001
Pinctada sugillata (left valves)	***r***	***p***	***r^2***	***A***	***b***	***F***	**df**	***p***
log PLH	0.977	<0.001	0.955	0.15	0.954	987.26	1	<0.001
log MW	0.957	<0.001	0.916	-.007	0.998	381.019	1	<0.001
log PLW	0.934	<0.001	0.873	0.159	0.964	315.996	1	<0.001
log AAMSHa	0.901	<0.001	0.811	0.681	0.704	180.607	1	<0.001
log AAMSHb	0.866	<0.001	0.75	1.019	0.656	125.952	1	<0.001
log HL	0.858	<0.001	0.737	0.321	0.899	126.113	1	<0.001
log HTL	0.819	<0.001	0.67	0.878	0.743	77.195	1	<0.001
log AELBN	0.63	<0.001	0.396	1.058	0.622	11.816	1	<0.001
Saccostrea cuccullata (right valves)	***r***	***p***	***r^2***	***A***	***b***	***F***	**df**	***p***
log TH	0.994	<0.001	0.988	0.108	0.954	9147.625	1	<0.001
log PLH	0.99	<0.001	0.98	0.213	0.915	5447.411	1	<0.001
log AASHa	0.976	<0.001	0.952	0.291	0.897	2285.204	1	<0.001
log AASHb	0.927	<0.001	0.859	0.747	0.683	696.707	1	<0.001
log MW	0.833	<0.001	0.693	0.276	0.876	257.803	1	<0.001
log TW	0.813	<0.001	0.661	0.461	0.809	222.305	1	<0.001
log PLW	0.802	<0.001	0.642	0.685	0.734	204.799	1	<0.001
log HL	0.711	<0.001	0.506	0.803	0.691	115.595	1	<0.001
Saccostrea cuccullata (left valves)	***r***	***p***	***r^2***	***A***	***b***	***F***	**df**	***p***
log TH	0.99	<0.001	0.98	0.129	0.946	2102.199	1	<0.001
log MW	0.829	<0.001	0.688	0.297	0.855	130.139	1	<0.001
log TW	0.792	<0.001	0.627	0.508	0.791	99.299	1	<0.001
log HL	0.646	<0.001	0.418	0.917	0.59	42.299	1	<0.001
Nerita chamaeleon	***r***	***p***	***r^2***	***A***	***b***	***F***	**df**	***p***
log MH	0.993	<0.001	0.987	0.33	0.91	11677.955	1	<0.001
log ATL	0.977	<0.001	0.954	0.164	1.033	3186.454	1	<0.001
log TW	0.940	<0.001	0.884	.117	1.022	1178.454	1	<0.001
log AW	0.92	<0.001	0.847	0.267	1.041	854.875	1	<0.001
log AL	0.923	<0.001	0.852	0.649	0.887	893.691	1	<0.001
Lunella cinerea	***r***	***p***	***r^2***	***A***	***b***	***F***	**df**	***p***
log BWW	0.996	<0.001	0.992	0.88	0.993	25546.648	1	<0.001
log MH	0.989	<0.001	0.979	0.146	0.958	9113.586	1	<0.001
log AL	0.987	<0.001	0.974	0.4	0.92	7461.136	1	<0.001
log UA	0.982	<0.001	0.965	0.56	0.847	5380.115	1	<0.001
log AW	0.959	<0.001	0.92	0.82	1.078	2265.542	1	<0.001
Acanthopleura gemmata	***r***	***p***	***r^2***	***A***	***b***	***F***	**df**	***p***
log MLG	0.989	<0.001	0.977	-.022	0.973	3949.95	1	<0.001

log PV8W	0.97	<0.001	0.942	0.63	0.978	1486.582	1	<0.001
log V7W	0.967	<0.001	0.935	0.493	1.006	1320.494	1	<0.001
log AV1W	0.966	<0.001	0.933	0.482	1.095	1273.093	1	<0.001
log V2W	0.964	<0.001	0.93	0.43	1.081	1207.548	1	<0.001
log V3W	0.964	<0.001	0.929	0.438	1.04	1208.461	1	<0.001
log V6W	0.963	<0.001	0.927	0.459	1.006	1175.835	1	<0.001
log V5W	0.962	<0.001	0.925	0.457	1.003	1132.26	1	<0.001
log V4W	0.959	<0.001	0.92	0.431	1.029	1063.329	1	<0.001

Table 5.9 Biometric equations for predicting maximum shell sizes.

Asaphis violascens	**Attribute**	**Equation**	
	MH	$y = (10^{0.25}) (x^{0.94})$	
	MB	$y = (10^{0.73}) (x^{0.91})$	
	ULT	$y = (8.1)+(x*2.17)$	
Pinctada sugillata	**Attribute**	**Equation**	
	Right Valves		Left Valves
	PLH	$y = (10^{0.19}) (x^{0.94})$	$y = (10^{0.15}) (x^{0.95})$
	PLW	$y = (10^{0.21}) (x^{0.94})$	$y = (10^{0.16}) (x^{0.96})$
	MW	$y = (10^{0.09}) (x^{0.95})$	$y = (10^{0.09}) (x^{0.95})$
	AAMSHa	$y = (10^{0.56}) (x^{0.8})$	$y = (10^{0.68}) (x^{0.7})$
Saccostrea cuccullata	**Attribute**	**Equation**	
	Right Valves		Left Valves
	TH	$y = (10^{0.11}) (x^{0.95})$	$y = (10^{0.13}) (x^{0.95})$
	PLH	$y = (10^{0.21}) (x^{0.92})$	-
	AASHa	$y = (10^{0.29}) (x^{0.9})$	-
	AASHb	$y = (10^{0.75}) (x^{0.68})$	-
Nerita chamaeleon	**Attribute**	**Equation**	
	MH	$y = (10^{1.71}) (x^{1.56})$	
	TW	$y = (10^{0.12}) (\mathrm{x}^{1.02})$	
	ATL	$y = (10^{0.16}) (x^{1.03})$	
	AW	$y = (10^{0.27}) (x^{1.04})$	
	AL	$y = (10^{0.65}) (x^{0.89})$	
Lunella cinerea	**Attribute**	**Equation**	
	BWW	$y = (10^{0.09}) (x^{0.99})$	
	MH	$y = (10^{0.15}) (x^{0.96})$	
	AL	$y = (10^{0.4}) (x^{0.92})$	
	UA	$y = (10^{0.56}) (x^{0.85})$	
	AW	$y = (10^{0.08}) (x^{1.08})$	
Acanthopleura gemmata	**Attribute**	**Equation**	
	log MLG	$y = (10^{-0.02}) (x^{0.97})$	
	log PV8W	$y = (10^{0.63}) (x^{0.98})$	
	log V7W	$y = (10^{0.49}) (x^{1.01})$	
	log AV1W	$y = (10^{0.48}) (x^{1.09})$	
	log V2W	$y = (10^{0.43}) (x^{1.08})$	
	log V3W	$y = (10^{0.44}) (x^{1.04})$	
	log V6W	$y = (10^{0.46}) (x^{1.01})$	
	log V5W	$y = (10^{0.46}) (x^{1})$	
	log V4W	$y = (10^{0.43}) (x^{1.03})$	

5.5 Mazie Bay Cultural Mollusc Shell Size Analyses

Due to the fragmentation patterns of the Mazie Bay cultural mollusc remains, only selected attributes that were explored with the independent museum samples could be applied. Although good predictive power between attributes in other biometric studies maintain $r^2 \geq 0.75$ as acceptable (Jerardino and Navarro 2008), r^2 values of ≥ 0.85 were used in the following assessments. This is because adequate sample sizes were obtained from Mazie Bay species assemblages with r^2 values of ≥ 0.85. Due to the highly fragmented nature of *P. sugillata* shells recovered from the Mazie Bay cultural site, biometric assessments on this species was not undertaken (i.e. shell samples had no measurable attributes). The following reports on the biometric analyses of Mazie Bay *A. violascens*, *S. cuccullata*, *L. cinerea*, *N. chamaeleon*, and *A. gemmata* for the total assemblage and per phase.

5.5.1 Total Number of Statistically Testable Cases

To identify broad size characteristics of species populations in the Mazie Bay cultural assemblage, samples from Square A1 and Square A5 retaining measurable attributes from the four determined phases were assessed. Linear regression equations extrapolated from the independent museum samples increased the number of statistically testable cases. Figure 5.17 provides the size frequency distributions for each species.

Asaphis violascens

The left valves of *A. violascens* were chosen for statistical analyses as they provided a larger sample size for analysis than right valves. One ML value was therefore extracted per individual, rather than twice if the right valves were also included. For the total assemblage, up to 5 attributes could be used from the fragmented materials to predict ML. Available ULT attributes provided the strongest predictive power to reconstruct original shell length, increasing the *A. violascens* sample size from n=6 to n=88 or by 1366%. The mean ML of *A. violascens* shells is 52.69mm, with minimum and maximum lengths of 31.51mm and 71.33mm respectively.

Saccostrea cuccullata

For *S. cuccullata*, the right valves were chosen for size analyses as key attributes in the left valves were difficult to access due to concavity. The MH measurements from right valves n=374 was increased by 135% to n=879 statistically testable cases using TH, AASHa and AASHb regression equations. The mean MH of *S. cuccullata* shells is 40.71mm, with minimum and maximum heights of 15.21mm and 69.17mm respectively.

Lunella cinerea

BWW, MH and UA regression equations increased the *L. cinerea* sample size by 1504% from n=110 to n=1765 statistically testable cases to assess ML. The mean ML of *L. cinerea* shells is 27.10mm, with minimum and maximum lengths of 10.31mm and 41.92mm respectively.

Nerita chamaeleon

Predicted ML of *N. chamaeleon* samples using the TW regression equation, n=124, provided a total of n=273 cases to be statistically tested for the total assemblage, a 120% increase. The mean length of *N. chamaeleon* shells is 16.38mm, with minimum and maximum lengths of 7.85mm and 23.85mm respectively.

Acanthopleura gemmata

So as not to count the same individual twice, the posterior valves (PV8W) of *A. gemmata* samples were chosen for size analyses. A higher MNI value based on posterior valves, in comparison to anterior valves, was found for the cultural assemblage. Additionally, when tested against ML, the predictive power of the PV8W attribute (r^2 0.942) is marginally stronger than the AV1W (r^2 0.933) attribute. Due to the disarticulation of valves in the deep time record, all n=402 statistically testable ML cases (100%) were used in predicting *A. gemmata* size using the PV8W log10 linear regression equation. The mean ML of *A. gemmata* shells is 16.98mm, with minimum and maximum lengths of 8.44mm and 25.03mm respectively.

In all cases, the pred. ML or pred. MH sample assemblages are unimodal in distribution and approximately symmetric, with skewness values ranging between -0.5 and 0.5 (Table 5.10). Kurtosis values were also measured for each case. Normal or mesokurtic distributions have a kurtosis value of 0 (Pallant 2013:59). Distributions can be platykurtic (negatively skewed), with values being clustered towards the right of the graph, and having short tails either side of a wide flat peak (Pallant 2013:59). Or, distributions can be leptokurtic (positively skewed), with values being clustered towards the left of the graph, and having heavy tails either side of a narrowly curved peak (Pallant 2013:59). Platykurtic distributions have fewer outliers than leptokurtic distributions (Pallant 2013:59). In the analyses below, each pred. ML or pred. MH assemblage shows platykurtic distributions, as indicated by low kurtosis values. Even though *L. cinerea* and *A. gemmata* have a significant number of outliers they are minimal in comparison to the distributions represented by other species. Table 5.10 reports the descriptive statistics for each species including the kurtosis values (note SPSS reports excess kurtosis values). The Shapiro-Wilk *p* value shows normal distributions of values, except for those marked with an asterisk (*).

Table 5.10 Total assemblage descriptive statistics (*indicates non-normality in distribution). Unit of measure = mm.

Species	n=	Mean	SD	Min	Max	Skew	Kurtosis	Shapiro-Wilk
BIVALVES								
Asaphis violascens								
pred. ML	88	52.69	7.69	31.51	71.33	0.28	0.27	*W*=0.979, df=88, *p*=0.155
ULT	88	20.45	3.56	10.79	29.14	0.37	0.28	*W*=0.970, df=88, *p*=0.041*
Saccostrea cuccullata (right valves)								
pred. MH	879	40.71	9.01	15.21	69.17	0.46	-0.12	*W*=0.998, df=879, *p*=0.606
TW	605	37.74	8.40	14.13	67.82	0.26	0.23	*W*=0.995, df, 605, *p*=0.051
AASHa	859	30.35	6.85	10.53	53.34	0.27	0.22	*W*=0.994, df=859, *p*=0.017*
AASHb	830	18.78	5.34	4.65	36.65	0.37	0.23	*W*=0.991, df=830, *p*=0.001*
GASTROPODS								
Lunella cinerea								
pred. ML	1765	27.10	3.81	10.31	41.92	0.34	0.59	*W*=0.988, df=1765, *p*=0.001*
BWW	1092	21.30	3.18	7.78	32.43	0.40	4.44	*W*=0.901, df=1092, *p*=0.001*
MH	126	21.61	3.56	6.6	35.97	0.50	4.56	*W*=0.898, df=126, *p*=0.001*
UA	1727	11.23	2.09	4.64	18.14	0.76	2.18	*W*=0.930, df=1727, *p*=0.001*
Nerita chamaeleon								
pred. ML	273	16.38	3.27	7.85	23.85	0.12	-0.78	*W*=0.981, df=273, *p*=0.001*
TW	274	9.78	1.12	5.75	14.48	-0.22	1.42	*W*=0.982, df=274, *p*=0.002*
POLYPLACOPHORA								
Acanthopleura gemmata								
pred. ML	402	16.98	2.54	8.44	25.03	-0.09	0.27	*W*=0.996, df=402, *p*=0.452
PV8W	402	68.44	10.04	34.5	100.11	-0.10	0.28	*W*=0.996, df=402, *p*=0.451

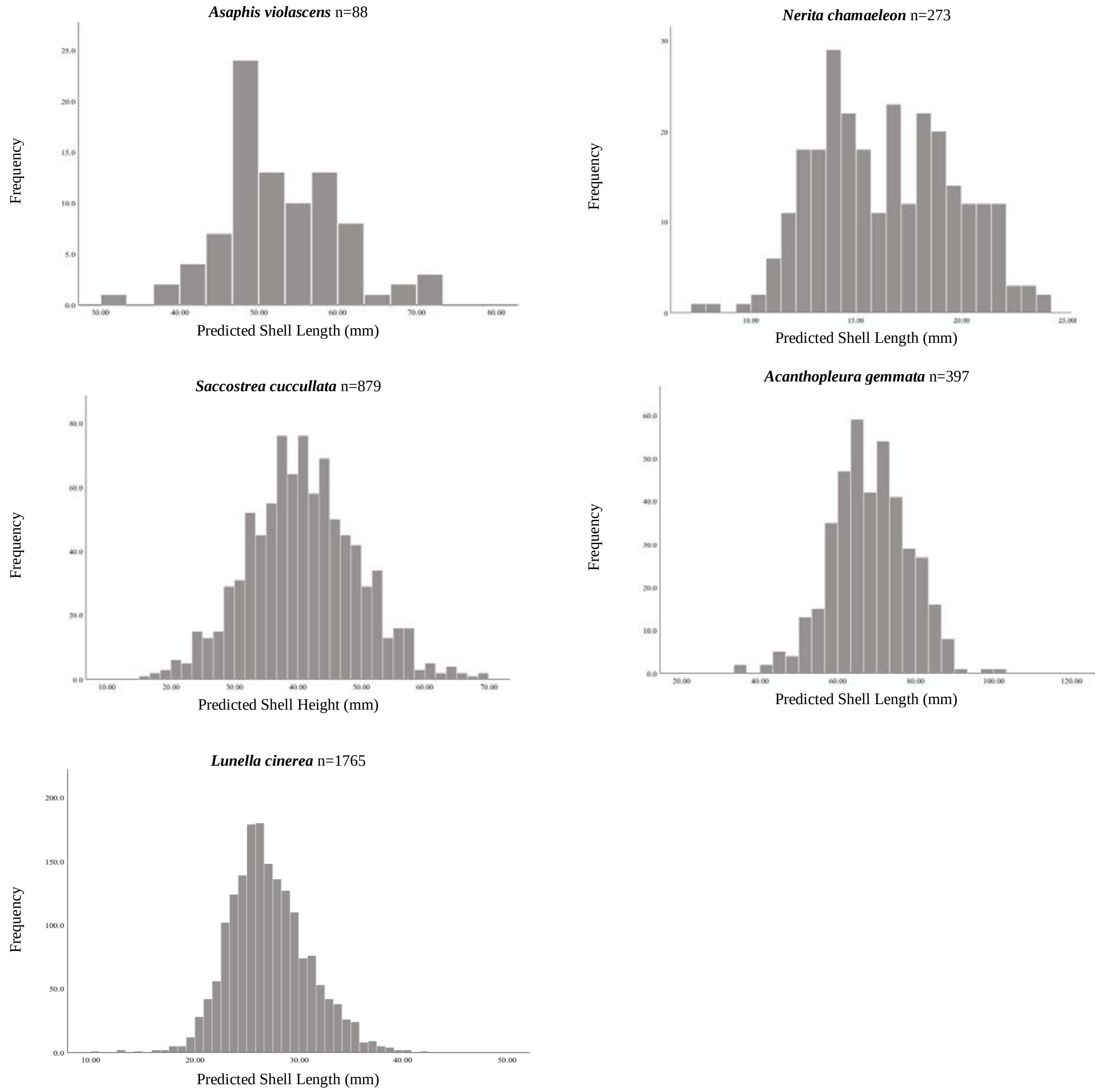


Figure 5.17 Total assemblage size frequency distributions and boxplots for predicted shell lengths *Asaphis violascens*, *Lunella cinerea*, *Nerita chamaeleon* and *Acanthopleura gemmata*, and total assemblage predicted shell height for *Saccostrea cuccullata*. Note: *Pinctada sugillata* was not assessed.

5.5.2 Mollusc Shell Size Profiles

For each species assemblage, the pred. ML or pred. MH values were used to analyse species size profiles per phase. The descriptive statistics are summarised in Table 5.11, with the Shapiro-Wilk *p* statistic indicating the normality of distribution. In cases where species assemblages are normally distributed, a one-way analysis of variance (ANOVA) test at the $p<0.05$ level was run, followed by a Tukey Honestly Significant Difference (HSD) post-hoc test where the ANOVA indicated statistically significant differences. The non-parametric Kruskal-Wallis H test, with post hoc pairwise comparisons incorporating Bonferroni corrections, was used for assemblages that showed non-normal distributions of data. The measure of tendency for ANOVA tests are based on mean values whereas the non-parametric equivalent, the Kruskal-Wallis H test, uses median values (Pallant 2013). For this reason, the measure of tendencies between the two tests differ below, however both mean and median values for each case are included in Table 5.11. The eta squared (η^2) value is a measure that reports effect size, or practical significance. Effect sizes are reported in accordance with Wolverton et al. (2016) and with eta squared criteria as explained in Pallant (2013:218) (i.e. measures of strength: low = 0.01 or 1%, medium = 0.3 0.06 or 6%, and strong = 0.138 or 13.8%). For assemblages tested using parametric one-way ANOVAs, the eta squared value was taken directly from reports. For assemblages tested using non-parametric Kruskal-Wallis H tests, equation (3) was used to calculate the eta squared value. Where *H* is the Kruskal-Wallis H statistic, *k* is the number of groups and *n* is the number of observations:

$$\eta^2 = (H - (k + 1) / (n - k) \qquad (3)$$

Histograms and boxplots for each species per phase are presented in Figure 5.18. Please note, as the number of statistically testable cases for some species per phase are low, some of the following results may be affected.

Asaphis violascens

In Phase 1 and Phase 2, *A. violascens* assemblages are moderately skewed. The Phase 3 and Phase 4 *A. violascens* assemblages show approximate symmetry, with all phases indicating platykurtic distribution. Phase 1 and Phase 4 had low sample numbers (n=4, n=3), with n=46 individuals representing Phase 2, and n=35 individuals representing Phase 3. The smallest individual was recovered from Phase 3 (31.51mm) and the largest individual in Phase 2 (71.33mm). Between each of the phases, ≤ 3.26mm separates maximum shell length means. A one-way ANOVA test indicates that the differences in predicted *A. violascens* maximum shell lengths for Phase 4, Phase 3, Phase 2 and Phase 1 are not statistically significant ($F_{3, 88} = 0.546$, p=0.652, η^2=0.019). The eta squared (η^2) demonstrates a low effect size.

Between phases 1 and 4, *A. violascens* assemblages show no significant changes in shell size.

Saccostrea cuccullata

Phase 1 (n=99), Phase 2 (n=369), Phase 3 (n=283) and Phase 4 (n=128) *S. cuccullata* assemblages are approximately symmetrical with platykurtic distribution. Phase 2 shows the highest mean value of 42.54mm within the range of 19.76-65.14mm. Phase 3 has a mean of 39.73mm within the range of 15.21mm and 69.17mm. Phase 4 has a mean of 37.49mm; and Phase 1 a mean of 41.81mm. There is a statistically significant difference between predicted *S. cuccullata* maximum shell heights ($F(3, 879)$ = 13.485, p=0.0001, η^2=0.044) between each of the phases as indicated by a one-way ANOVA test. A

Tukey HSD post-hoc test indicated *S. cuccullata* differences in predicted shell heights occur between Phase 4 (M=37.4968, SD=7.6524) and Phase 1 (M=41.8108, SD=8.13723) *p*=0.001; Phase 2 (M=42.5485, SD=8.19732) and Phase 3 (M=39.7337, SD=9.43250) *p*=<0.0001; and Phase 2 (M=42.5485, SD=8.19732) and Phase 4 (M=37.4968, SD=7.65244) *p*=<0.0001.

Between phases 1 and 4, *S. cuccullata* assemblages underwent changes in shell size. Shell sizes were at their largest in Phase 2. Despite this being the case, the size effect statistic (η^2) demonstrates that changes in shell sizes between phases were low overall.

Lunella cinerea

Phase 1, Phase 2, and Phase 3 *L. cinerea* assemblages indicate approximate symmetry. Phase 4 is moderately skewed towards the smaller size classes, with all assemblages being platykurtic in their distribution. Median shell length in Phase 2 is 26.79mm, between a range of 10.31mm (minimum shell length) and 41.92mm (maximum shell length). The smallest assemblage (n=89), Phase 4, has a median shell length of 27.08mm. The smallest individual in this phase measures 22.33mm and the largest individual measures 34.84mm. In Phase 3, *S. cuccullata* shell lengths have a median of 26.68. The smallest individual in Phase 3 is 17.59mm and the largest is 39.85mm. The range in Phase 1 is 16.21mm (smallest individual) and 37.82mm (largest individual), with a median of 25.52mm, the smallest median value for all phases. Phase 2 and Phase 3 show non-normal distributions of data; therefore, a non-parametric Kruskal-Wallis H test was run. There is a statistically significant difference between predicted *L. cinerea* maximum shell lengths ($X^2(3) = 18.419$, p=<0.0001, η^2=0.002) between the four phases. The eta squared (η^2) demonstrates a low effect size. The post-hoc pairwise comparisons test with the Bonferroni correction indicates that differences in *L. cinerea* predicted shell lengths occur between Phase 1 (Mdn=25.5200, SD=4.0710) and Phase 3 (Mdn=26.6800, SD=3.4077) *p*=<0.0001; Phase 1 (Mdn=25.5200, SD=4.0710 and Phase 2 (Mdn=26.7900, SD=3.9688) *p*=<0.0001; and Phase 1 (Mdn=25.5200, SD=4.0710 and Phase 4 (Mdn=27.0800, SD=2.5231) *p*=0.0001.

Between phases 1 and 4, *L. cinerea*, assemblages underwent changes in shell size. Shell sizes were at their lowest during Phase 1 however, the effect size statistic (η^2) demonstrates that differences in shell sizes throughout time, were low overall.

Nerita chamaeleon

Approximate symmetry in *N. chamaeleon* assemblages for Phase 1, Phase 2, and Phase 3 with platykurtic distribution is apparent. The Phase 4 assemblage is a very small (n=3) negatively skewed sample although, it shows the largest shell size. The largest individual by shell length in Phase 4 measures 21.53mm. Phase 2 had the highest representation of individuals (n=149) with a median of 16.70mm. The smallest individual in Phase 2 measures 10.28mm and the largest at 23.85mm. Phase 3 has a range of individuals measuring between 8.5mm (smallest) and 23.0mm (largest), with a median shell length of 18.20mm. Phase 1 has a similar range in shell lengths (7.85mm and 21.6mm), with a median of 14.25mm. Phase 1, Phase 2 and Phase 3 assemblages are not normally distributed as determined by the Shapiro-Wilk *p* value. Therefore, a non-parametric Kruskal-Wallis H test was run. There is a statistically significant difference between predicted *N. chamaeleon* maximum shell lengths ($X^2(3) = 18.978, p=0.0001, \eta^2=0.011$) between the four phases. The eta squared (η^2) demonstrates a low effect size. The post-hoc pairwise comparisons test with the Bonferroni correction indicates that differences in *N. chamaeleon* predicted shell lengths occur between Phase 1 (Mdn=14.2500, SD=3.0413) and Phase 2 (Mdn=16.7000, SD=3.0547) $p=<0.0001$; and Phase 1 (Mdn=14.2500, SD=3.0413) and Phase 3 (Mdn=18.2000, SD=3.4318) $p=<0.0001$.

Between phases 1 and 4, *L. cinerea*, assemblages underwent changes in shell size. Through time, shell size gradually increased to peak in Phase 1. Overall however, the effect size statistic (η^2) demonstrates that changes in shell sizes between phases were low.

Acanthopleura gemmata

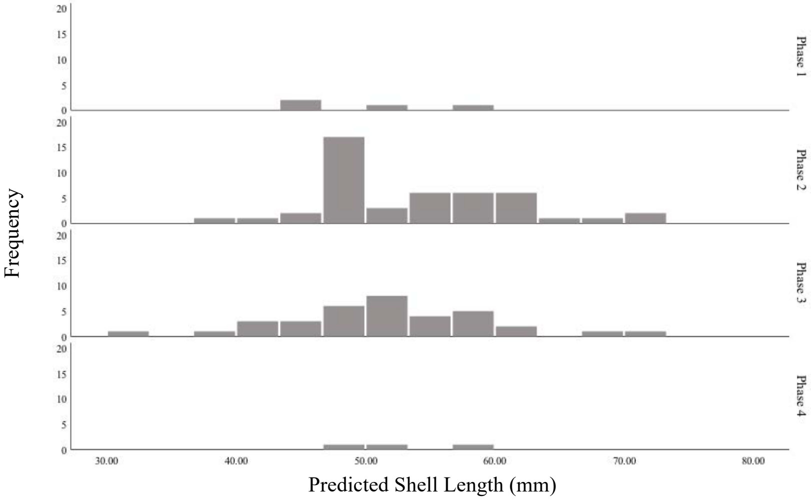
In all phases, *A. gemmata* assemblages show approximate symmetry with platykurtic distributions. The Phase 3 *A. gemmata* assemblage (n=218) has a mean maximum length of 69.61mm, within the minimum (41.06mm) and maximum (100.11mm) range. The smallest individual in Phase 4 measures 34.5mm, while the maximum shell measures 93.33mm. A mean maximum length of 64.27mm is present in this unit. Phase 2 shows a range between 57.32mm and 89.28mm. This phase has a mean maximum length of 71.19mm. Lastly, Phase 1 has a measurement range of 52.01mm and 78.54mm, and mean maximum length of 65.00mm. A one-way ANOVA revealed a statistically significant difference between predicted *A. gemmata* maximum shell lengths ($F(3, 402) = 9.611, p=<0.0001, \eta^2=0.068$) between each of the phases. The eta squared (η^2) demonstrates a medium effect size. Post hoc comparisons using the Tukey HSD post-hoc test indicated that differences in *A. gemmata* predicted shell lengths occur between Phase 2 (M=71.1927, SD=8.1272) and Phase 4 (M=64.2730, SD=10.1721) $p=<0.0001$; and Phase 3 (M=69.6173, SD=10.0540) and Phase 4 (M=64.2730, SD=10.1721) $p=<0.0001$.

Between phases 1 and 4, *A. gemmata*, assemblages underwent a moderate degree of change in shell size as indicated by the effect size statistic (η^2). The largest shell sizes peak in Phase 2 closely followed by Phase 3.

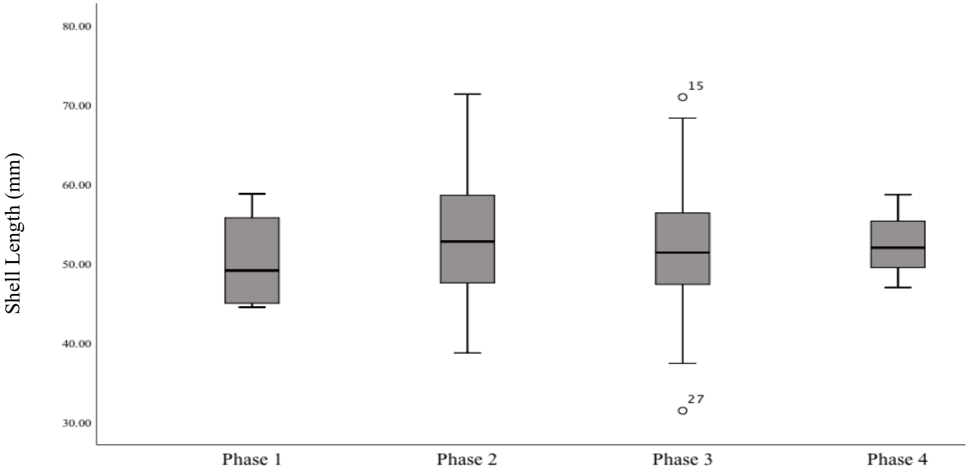
Table 5.11 Descriptive statistics per phase (* indicates non-normality in distribution) based on median values. Unit of measure = mm.

	n=	Mean	Median	SD	Min	Max	Skew	Kurtosis	Shapiro-Wilk
BIVALVES									
Asaphis violascens									
Phase 1	4	50.40	49.15	6.68	44.53	58.79	0.63	-2.26	*W*=0.903, df=4, *p*=0.448
Phase 2	46	53.66	52.79	7.62	38.78	71.33	0.54	-0.28	*W*=0.952, df=46, *p*=0.055
Phase 3	35	51.70	51.41	8.10	31.51	70.96	0.02	0.74	*W*=0.988, df=35, *p*=0.955
Phase 4	3	52.57	52.02	5.86	47.01	58.7	0.42	0	*W*=0.993, df=3, *p*=0.843
Saccostrea cucculata									
Phase 1	99	41.81	41.81	8.13	25.81	64.53	0.37	0.09	*W*=0.983, df=99, *p*=0.237
Phase 2	369	42.54	42.46	8.19	19.76	65.14	0.05	-0.12	*W*=0.998, df=369, *p*=0.875
Phase 3	283	39.73	38.85	9.43	15.21	69.17	0.33	0.27	*W*=0.992, df=283, *p*=0.105
Phase 4	128	37.49	37.76	7.65	17.38	55.89	-0.25	0	*W*=0.990, df=128, *p*=0.500
GASTROPODS									
Lunella cinerea									
Phase 1	169	25.95	25.52	4.07	16.21	37.82	0.23	-0.19	*W*=0.991, df=169, *p*=0.411
Phase 2	1114	27.33	26.79	3.96	10.31	41.92	0.33	0.55	*W*=0.984, df=1114, *p*=0.001*
Phase 3	393	26.89	26.68	3.40	17.59	39.85	0.43	0.67	*W*=0.986, df=393, *p*=0.001*
Phase 4	89	27.27	27.08	2.52	22.33	34.84	0.64	0.63	*W*=0.969, df=89, *p*=0.030
Nerita chamaeleon									
Phase 1	79	14.79	14.25	3.04	7.85	21.6	0.4	-0.58	*W*=0.962, df=79, *p*=0.018*
Phase 2	149	16.85	16.70	3.05	10.28	23.85	0.21	-0.70	*W*=0.980, df=149, *p*=0.027*
Phase 3	42	17.42	18.20	3.43	8.5	23	-0.41	-0.64	*W*=0.927, df=42, *p*=0.010*
Phase 4	3	20.38	21.31	1.79	18.31	21.53	-1.70	0	*W*=0.801, df=3, *p*=0.117
POLYPLACOPHORA									
Acanthopleura gemmata									
Phase 1	9	65.00	66.31	8.49	52.01	78.54	-0.13	-0.64	*W*=0.963, df=9, *p*=0.830
Phase 2	73	71.19	70.73	8.12	57.32	89.28	0.35	-0.73	*W*=0.967, df=73, *p*=0.056
Phase 3	218	69.61	69.71	10.05	41.06	100.11	-0.10	0.19	*W*=0.995, df=218, *p*=0.735
Phase 4	102	64.27	62.95	10.17	34.5	93.33	-0.06	0.64	*W*=0.987, df=102, *p*=0.400

Asaphis violascens

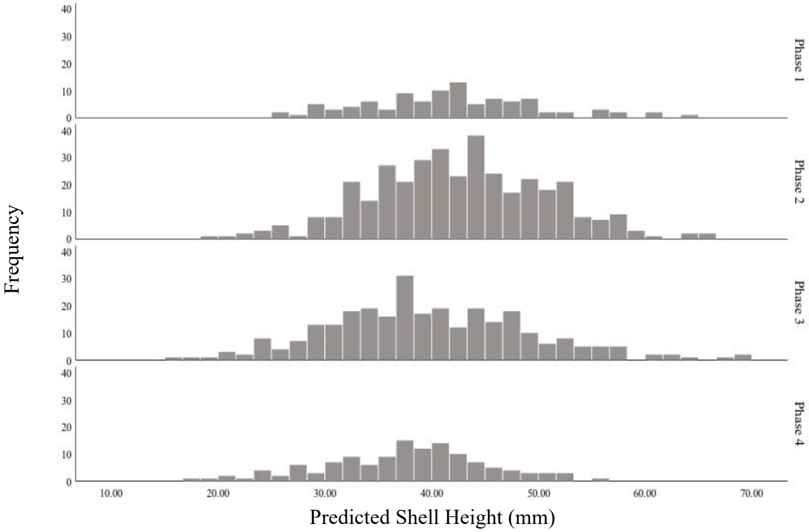


Asaphis violascens

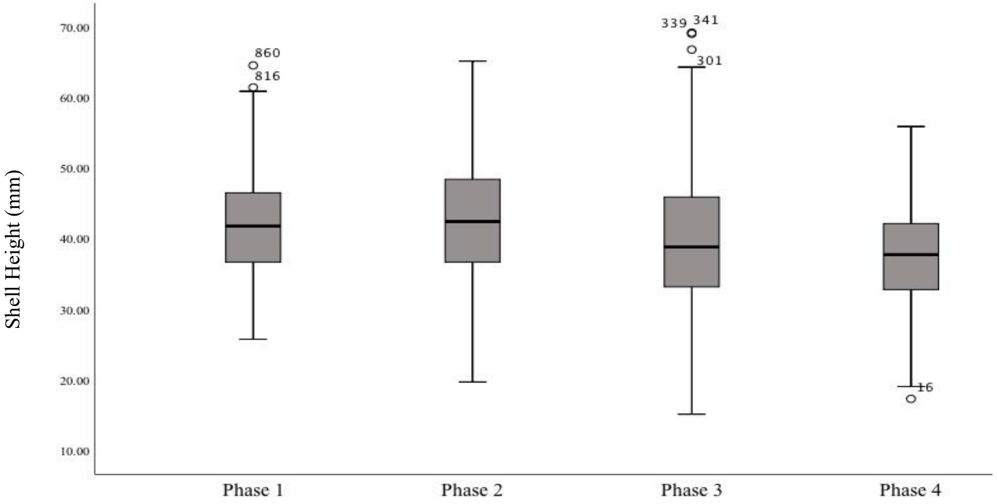


n=4; n=46; n=35; n=3

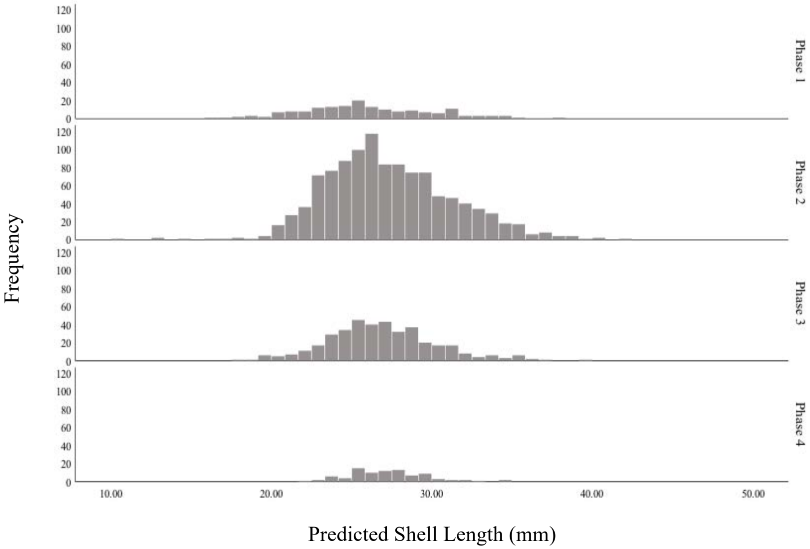
Saccostrea cuccullata

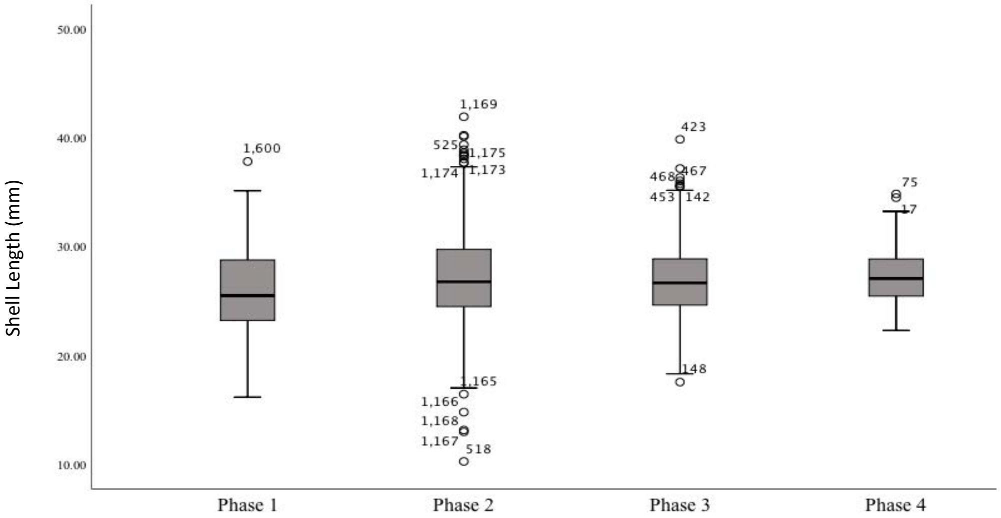


Saccostrea cuccullata

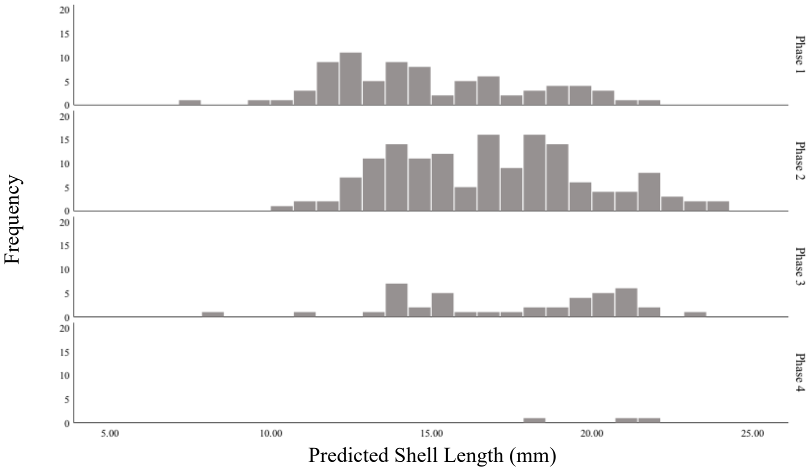


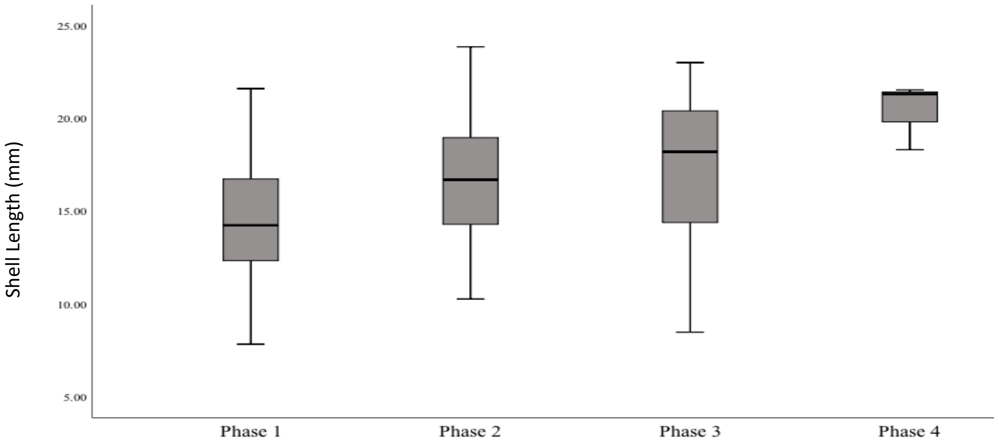
n=99; n=369; n=283; n=128


Lunella cinerea


Lunella cinerea

n=169; n=1114; n=393; n=89


Nerita chamaeleon


Nerita chamaeleon

n=79; n=149; n=42; n=3

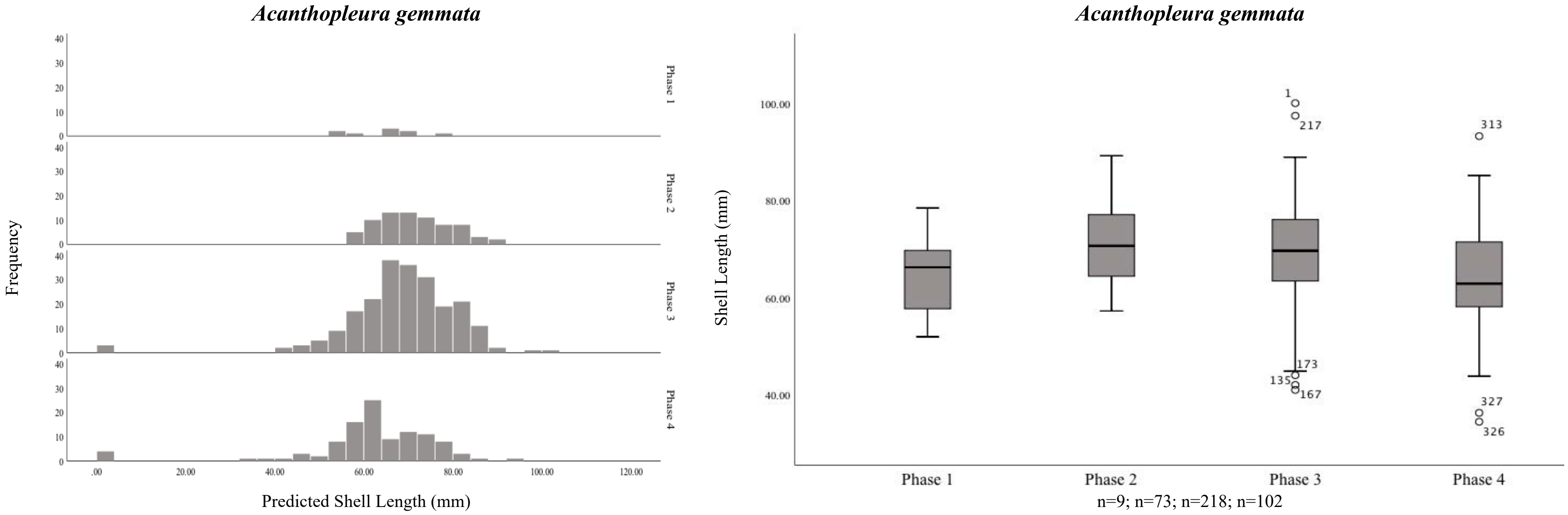


Figure 5.18 Per phase, species size frequency distributions and boxplots for predicted shell lengths *Asaphis violascens*, *Lunella cinerea*, *Nerita chamaeleon* and *Acanthopleura gemmata*, and predicted shell height for *Saccostrea cuccullata*.

5.6 Discussion

Early characterisations of the Mazie Bay cultural resource use site by Rowland (1999a), made arguments for changes in sediment deposition and changes in the abundances of faunal resources through time. Molluscan remains contributed to a significant proportion of cultural materials recovered from the site. A central argument made by Rowland (1999a) was the presence of a sand dune building hiatus phase at ~3500 BP, when the Woppaburra People either increased or decreased their use of certain taxa. Early quantifications of the molluscan assemblage (based on weight data – see Chapter 3, section 3.3.2, and see Figure 5.1 this chapter) informed Rowland (1999a) that the use of *Saccostrea* spp. and Polyplacophorans increased through time but the use of *Pinctada* spp. decreased. Speculations coincident with geomorphological observations, sea-level changes and climatic oscillations was targeted by Rowland as potential reasons for these changes (see Rowland 1999a and 1999b). Although geomorphological processes at Mazie Bay could not be directly reassessed here, a compelling case for trends in species abundances, habitat representations, and shell sizes, emerges. Figure 5.19 assists as a visualisation of results to accompany the discussion below.

Ecological information derived for each of the assessed species, showed rocky shores to be the highest represented habitat. For most species, preferences for substrates in the intertidal zone is apparent. Species representing preference for the supratidal fringe and subtidal zones, each returned lower MNIs (*A. violascens* MNI=149 and *P. sugillata* MNI=883, *A. gemmata* MNI=543) in comparison to species occupying middle intertidal areas (*L. cinerea* MNI=2196, *N. chamaeleon* MNI=1732, *S. cuccullata* MNI=1313). High fragmentation of *P. sugillata* shells did not allow for biometric assessments to be made; however, analysis of *A. violascens* shells (representative of subtidal sand-mud flat habitats) indicates no size differences. The depth range (see Table 5.4) and/or the ability for *A. violascens* to burrow into sediments (capable of restricting predator visibility and accessibility) might have resulted in low harvesting of the species by the Woppaburra People.

The most intense period of mollusc harvesting by the Woppaburra People occurred in Phase 2, coinciding with Rowland's (1999a) proposed '3500 BP buried soil event'. This finding is informed by the observation of high MNIs across each of the species assemblages, except *A. gemmata* which underwent the highest levels of harvesting in Phase 3. In other case studies, frequent and intense harvesting has been indicated by either decreasing or in some cases increasing shell sizes through time (see discussion in Chapter 4). At Mazie Bay, all species representative of rocky shore intertidal habitats, are either sessile (i.e. *S. cuccullata*) or have some locomotion ability (i.e. *L. cinerea*, *N. chamaeleon*, *A. gemmata*). Moreover, the visibility of *S. cuccullata*, *L. cinerea*, *N. chamaeleon* and *A. gemmata* populations are considered to be reasonably high, particularly at low tides when rocky substrates are

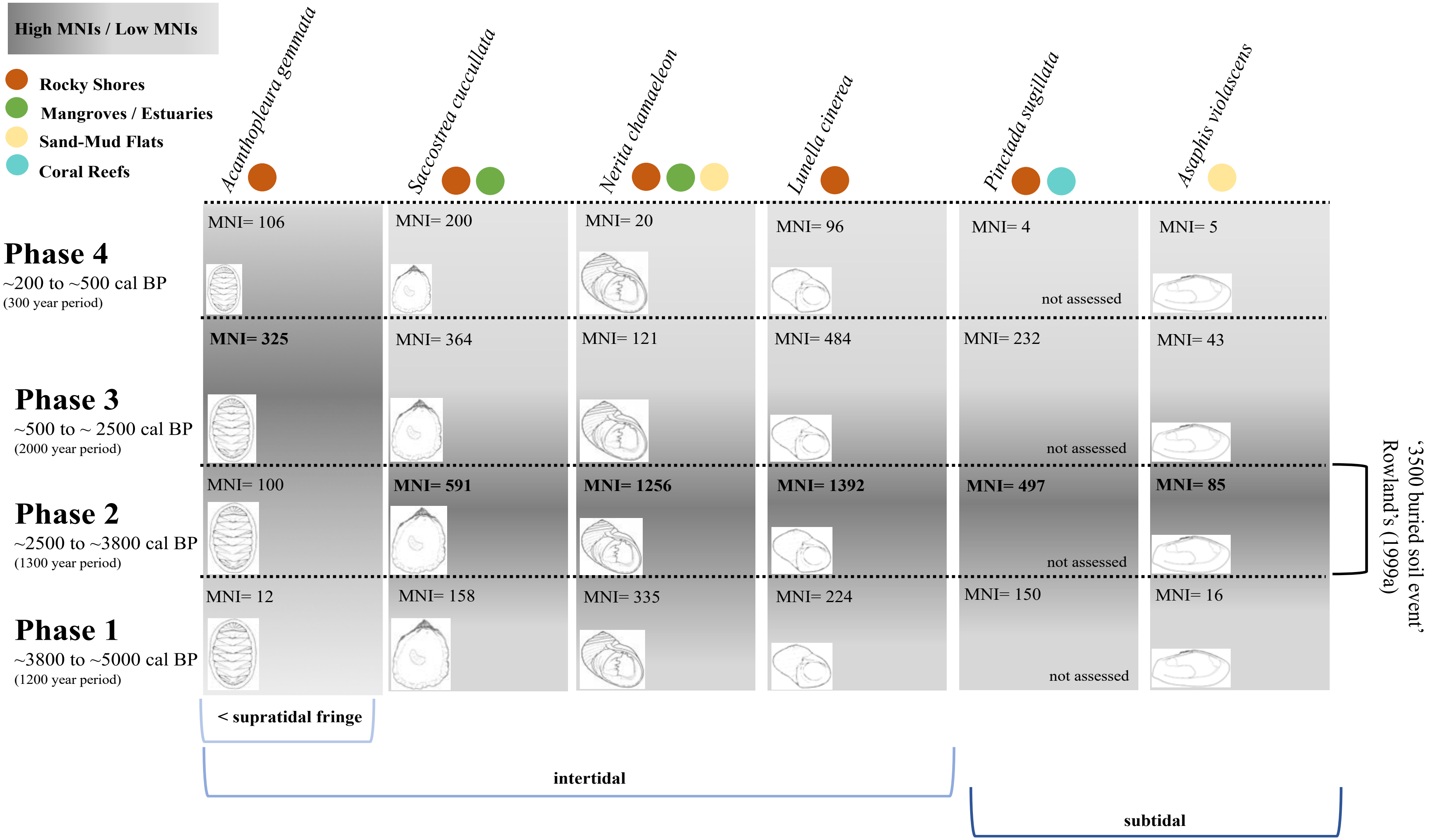


Figure 5.19 A visual representation of species assemblages by minimum number of individual (MNI) counts and relative size of individuals per phase. Interspecies image size comparisons are not valid.

exposed. Keeping these factors in mind, the most dominant species harvested by the Woppaburra People, *L. cinerea*, does not show any major changes in shell size through time. Indeed, shell size changes for this species are minimal between phases. A similar trajectory follows for *S. cuccullata* and *N. chamaeleon* – no major size differences in shells through time. Although only slight changes in shell sizes are apparent, *N. chamaeleon* assemblages show an increasing rather than decreasing shell size trend between Phase 1 and Phase 4.

An opposite trend for *A. gemmata* assemblages was found where shell sizes decrease rather than increase from Phase 2 and into Phase 4. A moderate size effect result argues that shell size changes in *A. gemmata* assemblages are indeed significant. In this case, Woppaburra harvesting intensity might have influenced a decrease in *A. gemmata* shell size through time; although, considering minimal shell size changes in other species assemblages, environmental and/or climatic variables should not be discounted as possible causes influencing mollusc growth. A possible reason for variations in rank orders between species and through time, might also be attributed to either Woppaburra harvesting preferences or patterns and/or changes in the availabilities of species (e.g. slight differences in the timing of possible seasonal harvesting and/or shifts in environmental and climatic variables governing mollusc growth). As indicated in the reviews above, shell size can be a good indicator of ontogenetic age in some species. In others, shell size is not a good indicator of ontogenetic age. For the species under assessment here, little to no information is available for size-at-age criteria typical of GBR populations. This has resulted in a limitation to assess species population size-age structures. Access to ontogenetic age indices of species might be possible using sclerochronological techniques which is undertaken in the next chapter, Chapter 6.

5.7 Summary

Although a wide variety of faunal resources was utilised by the Woppaburra People over a 5000-year period during the Holocene, only the dominant mollusc species represented in the assemblage was assessed here. The use of upper intertidal species by the Woppaburra People can be characterised as complex with evidence of variability in species rank orders through time. A key finding demonstrates that the highest levels of mollusc harvesting took place at the time of minimal sediment deposition during Rowland's (1999a) '3500 BP buried soil event'; although, further work is needed to confirm geomorphological features at the site. Minimal size changes in mollusc shells points to a non-random or size-selective harvesting approach adopted by the Woppaburra People. Exactly why rank orders varied through time and why *A. gemmata* shell sizes deviates from other intertidal species trends however, is still unclear.

6

Sclerochronology

6.0 Introduction

This chapter uses sclerochronology to estimate the ontogenetic ages of *Saccostrea cuccullata*, *Lunella cinerea*, and *Acanthopleura gemmata*. It is the first assessment of internal shell growth feature records for *L. cinerea* and *A. gemmata*; and, for *S. cuccullata* deriving from a Great Barrier Reef (GBR) location. Growth feature data, representative of life-history characteristics for each species, are used to make comparisons between modern live-collected samples and cultural deep time samples recovered from Mazie Bay. Although ontogenetic ages can be identified using sclerochronological techniques in each species, micrometric examinations find growth increment (GI) widths in all samples to be highly variable. These variations are assumed to be linked with changes in microhabitat conditions, interseasonal conditions and/or year-to-year conditions that were present during the life of each mollusc. High variability in GI widths might also be the reason for maximum shell sizes not being an appropriate proxy for ontogenetic ages. To confirm why GI width variations occur, and to potentially identify the seasons of mollusc collection by the Woppaburra People, stable isotope analyses is recommended at the end of the chapter.

6.1 Mollusc Shell Growth Feature Identification

In the previous chapter, biometric techniques were used to assess any changes in species shell sizes through time. Interpretations for why some species showed changes in shell sizes and in rank orders per phase was limited due to an inability to estimate ontogenetic ages. To account for ontogenetic ages and other life-history growth characteristics in *S. cuccullata*, *L. cinerea* and *A. gemmata* samples, sclerochronological assessments are undertaken here. Section 6.2 in this chapter, details why only 3 species were prioritised for sclerochronological assessments. The next section evaluates how previous studies have approached the sclerochronologies of oyster, turbinid and chiton shells in the past. This review is not concerned with how shell is laid down in each species, but rather what internal shell features can be used to record periods of growth and age-at-death indices (for shell growth and specifically see Chapter 4, section 4.3.1). Ontogenetic ages and sub-annual growth markers can usually be identified by visual inspection of pigmentation patterning and/or by measuring the distances between growth features. These characteristics often reflect changes in environmental and climatic conditions and as such, can be used to estimate annual, seasonal, daily or sub-daily resolutions of growth (see review in Chapter 4). Daily and sub-daily growth is not a focus in the following review. Rather annual and seasonal growth are the focus of the Mazie Bay mollusc shell assessments. Growth lines (GLs) (i.e. tightly or loosely spaced features) and growth increments (GIs) (i.e. usually representing periods of accelerated growth between growth line intervals), are expected to be recognisable to varying extents in each taxon. Disturbance lines (DLs) or growth anomalies are shown to be another feature worth investigating to detect periods of slowed growth or growth stoppages. The terms 'opaque' and 'translucent' are expressions often used to describe the types of patterning encountered in mollusc shell (i.e. density of organic materials and minerals) (Jones and Quitmyer 1996) which can manifest in GLs, GIs, or growth anomalies (DLs). In the following sections I refer to opaque and translucent growth features as either 'light' pigmentations or 'dark' pigmentations and use these terms interchangeably.

Ostreidae

While there are a few areas in a mollusc shell that can be used to age individuals, the majority of studies have focused on the hinge areas in the left valve (for e.g. see Andrus and Crowe 2000, Altamaha Sound *Crassostrea virginica*; Bougeosis et al. 2014, western China *Sokolowia buhsii*; Custer and Doms 1990, Chesapeake Bay *C. virginica*; Kirby 2000, North America – Chesapeake Bay and Mississippi Delta *Crassostrea gigantissima* and *C. virginica*; Milner 2001 *Ostrea edulis*; Tynan et al. 2017). The hinge area in left valves are usually prioritised due to the likelihood of dissolution in other areas of the shell (e.g. ventral margins) (Milner 2001:864), fundamentally caused by anaerobic respiration. In contradistinction, Arkhipkin et al. (2014) successfully record growth features in the right valves of Ascension Island oysters. They found two areas of equivalent growth in right valves of *S. cuccullata*: (1) the area directly adjacent to the hinge and (2) the area near the adductor muscle scar. Arkhipkin et al. (2014) reason that *S. cuccullata* hinges, similar to other species, can be damaged when removed from substrates or during meat extraction processing by humans. In addition, Milner (2001:864) confirms using the left valves of oysters can make 'sectioning problematic' as they are cupped in shape. Typically 'flatter' right valves, at least in *S. cuccullata*, might be more appropriate for assessing growth features. In the Ascension Island *S. cuccullata* samples, after sectioning the right valves longitudinally along the growth axis, Arkhipkin et al. (2014) counted thin dark GLs and thick light GIs, finding the species to have heightened rates of growth in the cooler seasons.

In other studies using oyster shell, sclerochronology has been applied to compare growth rates between modern and deep time sample assemblages. For instance, Bougeosis et al. (2014) compared middle Eocene oyster hinges from the Tarim Basin to identify temporal and spatial shifts in seasonality across southeastern and central Asia (i.e. variation between monsoonal activity and dry arid conditions). Like Arkhipkin et al. (2014), seasonality was inferred through visual inspection of opaque and translucent patterning in shell microstructures. Summer growth periods were observed in *S. buhsii* as thick light GIs and winter growth periods as thin dark GLs (Bougeosis et al. 2014). In Andrus and Crowe's (2000) assessments of *C. virginica*, they determined dark GLs to correspond with winter growth periods and light GIs to correspond with summer growth periods. Summer growth periods produced the highest growth rates in the species (Andrus and Crowe 2000). Moreover, rather than producing a DL per se, sporadic heat extremes or flooding caused irregular 'precipitation of dark bands' (Andrus and Crowe 2000). In tropical settings, heat extremes and flooding caused by storms in monsoonal summer months is not uncommon and should be anticipated in shells deriving from such localities. An important finding from Milner's (2001) assessment of *O. edulis*, was that despite the occurrence of predictive cyclic seasonal cues, year-to year growth within the same season and between species cohorts can vary. Instances of extended periods of warm or cool temperatures (and other potentially coinciding variables e.g. delivery of food and nutrients) outside of the typical time slot, could also result in growth feature variations within shell microstructures.

Turbinidae

Species in the family Turbinidae (i.e. turbinid shells), also record growth in their shells. Growth stops (or DLs) in response to periodic growth cessations, and seasonal GLs and GIs, have been identified in some species (e.g. Garcia-Escárzaga et al. 2019; Prendergast et al 2016). A key feature in the body whorls of turbinid shells, is the presence of a thick DL in the outer shell layer (microstructural prismatic layer or M1) which protrudes into the inner shell layer (microstructural nacreous layer or M2). García-Escárzaga et al. (2019) found this feature to correspond to a period of slowed growth. Thinner annual and sub-annual GLs and GIs also appear in the inner shell layer, resembling growth reliance on spring and neap tides, otherwise known as 'tide controlled shell growth' (i.e. thin GLs with thick GIs during spring tides and thick GLs with thin GIs during neap tides) (García-Escárzaga et al. 2019). When periods of slowed sub-annual growth occurs, GLs do not appear in the shell microstructure (García-Escárzaga et al. 2019). This irregularity is reported to occur in ontogenetically older *Phorcus lineatus* during seasonal changes (winter and spring) and/or at certain reproductive intervals (e.g. gametogenesis) (García-Escárzaga et al. 2019). The highest rate of growth in *P. lineatus* is in warm summer months (García-Escárzaga et al. 2019). In other species, irregular growth features are reported to be from heat stress (see *P. turbinatus* shells derived from Italian sites in Colonese et al. 2009; Mannino et al. 2008). Determining what is considered a 'normal' period of growth or a growth anomaly is critical when defining the season-of-death of an individual.

Prendergast et al. (2016) reconstructed season-of-death records for *P. turbinatus* using body whorl samples recovered from a deep time cultural site at Haua Fteah, Libya. Importantly, sclerochronological records of *P. turbinatus* shells in this study were coupled with stable isotope values. The most recent periods of growth, located at the ventral margins of each shell sample, were found to be sufficient for defining season-of-death indices (Prendergast et al. 2016). From the season-of death indices, information for the season-of-collection of shells by humans could then be extrapolated. During the

Late Glacial Oranian at Haua Fteah, *P. turbinatus* were collected throughout the year where the site was as utilised a 'refugium', after which time in the Pleistocene and Holocene phases, the species was targeted for collection in cooler seasons (Prendergast et al. 2016). In a separate case, Galimberti et al. (2017) used the opercula of *Turbo sarmarticus* shells to understand seasonal growth. Rather than using potentially available internal growth feature characteristics however, Galimberti et al. (2017) used geochemical values to determine season-of-death indices. Based on these findings, it is not yet clear if turbinid opercula can be used to interpret ontogenetic ages and seasons-of-death using internal growth feature characteristics alone.

Chitonidae

Only limited attempts at recording growth features from Chitonidae have been made in the past using intermediate and terminal shell valves. Lord (2012) examined the internal shell growth features of intertidal species, *Cryptochiton stelleri* and *Katharina tunicata*. Samples of these species were live-collected from Oregon, United States of America. Resembling some other molluscan shell species, the outer ventral margins in Chitonidae shell valves represents the most recent period of growth (around the perimeter of each of the 8 valves) (see Jones and Crisp 1985:137). Due to Chitonidae valve form, internal growth features typically appear concentric in shape and, in 7 of the 8 valves including the anterior valve but excluding the posterior valve, shell is laid down starting from centrally located points (after description in Lord 2012; and see Jones and Crisp 1985). The posterior valve (8th valve) has 'two growing edges, in the longitudinal plane of the animal' (Jones and Crisp 1985:137). In Lord's (2012) assessments of *C. stelleri* and *K. tunicata*, sample valves were sectioned along both the 'short and long axes' to access GLs and GIs. The *C. stelleri* valves showed light GLs with dark GIs, and *K. tunicata* valves showed dark GLs with light GIs (Lord 2012) (see also Jones and Crisp 1981:133). In ontogenetically older individuals, growth features are reported to appear faded, particularly near the centre point of each valve (Lord 2012). Lord (2012:47) showed growth rates were highest in summer months with periods of slow growth occurring in winter. Tightly spaced sub-annual GLs are reported to reflect periods of slow growth and loosely spaced sub-annual GLs are representative of faster growth periods (Lord 2012).

6.2 The Present Study

To increase the reliability of understanding potential changes in mollusc growth, modern live-collected samples were used to compare with the deep time samples. Each species assemblage was used to investigate: (1) which growth features could be representative of annual and seasonal markers or growth anomalies (2) ontogenetic age estimates and age-at-collection of deep time samples (3) annual growth rate trends; and, (4) if maximum shell size could be used as a proxy for ontogenetic age. Discrimination between male and female individuals was not attempted due to the absence of the soft tissue components in deep time samples (but see relevance in other studies e.g. *A. islandica* in Schöne 2013:201).

6.2.1 Live-collected Control Samples

Modern mollusc shell samples were collected from Mazie Bay, North Keppel Island, over 3 consecutive days in September 2018 when spring tides were at their lowest (see Table 6.1 and Figures 6.1 and 6.2). Samples were collected with the permission of the Great Barrier Reef Marine Park Authority (GBRMPA) (G18/38392.1), and in accordance with the GBRMPA zoning conditions (see zoning map in Chapter 3, Figure 3.2). A handheld Garmin GPSmap 64 was used to record the location of each sample and a Canon G1X Mark II digital camera was used to photograph each sample *in situ* (see Figure 6.3). Live-collected samples were chosen on the basis that they were large enough to be sectioned with a precision saw. Some *S. cuccullata* and *A. gemmata* individuals observed in the field were <20mm in size and therefore determined inadequate based on the risk of shells being fractured during the cutting process. Large bodied individuals at least ≥ 20mm for each species were therefore prioritised for collection. After carefully removing samples from the substratum, each individual was given a field sample number and placed into a clearly labelled bag. Wet weights of each sample (including shell and soft tissue components) were measured to the nearest 1g. Samples were then placed into the freezer at the North Keppel Island Environmental Education Centre (NKIEEC) overnight and then defrosted to room temperature. Once defrosted, the soft tissue components of each sample were carefully removed using toothpicks and a scalpel. Clean freshwater was used to rinse the samples before air drying. Dry shell weights and maximum size measurements for each live-collected sample were recorded before being transported to the ARC Centre of Excellence for Coral Reef Studies laboratory at James Cook University (JCU), Townsville. A summary of collection information, wet mollusc weights, dry shell weights and maximum size measurements for each live-collected mollusc sample is provided in Table 6.2 and Table 6.3.

Table 6.1 Predicted tides for North Keppel Island on collection fieldwork days (Rosslyn Bay datum, Bureau of Meteorology 2018b).

Date	Time	Tidal Maximums (m)	General Field Observations
11th September 2018	0411 1007 1621 2222	0.19 4.17 0.34 4.55	Sunny conditions with no rain (~26-29ºC, solar radiation ~21 MJm^{-2}) (BoM 2018b). Upper intertidal zone is lined with *Casuarina* sp.. Extensive sand flat in the intertidal zone. At the extremities of Mazie Bay, rocky outcrops dominate. In these areas, rock and coral rubble is mixed into sand-mud substrates. Shell debris is also present. Sandy seagrass meadows are not immediately obvious. On approach to the channel between Mazie Bay and Pumpkin Island at low tide, coral rubble and sand-mud substrates with some living soft corals was observed.
12th September 2018	0449 1051 1703 2302	0.34 4.10 0.60 4.21	
13th September 2018	0524 1135 1748 2343	0.57 3.96 0.92 3.82	

Figure 6.1 North Keppel Island (centre) showing live-collection zones in proximity to the Mazie Bay cultural resource use site (Basemap: Google Earth, last updated 13th May 2016). Top left live-collection zone: *Acanthopleura gemmata* samples 5-8, *Saccostrea cuccullata* samples 4-6. Top right live-collection zone: *Saccostrea cuccullata* samples 1-3, *Acanthopleura gemmata* samples 1-4. Bottom centre live-collection zone: *Lunella cinerea* samples 1-8.

Figure 6.2 A) Outgoing tide at Mazie Bay during the Austral spring with Pumpkin Island in the background, facing south. B) Intertidal rocky shore habitat featuring exposed bedrock, Mazie Bay, North Keppel Island. Facing north towards the Mazie Bay midden 1978 excavation site (Photographs: Aird 2018).

Saccostrea cuccullata samples were hand collected from the upper intertidal zone (n=6) (Figure 6.3, A). A flat-head screwdriver and hammer were used to lift *S. cuccullata* from the rocks by gently tapping underneath the hinge. A small amount of damage to the shell of the left valve (attached to the rock) was unavoidable during the extraction process (see Arkhipkin et al. 2014 for a similar extraction issue). Most *S. cuccullata* were tightly clustered and directly exposed to the sun. Individuals found in larger clusters were small, while those outside of clusters tended to be larger. Small Patellidae (limpets) and barnacles were found in the same habitat area and sometimes on *S. cuccullata* shells. Fragments of *S. cuccullata* shells were occasionally identified at the collection site and adjacent beach. *Balanus* sp., Littorinidae (periwinkles), *Monodonta labio*, Muricidae (rock shells), and Trochidae (top shells) were also observed in the same habitat area.

Lunella cinerea samples were hand collected from the upper intertidal zone (n=8) (Figure 6.3, B). The species was found loosely clustered in moist shady rock crevices a few centimetres apart from each other and easy to extract by hand. Populations of *S. cuccullata* and *A. gemmata* were not observed in or near the same area as *L. cinerea*. Fewer *N. chamaeleon* were observed in this zone than in other areas; however, large hauls of Cerithiidae occupying lower rocky rubble substrates was noted. Fragments of *L. cinerea* shells were not observed at the site or adjacent beach. In comparison to other areas at Mazie Bay, higher turbidity from wave action and highly visible green algae was observed in *L. cinerea* habitats.

Acanthopleura gemmata samples were hand collected from the upper intertidal zone (n=8) (Figure 6.3, C) from moist shady overhangs, crevices, or home scars. This species was easy to identify but difficult to extract off the rocks. The foot muscle of each *A. gemmata* retracted when shaded by the collectors hand. A flat-head screwdriver and hammer were used to prise each individual off each rock surface by gently tapping underneath either the posterior or anterior end. No *A. gemmata* fragments were observed at the site or adjacent beach. The species was generally found in the same areas as *S. cuccullata* but in shady positions.

Figure 6.3 A) *Saccostrea cuccullata* field specimen 3 (LC#3), live-collected from Mazie Bay North Keppel Island, September 2018. B) *Lunella cinerea* field specimen 1 (LC#1), live-collected from Mazie Bay North Keppel Island, September 2018. C) *Acanthopleura gemmata* field specimen 3 (LC#3), live-collected from Mazie Bay North Keppel Island, September 2018 (Photographs: Aird 2018).

Mazie Bay and Considine Beach at North Keppel Island, were surveyed for other target species including *Asaphis violascens*, *Pinctada sugillata* and *Nerita chamaeleon*. Live specimens of *A. violascens* and *P. sugillata* could not be located; however, fragments of *P. sugillata* and *A. violascens* were identified in shell grit along the estuary at Considine Beach. Local staff from the NKIEEC and local fisherman advised they had not observed *P. sugillata* in the area. Further, Creighton (1984) describes not having located *P. sugillata* during his survey in the early 1980s. Small amounts of *A. violascens* fragments were observed at the western end of Mazie Bay on the surface of soft intertidal sands. Several techniques for extracting *A. violascens* from intertidal sands was employed in the field such as: stirring moist sandy substrates with feet, digging into the sandy substrate with hands, and test pitting along X and Y axes of the beach with a spade. No samples were recovered. Seasonality, changed environmental or habitat conditions, or predation may be causes for why these species could not be located. *N. chamaeleon* samples were not included in sclerochronological assessments due to time constraints. Information for the collection of *N. chamaeleon* samples from Mazie Bay can be consulted in Appendix E.

Table 6.2 Summary data of mollusc samples live-collected from rocky shore habitats at Mazie Bay, North Keppel Island. Rocky shore habitats consisted of large sandstone boulders that are mostly inundated during high tides (i.e. below the extreme high water spring tide mark).

Date	Coordinates	Tide	Collection Time	Species	Field Specimen #
11th September 2018	S 23 05.035 E 150 53.617	Low tide	3.30pm-4.30pm	*A. gemmata*	1
11th September 2018	S 23 05.034 E 150 53.618	Low tide	3.30pm-4.30pm	*A. gemmata*	2
11th September 2018	S 23 05.035 E 150 53.619	Low tide	3.30pm-4.30pm	*A. gemmata*	3
11th September 2018	S 23 05.037 E 150 53.617	Low tide	3.30pm-4.30pm	*S. cuccullata*	1
11th September 2018	S 23 05.036 E 150 53.619	Low tide	3.30pm-4.30pm	*S. cuccullata*	2
11th September 2018	S 23 05.036 E 150 53.618	Low tide	3.30pm-4.30pm	*S. cuccullata*	3
12th September 2018	S 23 04.923 E 150 53.555	Outgoing tide	2.30pm-3.30pm	*S. cuccullata*	4
12th September 2018	S 23 04.927 E 150 53.555	Outgoing tide	2.30pm-3.30pm	*S. cuccullata*	5
12th September 2018	S 23 04.931 E 150 53.553	Outgoing tide	2.30pm-3.30pm	*S. cuccullata*	6
12th September 2018	S 23 04.926 E 150 53.555	Outgoing tide	2.30pm-3.30pm	*A. gemmata*	4
12th September 2018	S 23 04.928 E 150 53.554	Outgoing tide	2.30pm-3.30pm	*A. gemmata*	5
12th September 2018	S 23 04.928 E 150 53.551	Outgoing tide	2.30pm-3.30pm	*A. gemmata*	6
12th September 2018	S 23 04.929 E 150 53.556	Outgoing tide	2.30pm-3.30pm	*A. gemmata*	7
12th September 2018	S 23 04.929 E 150 53.556	Outgoing tide	2.30pm-3.30pm	*A. gemmata*	8
13th September 2018	S 23 05.012 E 150 53.513	Incoming tide	8.30am-9.30am	*L. cinerea*	1
13th September 2018	S 23 05.012 E 150 53.513	Incoming tide	8.30am-9.30am	*L. cinerea*	2
13th September 2018	S 23 05.012 E 150 53.513	Incoming tide	8.30am-9.30am	*L. cinerea*	3
13th September 2018	S 23 05.012 E 150 53.513	Incoming tide	8.30am-9.30am	*L. cinerea*	4
13th September 2018	S 23 05.020 E 150 53.522	Incoming tide	8.30am-9.30am	*L. cinerea*	5
13th September 2018	S 23 05.020 E 150 53.522	Incoming tide	8.30am-9.30am	*L. cinerea*	6
13th September 2018	S 23 05.020 E 150 53.522	Incoming tide	8.30am-9.30am	*L. cinerea*	7
13th September 2018	S 23 05.020 E 150 53.522	Incoming tide	8.30am-9.30am	*L. cinerea*	8

Table 6.3 Summary of wet weights, dry weights, and maximum size measurements of live-collected mollusc samples. Wet weights include both left and right valves in *Saccostrea cucculata* and all eight valves in *Acanthopleura gemmata*. Dry weights include both left and right valves in *Saccostrea cucculata* and all eight valves in *Acanthopleura gemmata*.

Species	Field Specimen #	Wet weight (g)	Dry weight (g)	Max. Height (mm)	Max. Width (mm)	Max. Length (mm)
S. cuccullata	1	3	29	41.05	24.66	
S. cuccullata	2	12	9	32.50	15.96	
S. cuccullata	3	6		24.33	14.28	
S. cuccullata	4	20	16g	42.84	26.13	
S. cuccullata	5	28	22	38.91	21.83	
S. cuccullata	6	36	30	44.66	27.21	
A. gemmata	1 anterior	2	0.4		7.17	4.37
	1 posterior				7.10	3.55
A. gemmata	2 anterior	3	0.5		10.23	5.76
	2 posterior				9.94	4.17
A. gemmata	3 anterior	2	0.4		7.89	4.84
	3 posterior				8.68	3.51
A. gemmata	4 anterior	6	2		11.41	5.75
	4 posterior				10.20	4.69
A. gemmata	5 anterior	33	11		18.56	11.78
	5 posterior				18.66	9.35
A. gemmata	6 anterior	5	1		10.86	5.13
	6 posterior				11.24	4.83
A. gemmata	7 anterior	22	6		15.50	8.62
	7 posterior				15.83	7.30
A. gemmata	8 anterior	20	5		14.74	8.40
	8 posterior				14.87	6.27
L. cinerea	1	7	4	21.56	16.80	25.49
L. cinerea	2	7	5	22.74	22.12	25.97
L. cinerea	3	10	8	24.01	19.45	30.22
L. cinerea	4	6	5	21.00	16.97	25.29
L. cinerea	5	9	6	23.15	18.94	28.89
L. cinerea	6	6	5	20.87	20.63	26.36
L. cinerea	7	8	6	22.86	18.95	27.33
L. cinerea	8	8	6	23.15	22.93	28.24

6.2.2 Mazie Bay Cultural Mollusc Shell Samples

Sampling of deep time cultural mollusc shells for sclerochronological analyses was undertaken with the consent of the Woppaburra Traditional Owners and a Queensland Museum destructive analysis permit issued 17th May 2018 by the Queensland Museum Aboriginal and Torres Strait Islander Consultative Committee (QMATSICC). *Saccostrea cuccullata* samples (n=10), *L. cinerea* samples (n=10) and *A. gemmata* samples (n=10) were selected from the Mazie Bay, North Keppel Island, excavation unit (XU) materials. Selection criteria for samples depended on (1) high representation of the species determined by minimum number of individual (MNI) counts, (2) the absence of immediately obvious taphonomic impacts or weathering to the shell (e.g. chalkiness), and (3) the intactness of the maximum growth axis of each sample; for *S. cuccullata* the complete height and width of the right valve, for *L. cinerea* the body whorl and aperture lip, for *A. gemmata* the complete length and width of the anterior and posterior valves (and see further explanations below in section 6.3). Samples were selected from dominant cultural shell horizons but staggered across XUs comprising Square A1 and Square A5 (i.e. oldest to most recent phases of human occupation). Paired samples of each species from XUs were prioritised, although where this could not be achieved samples were selected from a close alternate unit. For example, a second *S. cuccullata* sample could not be obtained for the lowest XU in Square A5 in unit 255-265cm, so the second sample was selected from Square A5 in unit 220-230cm. Dry weights, maximum shell measurements, descriptions of each sample and photographs were collected before destructive sampling commenced and are summarised in Table 6.4. Mitutoyo Digimatic callipers were used for measuring shells to the nearest 0.1mm and a Canon G1X Mark II digital camera was used for photographing each sample.

Table 6.4 Summary of dry weights, maximum size measurements, and sample descriptions of deep time cultural mollusc shell samples.

Species	Specimen #	Excavation Square	Excavation Unit (cm)	Dry Weight (g)	Max. Height (mm)	Max. Width (mm)	Max. Length (mm)	Description
S. cucullata	1	A1	5-10	7	39.75	21.02		Intact, limited weathering.
S. cucullata	2	A1	5-10	6	51.83	22.63		Intact, limited weathering.
S. cucullata	1	A1	60-65	11	50.09	26.80		Intact, limited weathering.
S. cucullata	2	A1	60-65	10	53.34	32.61		Intact, limited weathering.
S. cucullata	1	A1	130-135	4	44.57	21.58		Intact, limited weathering.
S. cucullata	2	A1	130-135	6	45.63	23.26		Intact, limited weathering.
S. cucullata	1	A5	190-200	8	39.52	28.06		Intact, limited weathering.
S. cucullata	2	A5	190-200	7	39.02	21.32		Intact, limited weathering.
S. cucullata	1	A5	220-230	11	51.81	27.16		Intact, limited weathering.
S. cucullata	2	A5	255-265	2	26.24	15.82		Intact, outer surface features not pronounced.
A. gemmata	anterior 1	A1	5-10	1		18.18	10.25	Intact including eave.
A. gemmata	posterior 2	A1	5-10	1		21.15	9.78	Intact including eave and sutural laminae.
A. gemmata	anterior 1	A1	60-65	1		15.36	7.34	Intact although minor chipping to eave on left side.
A. gemmata	posterior 2	A1	60-65	1		17.57	8.58	Intact including eave and sutural laminae.
A. gemmata	anterior 1	A1	125-130	1		14.93	8.32	Eave intact. Appears sun-bleached, chalky texture.
A. gemmata	posterior 2	A1	125-130	1		16.30	6.25	Eave and sutural laminae non-existent. Appears sun-bleached, chalky texture. Chipping to posterior lateral margin.
A. gemmata	anterior 1	A5	180-190	2		21.71	12.85	Intact although minor chipping to eave in the centre.
A. gemmata	posterior 2	A5	180-190	1		21.34	10.23	Intact including eave and sutural laminae.

Species	Specimen #	Excavation Square	Excavation Unit (cm)	Dry Weight (g)	Max. Height (mm)	Max. Width (mm)	Max. Length (mm)	Description
								Very minor chipping to bottom left sutural laminae.
A. gemmata	anterior 1	A5	220-230	1		15.81	8.63	Intact including eave. Minor chipping around the top left and right edges.
A. gemmata	posterior 2	A5	220-230	1		17.82	8.63	Intact including eave. Minor chipping to bottom edges of sutural laminae.
L. cinerea	1	A1	5-10	6	18.97	17.18	26.40	Aperture edge intact. No abrasion observed on shell from hermitting.
L. cinerea	2	A1	5-10	6	20.50	18.23	28.38	Light chipping to the centre of aperture edge. No abrasion observed on shell from hermitting.
L. cinerea	1	A1	55-60	5		17.37	26.19	Light chipping along aperture edge. No abrasion observed on shell from hermitting.
L. cinerea	2	A1	60-65	5		15.91	24.61	Moderate chipping along aperture edge. No abrasion on shell from hermitting.
L. cinerea	1	A1	105-110	5			24.31	Extensive chipping along aperture edge. No abrasion on shell from hermitting.
L. cinerea	2	A1	110-115	3			23.00	Light chipping along aperture edge. No abrasion observed on shell from hermitting.
L. cinerea	1	A5	170-180	7		20.65	29.31	Moderate chipping along aperture edge. No abrasion on shell from hermitting.
L. cinerea	2	A5	170-180	18	30.64	26.55	39.59	Light chipping along aperture edge. No abrasion observed on shell from hermitting.
L. cinerea	1	A5	255-265	4			26.86	Extensive chipping along aperture edge, slight chalky appearance. No abrasion on shell from hermitting.
L. cinerea	2	A5	255-265	5			22.83	Extensive chipping along aperture edge, slight chalky appearance. No abrasion on shell from hermitting.

6.3 Sclerochronological Techniques

Although certain areas of shell in each taxon have previously been recommended for sclerochronological analyses (see review in section 6.1 above), strategic approaches for accessing growth characteristics in the samples deriving from Mazie Bay was needed. These strategies were constructed in response to (1) the inability to correctly distinguish between intermediate *A. gemmata* valves and (2) the taphonomic contexts of the deep time samples. Approaches taken for each species is explained further below.

Saccostrea cuccullata

In live oysters, acidic dissolution can damage the hinge area of shells. Where this occurs, ontogenetic age can either be over or underestimated due to the inability to correctly identify growth features (Milner 2001:864). In deep time assemblages, the hinge area can be damaged pre-mortem during meat extraction and processing, or post-mortem due to taphonomic processes (and see hinge damage to live-collected *S. cuccullata* in Arkhipkin et al. 2014). After review of Arkhipkin et al.'s (2014) work that uses the right valves of *S. cuccullata* for sclerochronological analyses, both the right valves and left valves of Mazie Bay *S. cuccullata* were targeted for examinations.

Lunella cinerea

In some contexts and in comparison to opercula, *L. cinerea* body whorls could be more prone to breakage or damage (e.g. during meat extraction processes). A large number of gastropod opercula in the Mazie Bay deep time assemblage does exist, although, given time constraints it was not possible to identify these materials to species level. A sufficient size of intact *L. cinerea* body whorls is available and were therefore targeted for sclerochronological assessments. Further, as Prendergast et al. (2016) and García-Escárgaza et al. (2019) have documented, sclerochronologies built from the body whorls of other Turbinidae species have been successful in the past.

Acanthopleura gemmata

Terminal chiton valves are easier to identify than the intermediate valves in deep time assemblages. This is particularly true when valves are encountered disarticulated and in the absence of the fleshy girdle. In the Mazie Bay deep time assemblage, a total of 4625 individual chiton valves were identified (by a number of individual specimens count), of which 453 valves were counted towards MNI estimates using terminal valves. The identification of intermediate chiton valves themselves is not difficult, although distinguishing the 3rd valve from the 4th valve for a single individual and among an assemblage of over 4000 intermediate valves of all age and size profiles is challenging. The 4th valve from a smaller individual could be confused for the 3rd valve in a larger individual. Growth features in the anterior and posterior terminal valves are therefore used in the following analyses.

6.3.1 Sample Preparation

Sample preparation and sclerochronology analyses was conducted under the supervision of Dr Amy Prendergast at the School of Geography, University of Melbourne. Live-collected and deep time *S. cuccullata*, *L. cinerea* and *A. gemmata* samples were cleaned with distilled water in an ultrasonic bath 3 times for 5 minutes each to remove sediments and organic particles. Samples were then dried overnight at ~40°C in a Labec Drying Oven. Photographs of each sample were taken with a Canon G1X Mark II digital camera with a photo scale. The maximum height, maximum width and maximum length measurements of each sample were recorded with Mitutoyo Digimatic callipers to the nearest 0.1mm. A clear quick setting epoxy resin (JB Clear-Weld) was used to mount samples onto plexiglass blocks (~60mm x 10mm): at the edge of *S. cuccullata* samples, at the apex of *L. lunella* samples and, at the valve edges of *A. gemmata* samples. Once dry, a dark grey steel reinforced quick setting epoxy resin (JB Kwik Weld) was used to coat the maximum GI area of each sample (~2mm thick). This preparatory step reinforced the structure of the samples, lessening the chance of fracturing and breakage during the cutting process. From each sample, 2 x 2-3mm thick sections were cut with a 0.4mm diamond-coated wafering blade on low speed, between 125-300 rpm using a Buehler Isomet 1000 Precision Saw.

All samples were sectioned along maximum growth axes taking extreme care to ensure section orientations were consistent among samples. For *S. cuccullata* a cut was made for each specimen from the umbo/hinge area, through the adductor muscle scar and to the posterior margin in the left valves. In the right valves, cuts were made from the umbo/hinge area through to the posterior margin. *L. cinerea* samples were cut from the apex through the columella, down through the base of the bottom whorl and to the lip of the aperture. Each anterior and posterior *A. gemmata* valve was sectioned across the width axis. Figures 6.4, 6.5 and 6.6 illustrate where each shell sample was sectioned. After the shell sections were made, each sample was mounted onto a Trajan glass slide with epoxy resin and left to air dry overnight. Each sample was sequentially hand polished using F800 grit powder, F1200 SiC grit powder and 1µm Al2O3 powder on a Buehler G-cloth. Between each polishing phase, samples were cleaned with distilled water in an ultrasonic bath to remove grit particles. After polishing, one shell section from each sample was reserved for sclerochronological analysis and the other reserved for stable isotope analysis (Chapter 7 details the stable isotope analyses). To enhance the visibility of growth features, samples were submerged in Mutvei's Solution heated to 37°C and continuously stirred with magnetic capsules for 10 minutes each (for a review of Mutvei's Solution and application see Schöne et al. 2005a and Prendergast and Schöne 2017). Sections were then removed from Mutvei's Solution, rinsed with deionised water, and left to air-dry overnight.

Figure 6.4 A) Example of a *Saccostrea cuccullata* sample selected for examination: sample 220-230cm#1, dorsal (left) and ventral (left) views. Note damage to hinge area, probably from processing, where the right and left articulated valves might have been prized apart for meat extraction. B) Showing where 2mm sections were cut on *Saccostrea cuccullata* samples.

Figure 6.5 A) Example of a *Lunella cinerea* sample selected for examination: sample 110-115cm#1. Left, dorsal view, right, ventral view. B) Showing where 2mm sections were cut on *Lunella cinerea* samples.

Figure 6.6 A) Example of *Acanthopleura gemmata* samples selected for examination: sample 5-10cm#2 posterior (left) and 5-10cm#1 anterior (right). B) Showing where valves were cut on *Acanthopleura gemmata* samples.

6.4 Mazie Bay Mollusc Shell Sclerochronology Results

Growth features in shell sections were visually inspected using a high-powered Leica M80 Microscope equipped with sectoral darkfield illumination with photographic capabilities. Photographs of x-y fields of view were taken across the entire cross-sections of each sample using different strengths and angles of light, and magnifications. Photos were stitched using Adobe Photoshop CC 20.0.1. and ImageJ 2.0.0 was used to measure GIs. Age estimates for each species were based on GI counts between GLs assumed to be annual markers. Following Schöne et al. (2005b:139) ontogenetic age 'is calculated as annual increment number minus one'. For example, in the live-collected specimens the first full year of the specimen's life begins 'when the second annual increment was laid down' (Schöne et al. 2005b:139). Sub-annual GLs were observed in most samples but micrometric assessments of these features was not undertaken. Examples of sectioned shell sample images are presented below. Section images and metric values for all assessed samples can be consulted in Appendix F and see Appendix G for deep time anterior *A. gemmata* valves.

6.4.1 Results: *Saccostrea cuccullata*

Articulated left and right valves of six live-collected *S. cuccullata* were analysed for growth features (see images in Figures 6.7 and 6.8). Growth features in the left and right valves of live-collected *S. cuccullata* samples are equivalent. Table 6.5 presents a comparison of the sclerochronology results for the left and right valves of live-collected *S. cuccullata* samples. Due to preservation qualities and ease of sample preparation, only right deep time *S. cuccullata* valves were used for sclerochronological analyses (as opposed to the cupped left valves). Table 6.6 presents the sclerochronology results for the right valves of deep time *S. cuccullata* samples.

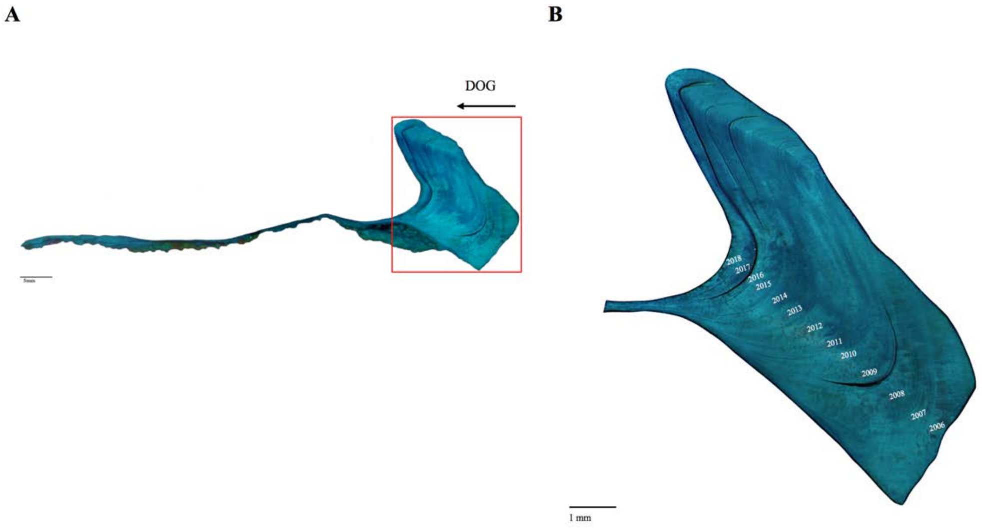


Figure 6.7 Example of a left *Saccostrea cuccullata* valve, live-collected sample LC#1, and determined growth features.

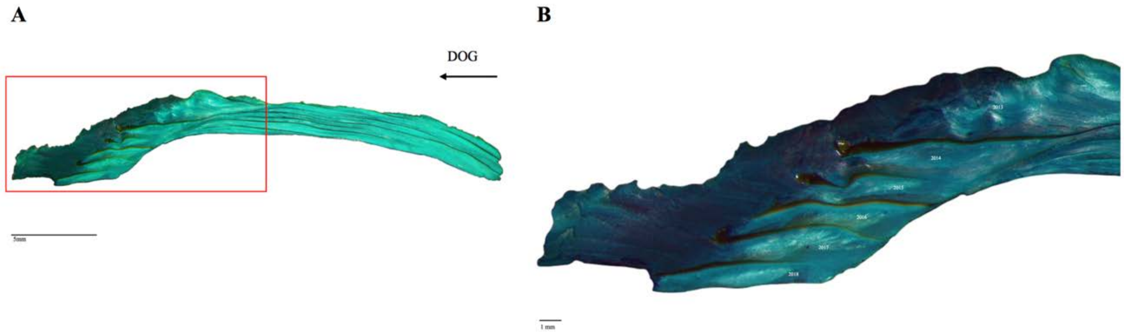


Figure 6.8 Example of a right *Saccostrea cuccullata* valve, live-collected sample LC#3, and determined growth features.

Table 6.5 Summary of growth features for live-collected *Saccostrea cuccullata* shell samples. Left and right valve growth feature data is presented in alternate order for ease of comparison.

Species	Sample	Valve	GL n=	GI n=	DL n=	Est. Age	Max. Shell Size (mm)
S. cucullata	LC#1	Left	12	13	0	12 years old	41.05
S. cucullata	LC#1	Right	12	13	0	12 years old	
S. cucullata	LC#2	Left	5	6	0	5 years old	32.50
S. cucullata	LC#2	Right	5	6	0	5 years old	
S. cucullata	LC#3	Left	5	6	0	5 years old	24.33
S. cucullata	LC#3	Right	5	6	0	5 years old	
S. cucullata	LC#4	Left	14	15	0	14 years old	42.84
S. cucullata	LC#4	Right	14	15	0	14 years old	
S. cucullata	LC#5	Left	8	9	0	8 years old	38.91
S. cucullata	LC#5	Right	8	9	0	8 years old	
S. cucullata	LC#6	Left	8	9	0	8 years old	44.66
S. cucullata	LC#6	Right	8	9	0	8 years old	

Table 6.6 Summary of growth features for deep time *Saccostrea cuccullata* shell samples (right valves).

Species	Sample	Valve	GL n=	GI n=	DL n=	Est. Age	Max. Shell Size (mm)
S. cucullata	5-10cm#1	Right	13	14	0	13 years old	39.75
S. cucullata	5-10cm#2	Right	16	17	0	16 years old	51.83
S. cucullata	60-65cm#1	Right	10	11	0	10 years old	50.09
S. cucullata	60-65cm#2	Right	8	9	0	8 years old	53.34
S. cucullata	130-135cm#1	Right	13	14	0	13 years old	44.57
S. cucullata	190-200cm#1	Right	6	7	0	7 years old	39.52
S. cucullata	190-200cm#2	Right	8	9	0	8 years old	39.02
S. cucullata	220-230cm#1	Right	8	9	0	8 years old	51.81

6.4.2 Results: *Lunella cinerea*

Five live-collected *L. cinerea* were analysed for growth features (see images in Figure 6.9). Table 6.7 presents a summary of the sclerochronology results for each live-collected *L. cinerea* sample. Table 6.8 presents the sclerochronology results for deep time *L. cinerea* samples.

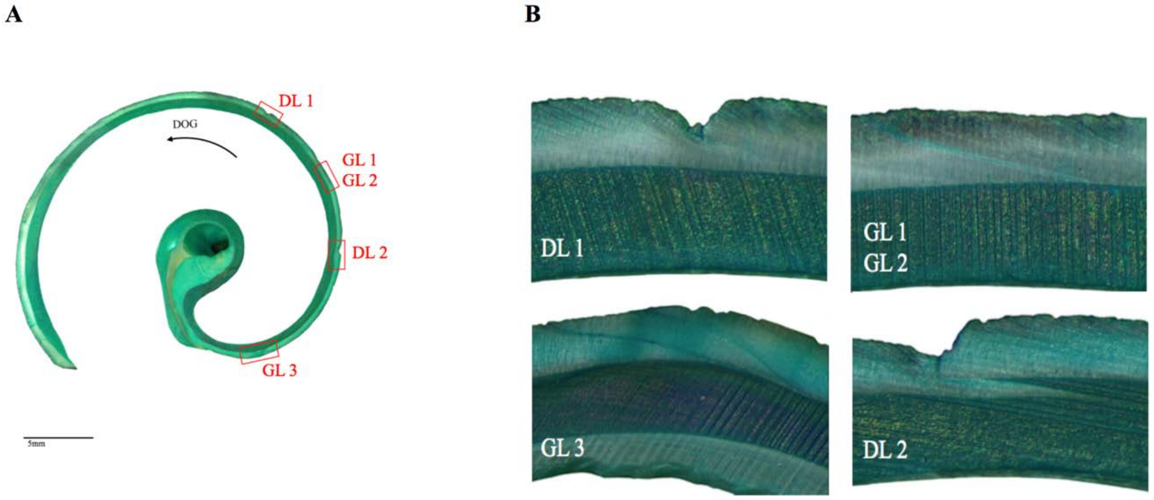


Figure 6.9 Example *Lunella cinerea*, live-collected sample LC#3, and determined growth features.

Table 6.7 Summary of growth features for live-collected *Lunella cinerea* shell samples. Note: Growth increment counts were recorded from prismatic shell layers.

Species	Sample	GL n=	GI n=	DL n=	Est. Age	Max. Shell Size (mm)
L. cinerea	LC#1	0	0	1	<1 year	25.49
L. cinerea	LC#3	3	4	2	3 years old	30.22
L. cinerea	LC#4	6	7	0	6 years old	25.29
L. cinerea	LC#6	5	6	0	5 years old	26.36
L. cinerea	LC#7	10	11	1	10 years old	27.33

Table 6.8 Summary of growth features for deep time *Lunella cinerea* shell samples.

Species	Sample	GL n=	GI n=	DL n=	Est. Age	Max Shell Size (mm)
L. cinerea	5-10cm#1	8	9	1	8 years old	26.40
L. cinerea	5-10cm#2	4	5	2	4 years old	28.38
L. cinerea	55-60cm#1	3	4	0	3 years old	26.19
L. cinerea	60-65cm#1	2	3	0	2 years old	24.61
L. cinerea	105-110cm#1	2	3	0	2 years old	24.31
L. cinerea	110-115cm#1	6	7	1	6 years old	23.00

Species	Sample	GL n=	GI n=	DL n=	Est. Age	Max Shell Size (mm)
L. cinerea	170-180cm#1	11	12	0	11 years old	29.31
L. cinerea	170-180cm#2	11	12	0	11 years old	39.59
L. cinerea	255-265cm#1	1	2	0	1 year old	26.86
L. cinerea	255-265cm#2	2	3	0	2 years old	22.83

6.4.3 Results: *Acanthopleura gemmata*

The terminal valves of three live-collected *A. gemmata* samples were analysed for growth features (see images in Figures 6.10 and 6.11). Although eight samples were collected, only three samples were analysed due to the practicability of sectioning valves (i.e. some posterior valves were too small to section). The posterior valves were divided into 2 sections, the left side, and the right side. The left and right sides were then divided again into 2 subsections in the articulamentum area (L1 and L2, R1 and R2) and analysed for growth features. Growth features in the anterior valves were not identified. Growth features in the L1 and R1 articulamentum subsections of the posterior valves matched; however, variability in age estimates from features counted in the L2 and R2 subsections showed some discrepancies. Table 6.9 presents a comparison of the sclerochronology results for the anterior and posterior valves of live-collected *A. gemmata* samples. Table 6.10 presents the sclerochronology results for deep time *A. gemmata* posterior valve samples using L1 subsections.

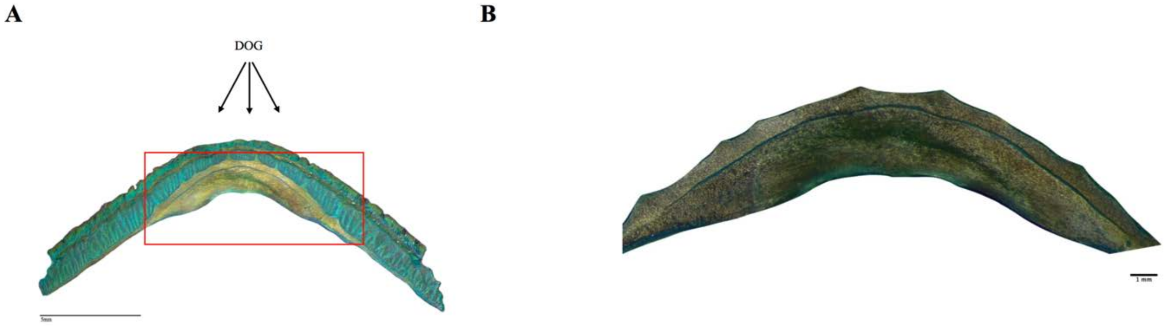


Figure 6.10 Example anterior valve of *Acanthopleura gemmata*, live-collected sample LC#8.

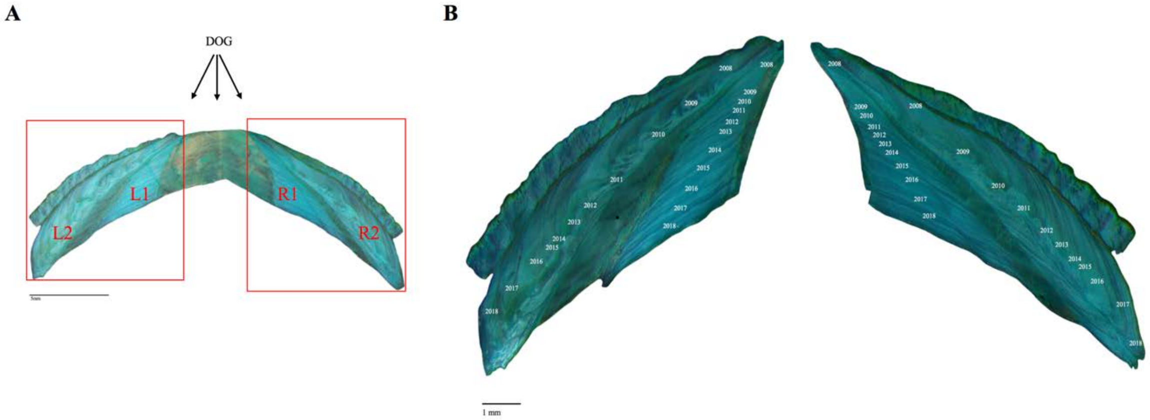


Figure 6.11 Example posterior valve of *Acanthopleura gemmata*, live-collected sample LC#5, and determined growth features.

Table 6.9 Summary of growth features for live-collected *Acanthopleura gemmata* shell samples. Anterior and posterior valve growth feature data are presented in alternate order for ease of comparison.

Species	Sample	Valve	GL n=	GI n=	Est. Age	Posterior Valve Width (mm)
A. gemmata	LC#5	Anterior	0	0		
A. gemmata	LC#5	Posterior L1	10	11	10 years old	18.66
A. gemmata	LC#5	Posterior R1	10	11	10 years old	
A. gemmata	LC#5	Posterior L2	10	11	10 years old	
A. gemmata	LC#5	Posterior R2	10	11	10 years old	
A. gemmata	LC#7	Anterior	0	0		
A. gemmata	LC#7	Posterior L1	8	9	8 years old	15.83
A. gemmata	LC#7	Posterior R1	8	9	8 years old	
A. gemmata	LC#7	Posterior L2	7	8	7 years old	
A. gemmata	LC#7	Posterior R2	4	5	4 years old	
A. gemmata	LC#8	Anterior	0	0		
A. gemmata	LC#8	Posterior L1	9	10	9 years old	14.87
A. gemmata	LC#8	Posterior R1	9	10	9 years old	
A. gemmata	LC#8	Posterior L2	5	6	5 years old	
A. gemmata	LC#8	Posterior R2	4	5	4 years old	

Table 6.10 Summary of growth features for deep time *Acanthopleura gemmata* shell samples.

Species	Sample	Valve	GL n=	GI n=	Est. Age	Posterior Valve Width (mm)
A. gemmata	5-10cm #2	Posterior L1	11	12	11 years old	21.15
A. gemmata	60-65cm #2	Posterior L1	8	9	8 years old	17.57
A. gemmata	125-130cm #2	Posterior L1	8	9	8 years old	16.30
A. gemmata	180-190cm #2	Posterior L1	12	13	12 years old	21.34
A. gemmata	220-230cm #2	Posterior L1	11	12	11 years old	17.82

6.5 Visual Interpretations and Micrometric Results

Saccostrea cuccullata

Growth features in the left and right valves of live-collected *S. cuccullata* are represented in all samples. Opaque and translucent patterning is consistent across articulated left and right valves. Most samples display thin dark annual GLs and thick light annual GIs. Sample LC#4, in the left and right valves, shows some pigmentation inversion. Interestingly, this sample was estimated to be approximately 14 years old, and as such is the oldest ontogenetic age recorded for the species in the live-collected assemblage. Sample LC#2 is the youngest sample with very distinct dark GLs. The average age at collection of the modern live-collected *S. cuccullata* samples is 8.6 years old (n=6). On visual inspection across all articulated samples, the left and right valves show equivalent growth features, but GI widths vary (in the left valves at the hinge area, and in the right valves at the adductor muscle scar area). The right valves in each articulated sample were consequently used for micrometric analyses. For each right valve sample, GI measurements located between annual GLs were plotted onto a graph and visually inspected for trends (Figure 6.12). Although some correlation in growth trends between samples LC#2 and LC#3 is apparent, no immediate annual growth trends are obvious when comparing other samples. Highly varied annual growth in modern *S. cuccullata* populations is therefore concluded.

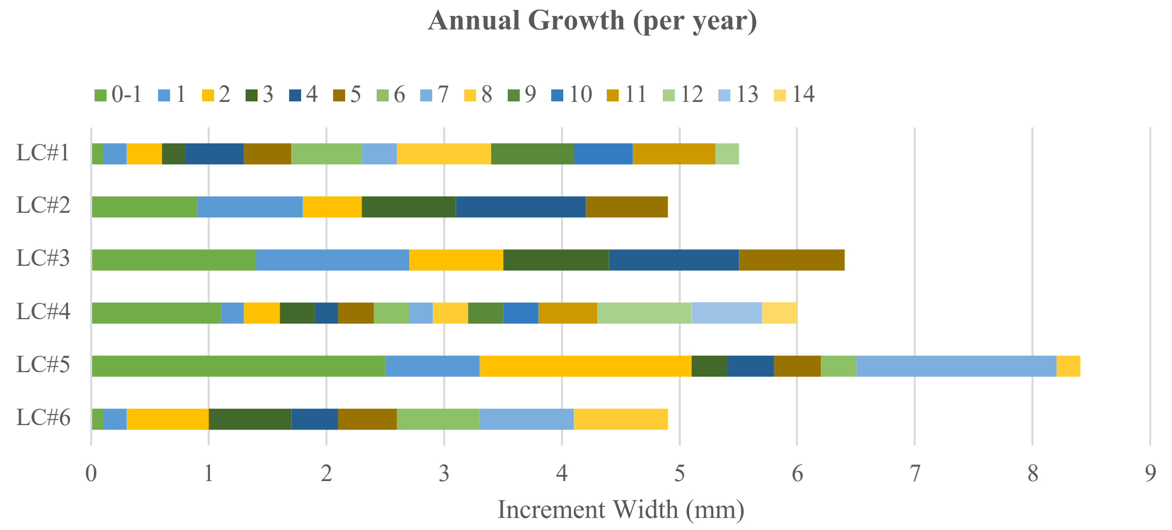


Figure 6.12 Plotted growth increment widths for live-collected Mazie Bay *Saccostrea cuccullata* right valves.

Deep time *S. cuccullata* samples have inverse pigmentation GLs in comparison to the live-collected samples. All deep time samples have thin light annual GLs and thick dark GIs. A few of the samples show precipitation of dark GLs, but the majority of their features follow suit with other deep time samples - light GLs and dark GIs. Samples showing evidence of inverted GL pigmentations, do not show any bias in ontogenetic age (i.e. younger versus older). Sample 5-10cm#2 is estimated to be 16 years old. The youngest sample, sample 190-200cm#1, is estimated to be 7 years old. The average age of *S. cuccullata* samples in this assemblage is 10.3 years old (n=8).

Annual GI widths were measured in the right valves of *S. cuccullata* samples and plotted onto a graph to visually inspect trends (Figure 6.13). For ease of comparison between samples from the same unit, they are plotted again in Figures 6.14, 6.15, 6.16. Samples comprising unit 5-10cm share some resemblance in increment width trends which is likely due to each individual deriving from the same cluster (i.e. same micro-habitat conditions and access to food and nutrients). Overall, annual growth is concluded to be highly variable for *S. cuccullata* samples across all temporal phases.

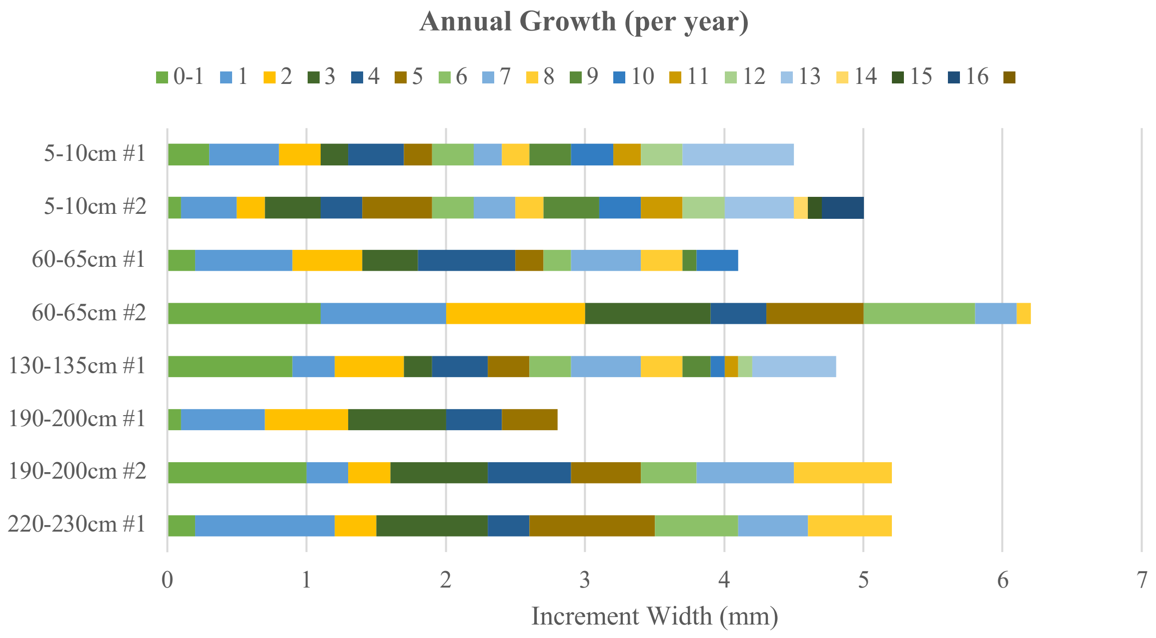


Figure 6.13 Plotted increment widths for *Saccostrea cuccullata* right valves excavated from Mazie Bay.

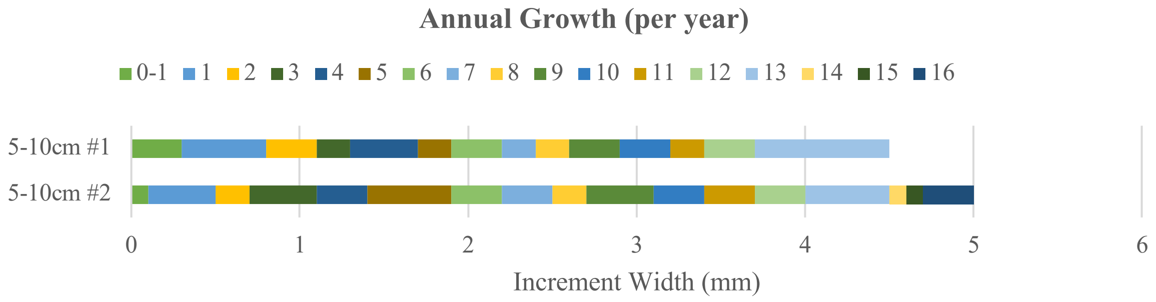


Figure 6.14 Plotted increment widths for *Saccostrea cuccullata* right valves recovered from Mazie Bay excavation unit 5-10cm.

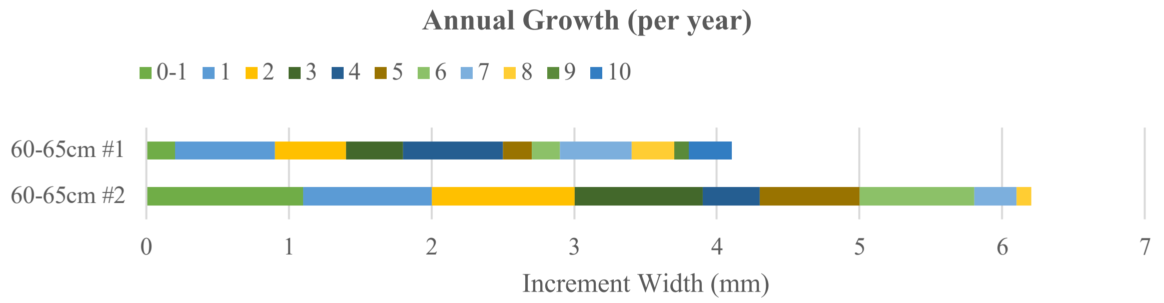


Figure 6.15 Plotted increment widths for *Saccostrea cuccullata* right valves recovered from Mazie Bay excavation unit 60-65cm.

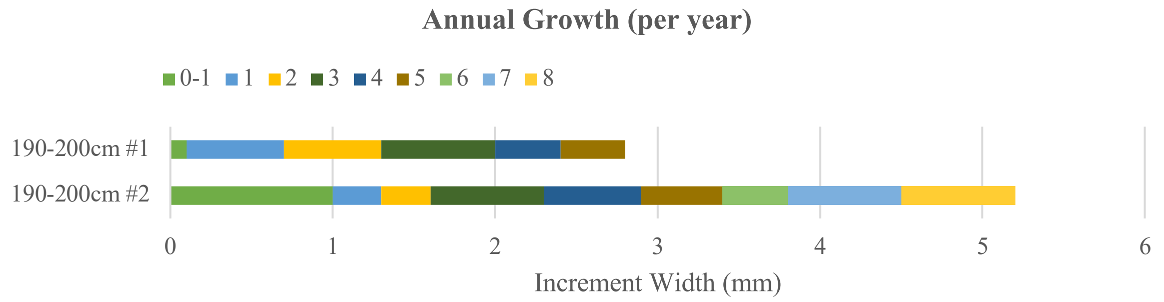


Figure 6.16 Plotted increment widths for *Saccostrea cuccullata* right valves recovered from Mazie Bay excavation unit 190-200cm.

Lunella cinerea

Live-collected and deep time *L. cinerea* revealed annual and sub-annual growth features. Annual GLs were assumed to be thicker than sub-annual GLs but not as thick as the GLs associated with disturbance notches. Although there is no deviation in the types of growth features expected in *L. cinerea*, not all samples displayed each type of growth feature. In particular, not all samples display annual GLs. One live-collected sample without GL features, LC#1, could be indicative of a <1-year life-history. Some samples show DLs which protrude as notches in the outer prismatic shell layer into the nacreous shell layer. In sample 105-110cm#1, sediments were observed along the length of GL. This could indicate the individual was subjected to turbid intertidal conditions during a period of its life. Across the live-collected and deep time samples there is no variability in light versus dark pigmentation patterning. In sample LC#7 however, a single GL (GL 7) shows dark pigmentation in the outer shell layer and then, following through to the inner layer, the same GL changes to a lighter shade.

Growth feature widths in *L. cinerea* samples vary. For instance, a single GL can change widths between the inner and outer layers. For this reason, micrometric assessment of GI widths in *L. cinerea* samples was not attempted. Nonetheless, an estimate of ontogenetic ages, by counting annual growth features could be completed. Live-collected sample LC#7 showed the highest count of annual GIs and is estimated to be 10 years old. The youngest sample, LC#1 estimated to be <1 year-old, showed no GLs.

The average age at collection of the modern live-collected *L. cinerea* samples is 6 years old (n=4). Of the deep time samples analysed, 170-180cm#1 and 170-180cm#2, are both approximately 11 years old. These samples have the oldest life-history in the *L. cinerea* assemblage. The youngest sample, 255-265cm#1, is estimated to be 1 year old. The average age-at-collection of the deep time assessed *L. cinerea* samples is 5 years old (n=10).

Acanthopleura gemmata

Annual and sub-annual growth features in the anterior valves of *A. gemmata* are not represented in modern samples LC#5, LC#7 and LC#8. In the posterior valves however, growth features were clearly identifiable in the L1, L2, R1 and R2 articulamentum areas of each valve. Areas L1 and R1 presented equivalent growth features in all samples. L2 and R2 presented equivalent growth features in LC#5 but variation in the number of GIs was found in samples LC#7 and LC#8. The most reliable representation of growth features can therefore be obtained in the L1 and R1 articulamentum areas of posterior *A. gemmata* valves. Pigmentation patterns showing thin dark GLs and thick light GIs are consistent across all live-collected and deep time samples. Live-collected sample LC#5 showed the highest count of annual GIs and is estimated to be 10 years old. The youngest sample, LC#7, is 8 years old. The average age-at-collection of the modern live-collected *A. gemmata* samples is 9 years old (n=3).

The L1 areas of 5 posterior deep time *A. gemmata* valves showed annual and sub-annual growth features. In comparison to the modern samples, growth features in the *A. gemmata* valves are distinguishable but appear faded in some areas. The oldest sample, 180-190cm#2, revealed an age of 12 years old. Samples 60-65cm#2 and 125-130cm#2 were the youngest samples, both estimated to be 8 years old. The average age of the deep time *A. gemmata* samples is 10 years old (n=5). Micrometric assessments of the increment widths of modern live-collected samples and deep time samples, confirms variable growth trends (Figures 6.17, 6.18 and 6.19).

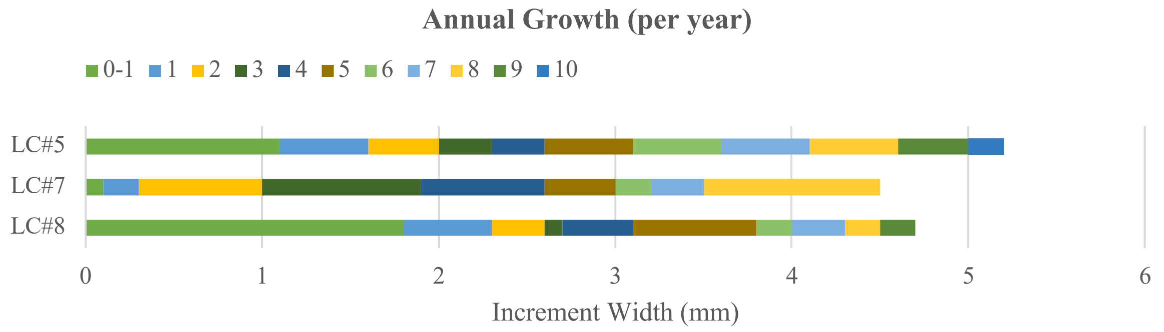


Figure 6.17 Plotted growth increment widths for live-collected Mazie Bay *Acanthopleura gemmata* in the posterior 'Left 1' section.

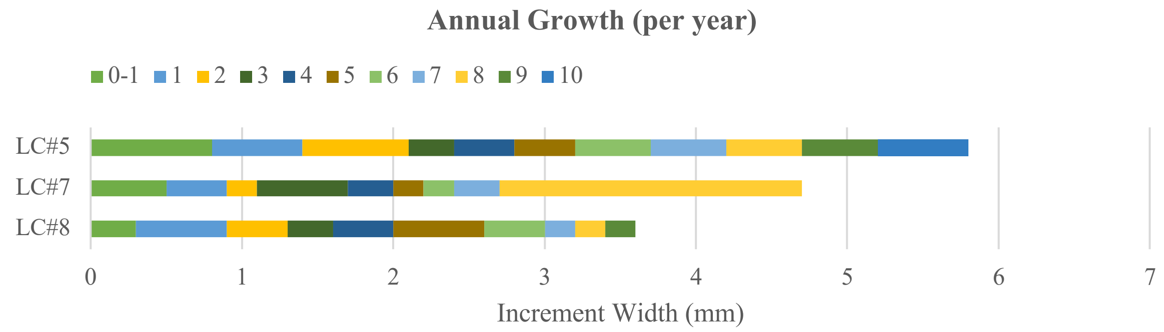


Figure 6.18 Plotted growth increment widths for live-collected Mazie Bay *Acanthopleura gemmata* in the posterior 'Right 1' section.

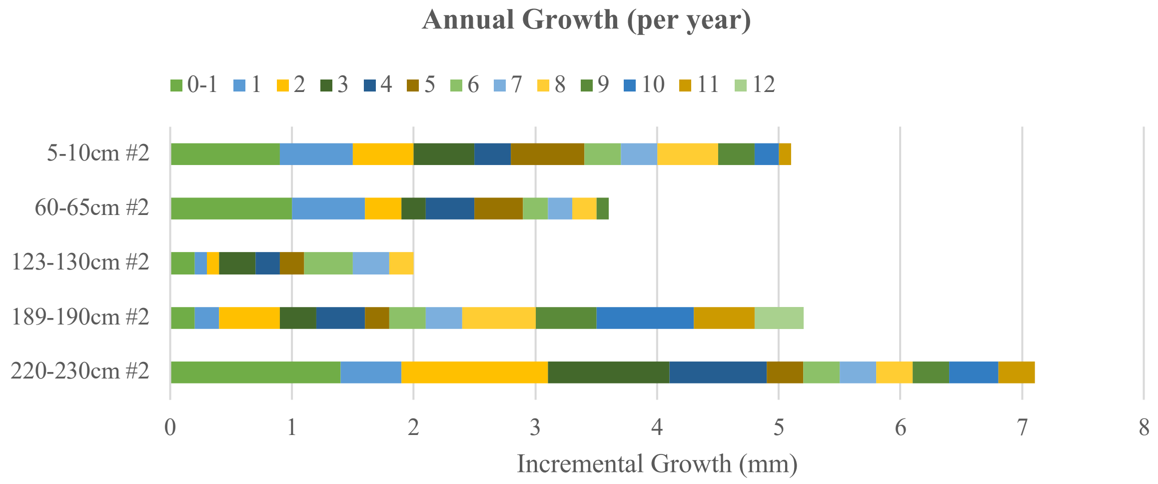


Figure 6.19 Plotted increment widths for *Acanthopleura gemmata* in the posterior 'Left 1' section, excavated from Mazie Bay.

6.5.1 Ontogenetic Age and Maximum Shell Size

Biometric results confirmed that maximum shell sizes in the deep time Mazie Bay assemblages showed some variations through time (detailed in Chapter 5). The posterior valves of *A. gemmata* samples showed a moderate degree of variation with the largest differences being present in the earliest and most recent phases of Woppaburra occupation. In the *S. cuccullata* and *L. cinerea* assemblages, shell sizes were only slightly different between phases. High variability in GI width measurements of sclerochronologically assessed samples suggests ontogenetic age should be weakly correlated with maximum shell sizes per species. Given potential sensitivities in the use of large sample sizes of deep time materials for destructive analyses, only small sample sizes could be used for sclerochronological assessments. As a result, any meaningful statistical analyses testing the relationship strengths between maximum shell sizes and estimated ontogenetic ages for each species, should not be considered conclusive. Linear regression results provided below are preliminary indications only. To increase sample sizes, modern live-collected values and cultural deep time values for each species were pooled before running each linear regression using equation (1):

$$Y = a + b(X) \tag{1}$$

Histograms and P-P plots versus residual plots indicated normally distributed data and therefore satisfied the conditions required for regression analyses. Poor predictive power between maximum shell sizes and ontogenetic ages is shown for *S. cucculata*, *L. cinerea,* and *A. gemmata*, where ≤ 58% of the relationships can be explained (Table 6.11). On a further note, variations in shell shape and growth rate per measure of time is not accounted for in these analyses which could be limiting interpretations. This point is returned to in the discussion, section 6.6. Table 6.11 presents the linear regression results for *S. cuccullata*, *L. cinerea* and *A. gemmata*. Descriptive statistics and scatter plots are provided in Appendix H.

Table 6.11 Summary of linear regression results for predicting maximum shell size with ontogenetic age estimates for *Saccostrea cuccullata* (n=14), *Lunella cinerea* (n=15) and *Acanthopleura gemmata* (n=8). The r^2 values highlighted in grey indicate weak relationships between maximum shell sizes and estimated ontogenetic ages. Note the width of the posterior valve in *Acanthopleura gemmata* is a good predictor for maximum body size and therefore used here (see Chapter 5, section 5.4.1).

	Pearson Correlation		**Linear Regression**			**ANOVA**			**Equation**
Saccostrea cuccullata (right valves)	***r***	***p***	***r^2***	***A***	***b***	***F***	**df**	***p***	
Maximum Height/Age	0.234	0.04	0.17	31.512	1.134	3.66	1	0.08	$y = (31.51)+(x*1.13)$
Lunella cinerea	***r***	***p***	***r^2***	***A***	***b***	***F***	**df**	***p***	
Maximum Length/Age	0.309	0.016	0.256	23.905	0.635	5.823	1	0.031	$y = (23.9)+(x*0.63)$
Acanthopleura gemmata (posterior valves)	***r***	***p***	***r^2***	***A***	***b***	***F***	**df**	***p***	
Posterior Width/Age	0.644	0.008	0.584	6.523	1.186	10.831	1	0.017	$y = (6.5)+(x*1.19)$

6.6 Discussion

Sclerochronology is a successful technique for observing internal growth features of *S. cuccullata*, *L. cinerea*, and *A. gemmata* shells. Ontogenetic ages and age-at-collection of modern live-collected and deep time samples was estimated by counting GL and GI features. The left and right valves of Mazie Bay *S. cuccullata* were compared, with both sides showing equivalent growth features. Due to the ease of sectioning flat right valves and avoiding use of often broken hinge areas, the right valves of *S. cuccullata* shells were used in the assessment of deep time samples. Inverted growth feature pigmentations in *S. cuccullata* was observed in some samples. In comparison, fewer modern samples showed inverted internal pigmentations to those comprising the deep time assemblage.

Exposure to heat stress or irregular flooding as noted by Andrus and Crowe (2000) are likely to be reasons for inverse representations of opaque and translucent growth features. Heat stress may be directed to molluscs from the sun or solar radiation (e.g. position of the individual in sunny versus shady positions), air or sea water temperatures (e.g. position of the individual during tidal changes or exposure to freshwater runoff), by geothermal activity (e.g. position of the animal on heated substrates such as rocks), or by reflective heat rebounded off substratum (Gizzi et al. 2016; Jones et al. 2010; Seuront et al. 2018; Vermeij 1978). In extreme cases, death can result from intense heat stress to individuals or entire populations (Jones et al. 2010). In other cases, coping mechanisms adopted to deal with extreme thermal changes in some species can be identified in the morphological traits of shell (e.g. see discussion in Vermeij 1978:26 for the growth of higher spires and/or nodules in some upper intertidal gastropods, and see also Gizzi et al. 2016 for the venus clam *Chamelea gallina*) and in the external colouration of shells (see discussions in Lindauer et al. 2018:531, and Seuront et al. 2018).

More compellingly, a study situated in Malaysia suggests that the upper thermal tolerance of *S. cuccullata* is ~43ºC and the minimum tolerance ~4.8ºC (Davenport and Wong 1992. This finding disqualifies the likelihood of sea or air temperatures being the cause of internal pigmentation inversions in Mazie Bay *S. cuccullata* shells, as air and sea temperature averages are well under ~43ºC and above ~4.8ºC (see Chapter 3, section 3.1.3). Further, *S. cuccullata* have been shown to not aerially respire (i.e. gaping only occurs during initial inundation by incoming tides) therefore avoiding internal exposure to air temperatures (Davenport and Wong 1992). Rocky substrates heated by the sun however, is how *S. cuccullata* draw in warmth and are consequently impacted during thermal extremes (Davenport and Wong 1992). Thermal alterations in the shells of deep time *S. cuccullata* samples could have arisen from stress encountered in their natural habitats (i.e. cumulative heat from rocky surfaces delivered by the sun), or from long periods of exposure to the sun at the surface of the cultural site (after shell discard events), or by the cooking of shells using dry roasting or boiling methods (see review in Chapter 4, section 4.4.3). Whether pigmentation inversions in Mazie Bay *S. cuccullata* are the product of the precipitation of light shaded GLs or resorption of pre-existing dark GLs (where organic matter and/or particular minerals might dissolve), remains to be confirmed. While heat stress is a likely cause for colour changes in shell more generally, further investigations might include examinations of internal pigmentation changes in GIs and GL more specifically.

For *L. cinerea*, we see consistency in the patterning of opaque and translucent features although sample LC#7 sample shows mixed pigmentation in the same GL (i.e. between the inner and outer shell layers). This feature has not been documented before for turbinid species and could well be, an isolated case. Further analysis is needed to reveal how and why this patterning might occur. Compellingly, opaque and translucent growth feature patterning in *A. gemmata* valves are highly consistent showing no variations between the modern live-collected and deep time samples. Perhaps the Woppaburra People had another processing method for *A. gemmata* (i.e. raw use versus dry roasting or boiling) or alternatively, the mineralogical and structural properties in the valves of this species might comprise some level of resistance to stressors (for e.g. heat) (see mineralogical properties of *A. gemmata* in Chapter 7, section 7.3). Indeed, a range of variables and taphonomic factors could have contributed to changes in the mineralogical properties and integrities of shell samples (e.g. see Oertle 2019 for taphonomic complexities in related *Saccostrea glomerata* and *Turbo setosus* shells deriving from tropical contexts).

In the Mazie Bay species assemblages, despite pigmentation variations occurring in some instances and low sample numbers available for sclerochronological analyses, ontogenetic ages could be estimated by counting GLs and GIs in each individual. Minimal differences in average age expectancies was found between modern and deep time *L. cinerea* (average collection ages are 6 years and 5 years respectively) and modern and deep time *A. gemmata* (average collection ages are 9 years and 10 years respectively). In comparison to modern samples, longer life spans for deep time *S. cuccullata* samples was found (average collection ages are 8.6 years and 10.3 years respectively). Human harvesting of *S. cuccullata* throughout deep time may have initiated longer life spans by way of creating more space on rocky substrates (i.e. lower clustering) and creating less competition to food and nutrients (Campbell 2010; Winder 2017:247-248). Alternatively, climatic and environmental conditions in deep time might have provided more favourable growing conditions. To increase insights into these factors, further examinations of these species (using a larger pool of samples) is recommended.

A very preliminary assessment of the relationship between ontogenetic ages and maximum shell sizes, indicates weak correlations in each case. Live mark and recapture experiments, measuring the rate of growth per unit of time, are required to better understand growth trends with ontogenetic age. Growth curve estimates could provide invaluable to future assessments targeting changes in population structures in either modern and deep time contexts. Nonetheless, biometric results in Chapter 5 showed *S. cuccullata* and *L. cinerea* shell sizes remained fairly consistent throughout deep time with sclerochronological results presenting a range of ontogenetic ages and increment widths. A decrease in *A. gemmata* valve sizes in the most recent phase of Woppaburra harvesting suggested decreased ontogenetic ages might be consequently detected; however, results show very little disparity in the average ages of *A. gemmata* samples between the modern and deep time assemblages. Similarities in expected ontogenetic ages between modern and deep time assemblages for *L. cinerea* and *A. gemmata*, and older ontogenetic ages expected in the deep time *S. cuccullata* assemblages does not point to population structures being drastically altered by human harvesting. Rather, these findings demonstrate dynamic and adaptive responses to socio-ecological cues perhaps coinciding with the Woppaburra seasonal resource use calendar (discussed further in Chapter 8).

Sub-annual growth features in shell sections were observed for each species however, identification of growth features representative of specific seasons and/or seasonal cyclic cues (i.e. spawning phases), was not possible. This is mainly due to the fact that despite sub-annual growth features being visible in shell sections, the season to which each growth feature might align to is not immediately obvious (and due to the scarcity of available data for the spawning schedules of each species). Indeed growth feature pigmentations and morphologies alone cannot be used as proxies for seasonal parameters. As Milner et al. (2001) note, using only visual and micrometric assessments of internal growth features to identify seasonal indices can be problematic because shell growth can vary from year-to-year and within the same season (i.e. summer, winter, autumn and spring cycles). To overcome this limitation, stable isotope testing using powdered samples extracted from internal shell growth features which might correlate with GBR seasons, is recommended. Subsequently, geochemical archives contained within the most recent periods of growth in each shell could provide more insight into seasonal harvesting patterns by the Woppaburra People.

6.7 Summary

This chapter has determined that sclerochronological applications to tropical mollusc species derived from GBR settings are indeed effective. Deep time derived *S. cuccullata*, *L. cinerea*, and *A. gemmata* samples can be used to improve the identification of life-history characteristics and profile ontogenetic ages. Moreover, sclerochronological records built using alternate areas of shell such as the posterior valve in *A. gemmata* and the right valves of *S. cuccullata*, provide strategic approaches to assessing samples recovered from deep time cultural assemblages. The next stage of analysis using stable isotopes, is imperative for refining understandings of seasonal mollusc growth and seasonal harvesting patterns adopted by the Woppaburra People. Chapter 7 details these results.

7

Stable Isotopes

7.0 Introduction

This chapter uses oxygen isotopes to calculate mid-Holocene sea surface temperature (SST) proxies and to interpret seasonal resource use patterns adopted by the Woppaburra People. First, Raman spectrometry was employed to confirm the mineralogical properties within *Saccostrea cuccullata*, *Lunella cinerea* and *Acanthopleura gemmata* shell microstructures. In addition to these examinations, Scanning Electron Microscopy (SEM) confirmed the mineralogical and crystallographic properties in *A. gemmata* valves. In all cases, shell samples showed characteristics of aragonite mineralogy. *Lunella cinerea* grow in near isotopic equilibrium with ambient SSTs and can therefore, be used to reconstruct mid-Holocene SST proxies. Edge samples taken from the apertural lips of deep time *L. cinerea* shells signals dry season harvesting of the species at Mazie Bay since the mid-Holocene. Further investigation of stable isotope and trace element values from *S. cuccullata* and *A. gemmata* samples is recommended at the end of the chapter.

7.1 Background

The sclerochronologies of live-collected and deep time Mazie Bay *S. cuccullata*, *L. cinerea*, and *A. gemmata* shells were examined in the previous chapter (Chapter 6). These analyses documented the incremental growth indices of samples through visual and metrical examination of growth features. Ontogenetic ages for each shell were estimated by counting annual growth lines (GLs) and growth increments (GIs). Sclerochronologies in Mazie Bay *S. cuccullata*, *L. cinerea*, and *A. gemmata* showed annual and sub-annual growth periods in their shell microstructures but, the measurements of increment widths demonstrated high variability in growth. Seasonal growth characteristics were suspected, based on the morphologies of growth features but could not be confirmed. This result was further complicated by a lack of spawning information available for Great Barrier Reef (GBR) populations. Consequently, the season-of-collection for each individual could not be detected.

Stable isotope analyses using powdered samples from shell GIs presents an alternative approach for isolating palaeo-seasonality parameters and for detecting long-term human harvesting trends. Consensus has it that temperate mollusc species show more defined isotopic values than tropical species due to differences in seasonal extremities (see review and examples in Twaddle 2016). Moreover, in comparison to temperate mollusc species frequenting deep-water habitats (e.g. the lifespan of *Arctica islandica* is ~500 years) (Schöne 2005b), tropical intertidal molluscs are generally short-lived. Despite these factors, GBR intertidal mollusc species could potentially be valuable biocultural markers because they have been directly accessible to humans since at least the mid-Holocene. The ecological histories of tropical intertidal species might be 'strung' together to build long time-series datasets (Schöne 2013) or used in isolation to reconstruct socio-ecological proxies at selected time intervals.

7.1.1 Sea Surface Temperatures and Climatic Oscillations

Growth of calcium carbonate ($CaCO_3$) accreting organisms in the GBR during the Holocene was encouraged by an interplay of environmental and climatic conditions (see review in Chapter 3). Although many variables are critical for ongoing reef development in general, SSTs are a major driver of faunal growth (Gosling 2015). SST is a product of solar radiation, or wavelengths of sunlight, which, at the sea's surface are absorbed by water molecules and converted to heat (Lalli and Parsons 1997:17). SST is primarily regulated by the sun, but it can also experience periods of cooling when penetrated by freshwater, during upwelling events or from wind. Sea surface salinity (SSS) refers to the amount of salt in seawater, which is formed by the evaporation of water on the sea's surface (Lalli and Parsons 1997:26). On average, the salinity of seawater is 36‰ but this can be reduced through inputs of freshwater from rainfall or by flooding from nearby creeks, rivers, dams or other freshwater sources (Hutchings 2008:5; Lalli and Parson 1997:26). Patterns in the delivery of freshwater and temperature extremes largely coincide with regional and global climatic oscillations (see review in Chapter 3, section 3.1.3) but refined details, relating to patterns experienced in each region of the GBR are debated.

Discrepancies existing for the interpretation of GBR climate trends argue for either increased or decreased SSTs, and a strengthening or weakening of precipitation rates since the mid-Holocene. Climate proxies used to interpret these trends are mostly captured from cores of massive *Porites* corals and death assemblages of *Acropora* corals from percussion cores. These records are typically analysed using a multitude of techniques: X-Ray Fluorescence (XRF), radiocarbon dating, and trace element analysis. Most studies apply interpretations on millennial or decadal timescales and use climate oscillation characteristics to define and describe conditions. Studies situated in the central and southern GBR reef regions generally agree that mid-Holocene SSTs were not too dissimilar to current conditions, but that precipitation rates were higher than present day (Leonard et al. 2016; Lough et al. 2014; Rodriguez-Ramirez et al. 2014, but see also Sadler et al. 2016 suggesting cooler SSTs by 2.76ºC-1.31ºC compared to modern times). Although, an earlier study by Gagan et al. (1998) proposed warmer SSTs were 1ºC warmer in the GBR during the period ~6500 BP – 5500 BP. Roche et al. (2014) support the argument of SSTs being 1ºC warmer in the northern GBR by 4500 BP.

Fluctuations in the Pacific Decadal Oscillation (PDO), the interannual El Niño- Southern Oscillation (ENSO) and La Niña cycles are offered as likely candidates for driving changes in coral reef growth. Associated temperature and precipitation patterns are speculated to have contributed to periods of slowed reef growth in the GBR from ~5500 BP; after which time, a region-wide reef growth hiatus period is suggested to have occurred at ~3500 BP (Perry and Smithers 2011; and see Leonard et al. 2016; Leonard et al. 2020a; Roche et al. 2014). In the northern GBR region, Roche et al. (2014) observe no great difference in SSTs between the mid-Holocene (since ~4700 BP) and modern times but do argue for more varied precipitation events. They identify the mid-Holocene experienced a greater salinity range due to the Australian-Indonesian Summer Monsoon (AISM) but make no commitment to arguing for strengthened or weakened precipitation trends. At Palm Island in the central GBR, Leonard et al. (2016) identify reef growth hiatus periods at ~5500 BP and 4600 BP but do not consider these events to have been ENSO driven (see also Smithers et al. 2006 and Perry and Smithers 2011).

Another study located in the central GBR by Lough et al. (2014) suspect changes to the growth of massive *Porites* corals were influenced by the intraseasonal Madden-Julian Oscillation (MJO), which has longer-lasting but 'lower intensity' rainfall. The MJO is an eastward 'moving pulse of cloud and rainfall … that typically recurs every 30-60 days' (BoM 2020; and see Suppiah 1992:302; Wheeler et al. 2009). Despite the MJO being suspected as a key driver of change within the study location, high-resolution data needed to examine temperature and salinity values from the skeletal properties of *Porites* corals is currently lacking. Nonetheless, Lough et al. (2014) assume the MJO could have been responsible for the delivery of less extreme freshwater influxes from adjacent mainland river catchments during the mid-Holocene. Scenarios for changes occurring within inshore Keppel Bay Island reefs have recently been targeted by Leonard et al. (2020a, 2020b) for further assessments.

After reef stabilisation at 5500 BP in the Keppel Bay Island group, Leonard et al. (2020a 2020b) explain inshore coral reefs prograded seaward. The suspected regional coral reef growth hiatus period at 3500 BP cannot be confirmed for the area. In fact, coral accretion data for Middle Island and Halfway Island show acceleration in reef growth at 3500 BP rather than deacceleration (see map in Chapter 3, Figure 3.2) (Leonard et al. 2020a). At Mazie Bay Leonard et al. (2020b) describe that an 'active shallow reef flat' was present between ~5600 BP and 5400 BP that underwent progradation between 4000 BP and 1500 BP. During the period spanning 1500 BP to 400 BP, reef growth was slow and then stopped altogether (Leonard et al. 2020b). This hiatus period was in response 'to limited accommodation space once the reef had reached the extent of the embayment' (Leonard et al. 2020a:10).

Preliminary analyses of coral accretion rates, derived from several Keppel Bay Island percussion cores, points to a range of variables likely contributing to periods of reef stability and instability since the mid-Holocene. Indeed, specific localised conditions in each reef patch must not be discounted for identifying the timing and nature of changes (Leonard et al. 2020a, 2020b). Flood plume events and run-off from the Fitzroy and Burdekin Rivers, that discharges into the southern GBR lagoon at 19.6 Mt yr^{-}, is coincidental with the formation of adjacent mainland sand dunes and mid-Holocene ENSO events (Brooke et al. 2008; Rodriguez-Ramirez et al. (2014). Leonard et al. (2020a, 2020b) discuss the potential relationship between changes deriving from the Fitzroy River and coral reef growth; however, high-resolution biogeochemical data from these assemblages has not yet been reported. The shortcoming is therefore, a limitation in assessing variables possibly operating within and between seasons, which might have contributed to changes in both human and ecological communities (Roche et al. 2014).

Calcium carbonate accreting organisms can be used to collect high-resolution data to inform these types of questions; however, the collection of these data requires techniques such as stable isotope analysis that are time-consuming, destructive, and expensive (see example the comparison to coral core XRF in Ellis et al. 2019). Particularly in regions that are considered to experience less extreme seasonal variations, high-resolution data are critical for pinpointing the timing of when and under what conditions, changes occurred (see example in Ellis et al. 2019). Analysis can become challenging when considering how variables affect taxa habitats, their behaviours and consequently their growth. Some microhabitats can experience cases of isolated effects where a variable or sets of variables might manifest in a different way to spatially larger or deeper habitats. Sadler et al. (2016) provide an example of isolated SST affects in shallow versus deep-water habitats where corals are often derived for climate analyses. They caution coral samples exposed to shallow 'ponded' reef environments versus deeper reef environments could lead to a misinterpretation of when regional thermal maximums occurred. This scenario is also likely to emerge in shallow intertidal mollusc habitats.

7.1.2 Thermal Changes and 'Micro-Climates' in Intertidal Habitats

Poikilothermic species that live in littoral-intertidal benthic habitats and where there is enough light to support life (euphotic zone <150m), experience the highest temperature and salinity fluctuations (Jell and Flood 1978; Lalli and Parsons 1997:21, 25, 197). Seawater temperatures in these habitats are the warmest given their typically shallow depth (Lalli and Parsons 1997:22). Other physical factors such as periods of aerial exposure between tides, or isolation of waters in tidal rock-pools causing ponding - a micro-climate effect, can contribute to heightened temperatures (Sadler et al. 2014:294 for coral ponding). To survive within these conditions, some nerite species for example, employ osmoregulation strategies by grouping together to cope with heightened thermal periods between tidal cycles (Eichhorst 2016). Rock oysters, such as *S. cuccullata*, being affixed to rocky substrates, have no refuge from full sun exposure unless situated in crevices, under overhangs, located in shady positions or protected with cloud cover (pers. obs. at Mazie Bay 2018). The relationship between behavioural traits (i.e. movement) and microclimate effects in *L. cinerea* that occupy GBR intertidal zones is not clear. At Mazie Bay, *L.*

cinerea were observed in part of the intertidal zone that was exposed to high turbidity, but the length of time or effect of aerial exposure/heat stress to each individual is not known. *Acanthopleura gemmata* migrate vertically to 'home scars' at the rise of high tides to avoid inundation (see Barbosa et al. 2008). Seawater might fill *A. gemmata* home scars which are situated in either full sun or part-shade (pers. obs. at Mazie Bay, 2018). Thermal and physiological stress in calcium accreting organisms may, in extreme cases, result in 'bleaching' which reduces the overall fitness of an individual and might even cause death (e.g. see discussion in Leonard et al. 2020a).

Some research has shown thermal and physiological stress on oyster species (*S. cuccullata*, *Crassostrea belcheri* and *C. iradelei*; see Davenport and Wong 1992), turbinid species (e.g. *Turbo militaris* and *Lunella undulata*; and see Lah et al. 2017), and species of chiton (e.g. *Acanthopleura granulata*; see Schill et al. 2002). Sclerochronology data provided in the previous chapter showed highly varied incremental widths across each of these species. These variations might coincide with responses to thermal changes specific to individual microhabitat conditions or be reflective of physiological responses to other variables (e.g. salinity changes, access to food or nutrients). Despite these complications, an important aim of the following analysis is to understand if seasonal temperature trends can be extracted from the shell microstructures of GBR *S. cuccullata*, *L. cinerea* and *A. gemmata*. An initial step in calibrating stable isotope values from mollusc shells is to first identify their mineralogical compositions. For some species, shell mineralogy may or may not vary with exposure to different temperatures, despite their geographic or microhabitat locations (see examples in the below review).

7.2 Microstructures and Mineralogies of Mollusc Shells

This section begins with a review of previous work detailing the mineralogy and microstructural properties of the relevant families, Ostreidae, Turbinidae and Chitonidae. It finds examination of chiton shell valves to be extremely limited and subsequently calls for a preliminary SEM analysis of Mazie Bay *A. gemmata* shell valves. Raman spectrometry results are provided for *S. cuccullata*, *L. cinerea*, and *A. gemmata* to confirm mineralogies. Orientational terms for describing shell mineralogy and microstructures follow Carter (1990) and Carter et al. (2012). Figure 4.1 in Chapter 4 can be consulted for the biomineralisation process in molluscs. Anatomical diagrams of Ostreidae, Turbinidae and Chitonidae can be consulted in Chapter 5 (Figures 5.4, 5.6, and 5.7).

Saccostrea cuccullata

One of the earliest summaries of *S. cuccullata* (formerly known as *Ostrea cuccullata*) shell microstructures is provided in Taylor et al. (1969:106-109). Their assessment of the left and right valves of a Seychelles *S. cuccullata* sample comprised both calcite and aragonite mineralogy, although other key differences were shown to exist between the left and right valves. They determined that while the pallial myostracum (a thin internal line extending from the hinge, through the adductor muscle scar and to the ventral margin) in the left and right valves is aragonitic, but the adductor muscle scar area in the right valve is prismatic aragonite (Taylor et al. 1969; and see Suzuki and Nagasawa 2013:353). In the right valve, the myostracal line serves as a visual aid to identify the area of shell comprising incremental growth features (see previous Chapter 6), and is alternately layered with sheaths of foliated calcite and fibrous calcite or 'chalk' (note foliated calcite and chalk layers also occur in the left valve, see Taylor et al. 1969, Checa et al. 2018 and references within). Chalk is defined as being porous, disordered, and mechanically weak (see examination of *Magallana angulata* valves in Checa et al. 2018 for comprehensive review on chalk growth) but it has a similar structure to that of the foliated layers and is argued to have identical isotopic properties (see *Crassostrea gigas* in Ullmann et al. 2013).

Observation by Checa et al. (2018) note that chalk is more abundant in valves with more irregular surfaces. Perhaps this coincides with Taylor et al.'s (1969) observation that the left valve, which rests directly on rocky substrates, has higher concentrations of chalk between foliated layers. A final observation is that cavities, sometimes appearing between foliated and chalk layers, are unrelated to chalk growth (Checa et al. 2018, and see discussion in Vermeij 2014). Instead, observation of these cavities by Taylor et al. (1969) indicates that they appear more prevalent in the left valves and can be described as pockets comprised of organic materials, bacteria, seawater, folic acids, or other debris. Cavities containing foreign particulates or seawater can result in dissolution (see Chapter 4, section 4.4.3 for review on dissolution). No examination attests to this quality (i.e. cavities) being present in other mollusc species that grow affixed to substrates. My review has also failed to find an example of cavities forming in mobile intertidal molluscs, including members of the families Turbinidae and Chitonidae.

Lunella cinerea

Many gastropods comprise nacre or mother-of-pearl microstructural properties in their shells (see Checa 2018:8, Marin et al. 2008:222, Susuki and Nagasawa 2013-352-353). Species in family Turbinidae are no exception, with tropical species comprising a nacreous aragonite inner shell layer and prismatic aragonite outer shell layer (Carter 1990; Szabó 2008; Watabe 1988:74). Although aragonitic structures are well known in turbinids, the mineralogy and microstructure of *L. cinerea* has not been described. A related species from the south west coast of Australia, *Lunella torquatus* (formerly known as *Turbo torquata*), was found to have a composite mineralogical structure which differed between local sites with an overall temperate climate trend (Roger et al. 2018). In Rottnest Island and Marmion Lagoon *L. torquatus* samples, Roger et al. (2018) identify that aragonitic mineralogy dominates the inner and outer shell layers; but, in Hamelin Bay *L. torquatus* shells, calcite is the primary mineral of the prismatic layer. Recrystallisation of aragonite-to-calcite transformation, which we might expect of shells exposed to intense heat (e.g. cooking on fires) can be discounted as these samples were live-collected and assessed accordingly (see Milano and Nehrke 2018 for discussion on aragonite-to-calcite transformations in *Phorcus turbinatus* shells; and see also Oertle 2019). Rather, environmental conditions likely influenced aragonite-to-calcite ratios in the species via ocean currents or infiltration of trace elements (i.e. Sr and Mg), and SSTs (Roger et al. 2018).

Roger et al. (2018) note that differences as low as 1ºC can influence aragonite-to-calcite ratios in shell. A cautionary approach to changed environmental conditions influencing shell mineralogy between localities and over the long-term is therefore a reasonable consideration. That said, long-term unchanged trends in shell mineralogy, derived from samples at the same locale and reflective of thermal conditions, should not be discounted. For instance, Sato et al. (2020) found aragonite-to-calcite ratios in western Pacific vent and seep limpets differed between local sites (dependant on environmental conditions), but that aragonite-to-calcite ratios remained unchanged in these species at each locale since the Cretaceous period. Indeed, unchanged mineralogical properties are often described for 'primitive' molluscs such as those in the family Chitonidae.

Acanthopleura gemmata

Although chitons are broadly defined as having all-aragonite mineralogy within their shell structures, mineralogical and crystallographic properties within *A. gemmata* shell valves have never been described (see review in Peebles et al. 2017 for various other species). Chiton radulae, girdle spicules and ocelli or shell-eye pockets have received the most attention in this field of study (see for e.g. Brooker and Shaw 2012; Speiser et al. 2011; Weaver et al. 2010). Despite limited attempts examining chiton shell valves (<3% of all species) they are noted to have complex microstructural layers (Peebles et al. 2017). SEM was therefore employed to undertake a preliminary examination of the mineralogical and microstructural properties of GBR *A. gemmata* shell valves.

7.2.1 Scanning Electron Microscopy: *Acanthopleura gemmata*

SEM analyses was undertaken at the Ramaciotti Centre for Cryo Electron Microscopy, Monash University. Dr Simon Crawford provided technical assistance for the preparation and imaging of samples on an A Nova NanoSEM 450 (2kV, spot size 2) instrument. The middle articulamentum layer of *A. gemmata* valves was given priority in this analysis as this area of shell comprises incremental growth features most suitable for isotope subsampling (i.e. noted as L1, L2, R1, R2 in the sclerochronological analyses, see previous Chapter 6, section 6.4.3). A preliminary examination of mineralogical and microstructural properties in a modern intermediate *A. gemmata* valve sample was investigated before methods were applied to deep time samples. Details of these results are provided below. Supplementary details and additional micrographs can be consulted in Appendix I.

Acanthopleura gemmata – sample #E4

Sample #E4 is an intermediate *A. gemmata* valve that was live-collected from Mazie Bay in 2018. A mallet was used to fracture the shell valve in order to observe the internal microstructure (Figure 7.1). The sample was then etched in hydrochloric acid (HCI) for 5 minutes before being rinsed in freshwater and dried in an 80ºC oven for 5 minutes. After the pre-treatment process was completed, the sample was mounted onto a slide and painted with carbon resin. Three major layers were observable with the SEM but only micrograph F shows rod-type crossed lamellar aragonite crystals.

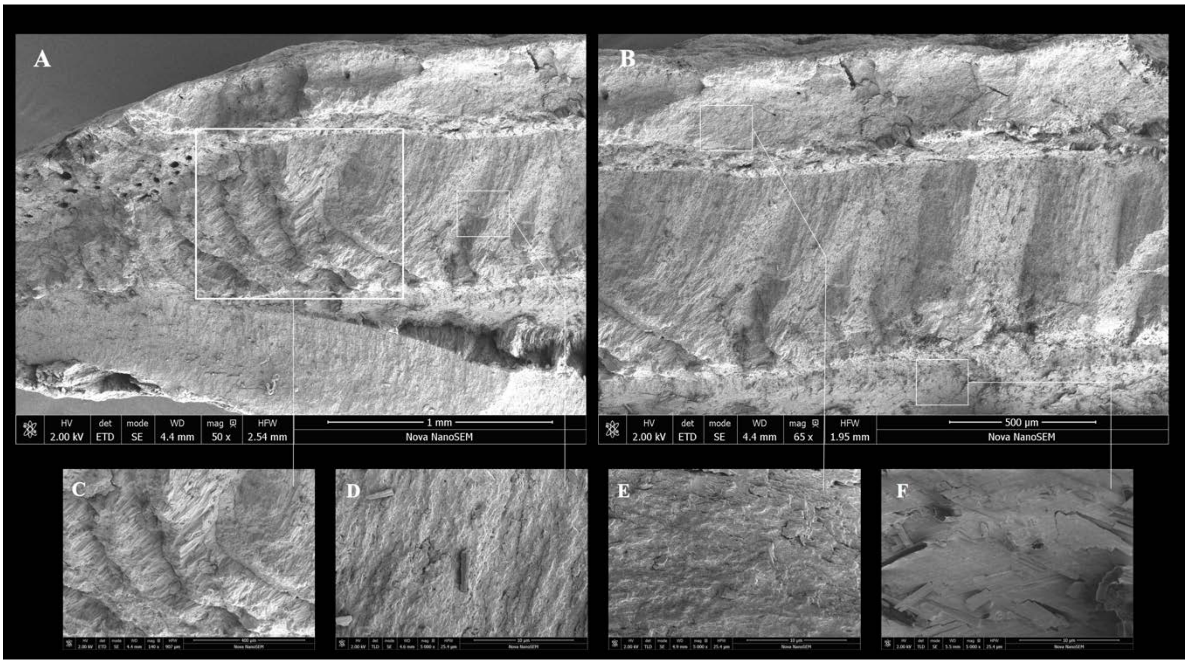


Figure 7.1 Examples of Scanning Electron Microscope (SEM) micrographs for *Acanthopleura gemmata* sample #E4. A) section of shell showing the top tegmentum layer, the middle articulamentum layer, and the bottom sublayer, note aesthete channels in the tegmentum on the top left, magnification x 50 scale = 1 mm; B) section of shell showing the tegmentum, articulamentum, and bottom sublayer, crystal structure not detected, magnification x 65 scale = 500 µm; C) the articulamentum, crystal structure not detected, magnification x 5000 scale = 400 µm; D) the articulamentum, crystal structure not detected, magnification x 5000 scale = 10 µm; E) the tegmentum, crystal structure not detected, magnification x 5000 scale = 10 µm. F) the bottom sublayer, rod-type crossed lamellar aragonite crystals, magnification x 5000 scale = 10 µm.

Deep time samples - 5-10cm#2 and 220-230cm#2

Two terminal posterior valves, 5-10cm#2 and 220-230cm#2, recovered from the deep time cultural site at Mazie Bay were analysed for mineralogical and crystallographic properties. Both samples were previously stained in Mutvei's solution and polished using 3 grits for the sclerochronological analysis. No further pre-treatments were applied before the SEM micrographs were captured. To ensure adequate imaging could take place, the samples were sputter coated in gold 300 nanometers thick for 3-4 minutes using a BAL-TEC SCD 005. Adobe Photoshop CC.2-.0.1 was used to stitch a series of micrographs for each sample (sample 5-10cm#2 see Figure 7.2 micrograph A, and sample 220-230cm#2 see Figure 7.3

micrograph A). The mineralogical composition in the articulamentum layers of both posterior *A. gemmata* valves comprises aragonite. Articulamentum microstructures are crossed lamellar but appear to have some diagenetic alteration of unknown cause. Secondary cementation of calcium polymorphs could not be identified.

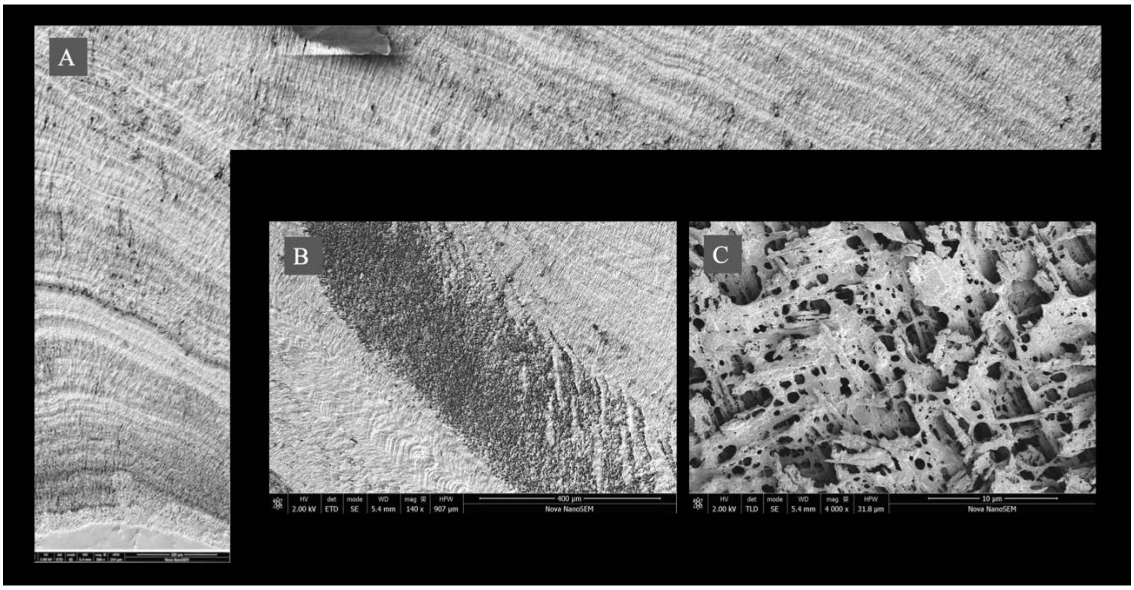


Figure 7.2 Scanning electron microscope micrographs of *Acanthopleura gemmata* 5-10cm#2 posterior.
A) articulamentum shell layer showing annual and sub-annual growth lines, magnification x 500 scale = 100 µm; B) articulamentum shell layer, magnification x 140 scale = 400 µm; C) articulamentum shell layer showing crossed lamellar aragonite, magnification x 4000 scale = 10 µm.

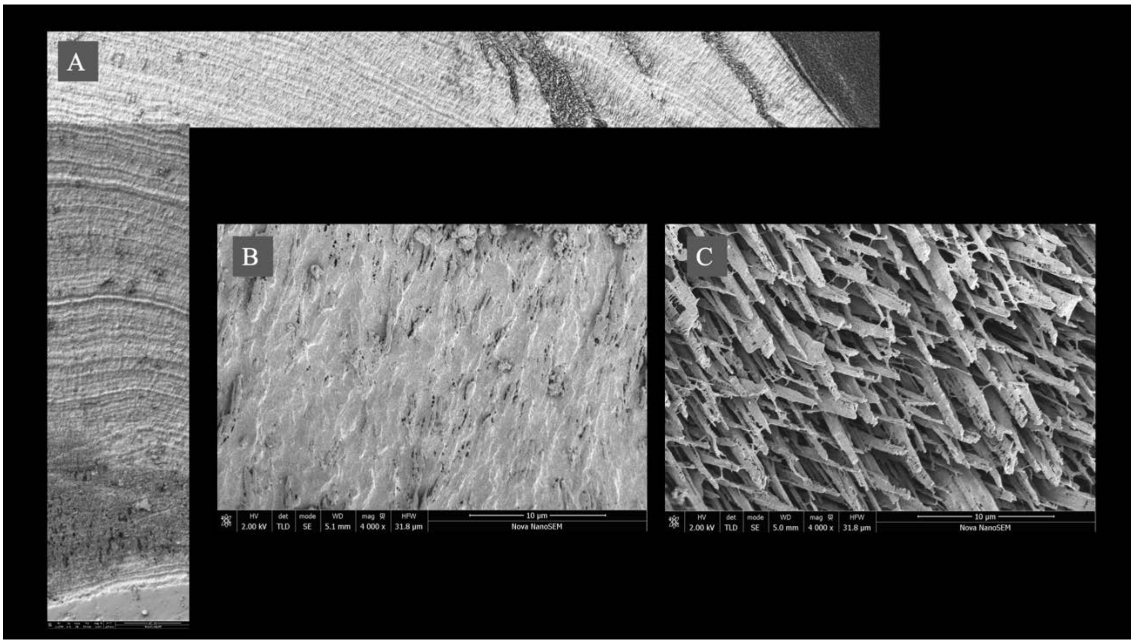


Figure 7.3 Scanning electron microscope micrographs of *Acanthopleura gemmata* 220-230cm#2 posterior.
A) articulamentum layer showing annual and sub-annual growth lines, magnification x 500 scale = 100 µm; B) tegmentum layer, magnification x 4000 scale = 10 µm; C) articulamentum layer showing crossed lamellar aragonite, magnification x 4000 scale = 10 µm.

The articulamentum layer, which comprises growth features (GLs and GIs) and which is of interest for isotope subsampling, can be defined as comprising crossed lamellar aragonite. These results broadly coincide with findings for other Chitonidae reported by Peebles et al. (2017) and for *Acanthopleura granulata* in Carter (1990). More work is recommended for recording differences in the mineralogical properties between the terminal and intermediate valves in *A. gemmata*.

7.2.2 Raman Spectroscopy

Raman spectroscopy analyses were undertaken by Dr Amy Prendergast at the University of Melbourne. A Renishaw Raman 532 nanometer laser wavelength, with a 400 µm confocal hole, a grating width of 1800 grooves/mm, an entrance slit width of 100 µm and 50× long-distance objective lens, was used to carry out each analysis on unstained shell-sections (i.e. the alternate side to the Mutvei's stained sections used in the sclerochronological analyses). Data were acquired with a time interval of 10 seconds, with 3 (or sometimes 4) accumulations per sample and plotted accordingly. Silicon standards were run prior to each session. Typical for materials within the spectra of aragonite, are peaks between 1000cm^{-1} and 1100cm^{-1} and sometimes small peaks at ~700cm^{-1}. Smaller internal peaks have previously been identified in 8 chiton species at ~700cm^{-1} (see Peebles et al. 2017:254). Raman spectra results for the following analyses were interpreted by making comparisons with the findings appearing in DeCarlo (2018), Peebles et al. (2017), and Urmos et al. (1991).

Saccostrea cucullata

The inner shell area consisting of GIs in the right valves of *S. cuccullata* were targeted for analysis in modern live-collected shells. Modes showed the highest peaks for each sample between 1000cm^{-1} and 1100cm^{-1} with small peaks existing at 300cm^{-1}, illustrating aragonite mineralogy. Sample LC#2 showed an additional small internal peak at 700cm^{-1} (Figure 7.4 and see Appendix J). Signs of diagenesis or recrystallisation are not apparent and therefore samples are treated as unaltered. Due to restricted access to laboratory facilities (i.e. during COVID-19), the mineralogical properties in deep time *S. cuccullata* shells could not be confirmed.

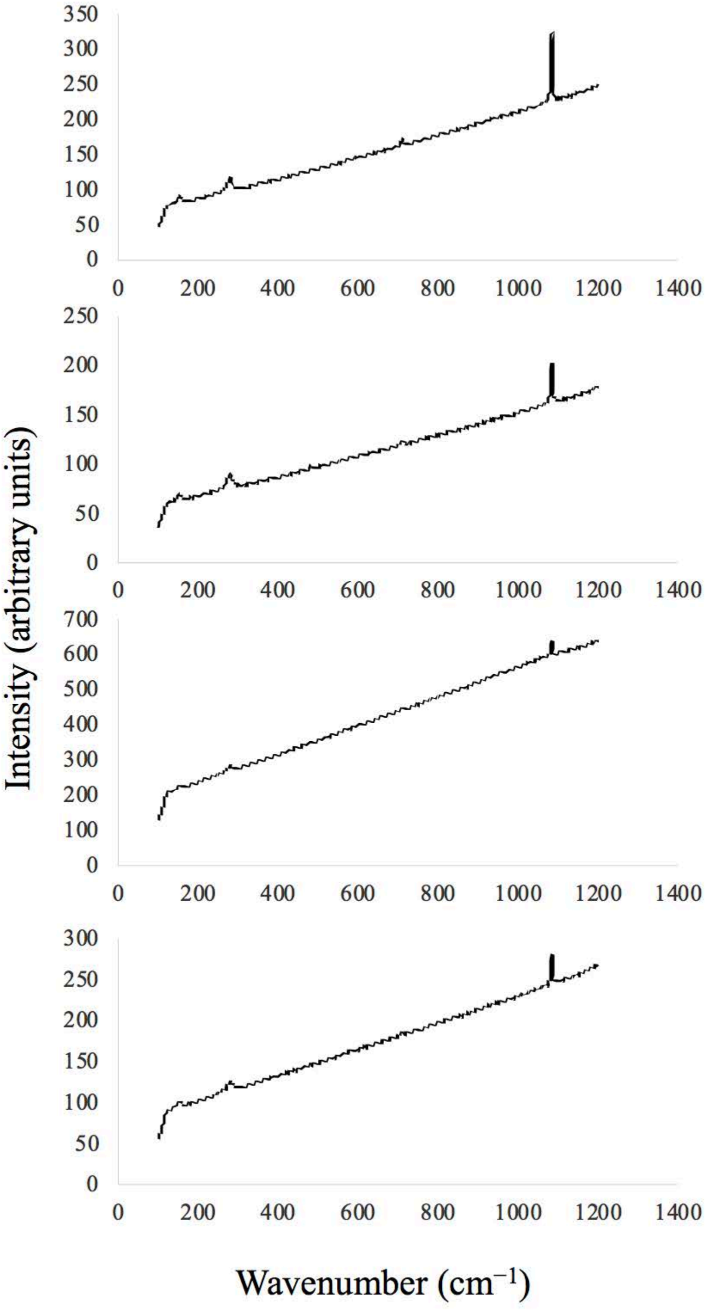


Figure 7.4 Raman spectra of live-collected *Saccostrea cuccullata* sample LC#2, showing aragonite mineralogy in the annual growth increment region of the right valve.

Lunella cinerea

The inner and outer shell layers in modern and a deep time *L. cinerea* samples were targeted for analyses. In all samples, a peak was evident between 1000cm^{-1} and 1100cm^{-1} in both the inner and outer shell layers, and is characteristic of aragonite mineralogy. Small peaks are present at 200cm^{-1} (Figure 7.5 and see Appendix J). Signs of recrystallisation in the deep time samples was tested for during the radiocarbon dating analyses (reported in Chapter 5, section 5.5.1) and were subsequently treated as unaltered.

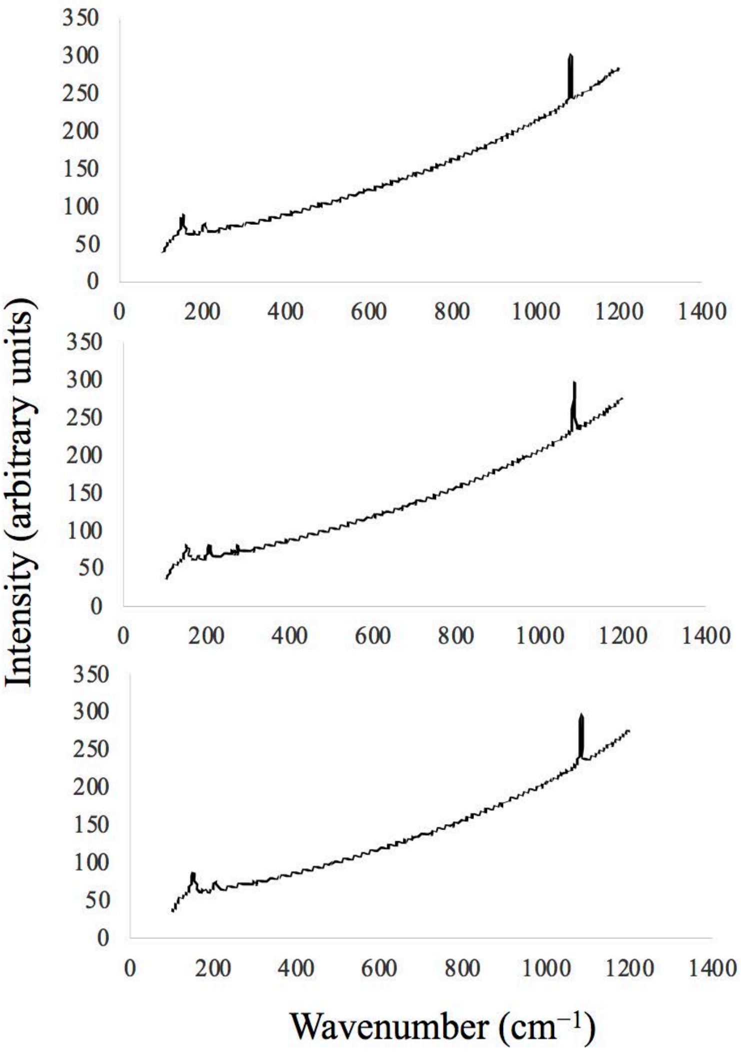


Figure 7.5 Raman spectra of live-collected *Lunella cinerea* sample LC#5, showing aragonite mineralogy in the inner shell layer.

Acanthopleura gemmata

The areas of the posterior and anterior shell valves of *A. gemmata* were targeted for analysis. Both modern and deep time samples were assessed in the articulamentum areas. Modes for the articulamentum areas of the anterior and posterior valves showed peaks between 1000cm^{-1} and 1100cm^{-1}, with very small peaks present at 700cm^{-1} (Figure 7.6 and see Appendix J). These peaks are consistent with aragonitic mineralogy which agrees well with the SEM results detailed above. Signs of diagenesis or recrystallisation are not apparent and therefore samples are treated as unaltered.

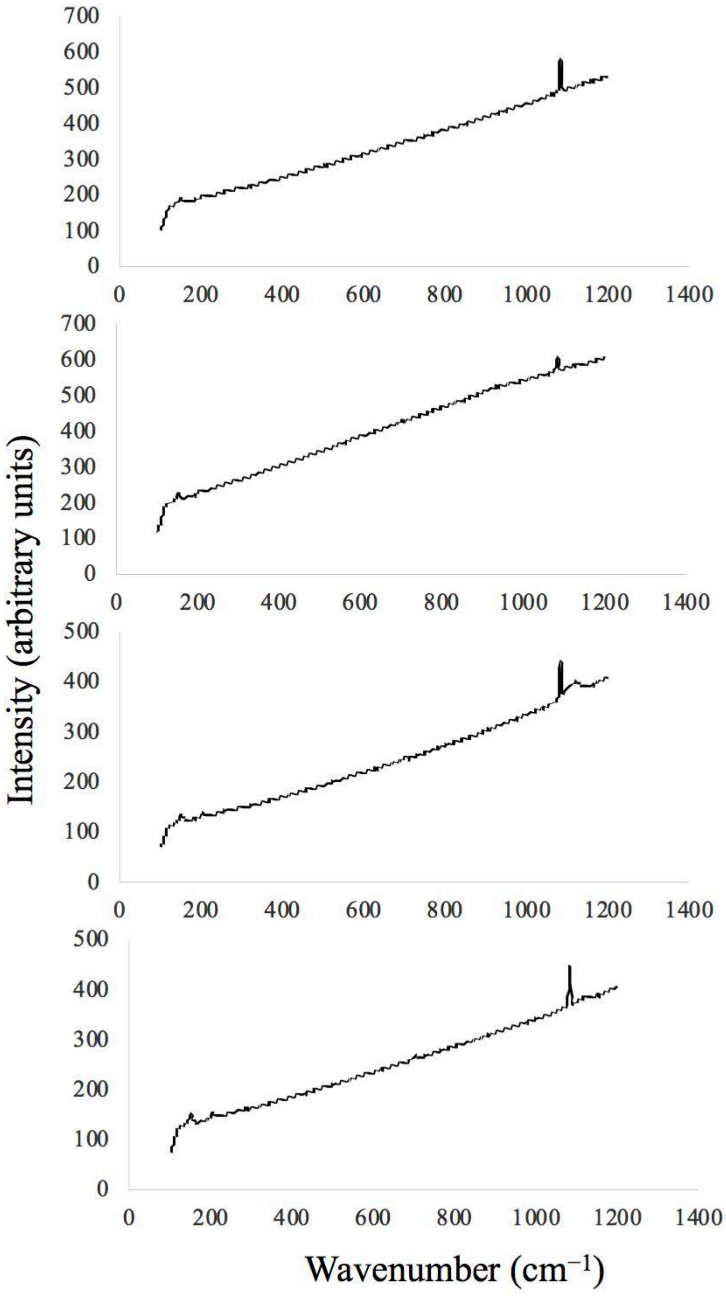


Figure 7.6 Raman spectra of a posterior *Acanthopleura gemmata* deep time sample 180-190cm#1, showing aragonite mineralogy in the articulamentum area.

Summary

Raman spectra analyses of all species samples indicate aragonite mineralogy. The mineralogical properties of deep time *S. cuccullata* shells is assumed to comprise of aragonite although future examinations are required for confirmation. In the following sections, stable isotope values are calibrated using an aragonite equation for calculating SSTs and compared with modern instrumental SST data for the Mazie Bay area.

7.3 Instrumental Datasets from the Keppel Bay Islands

Working on the assumption that mollusc shells recovered from the Mazie Bay cultural resource use site were collected from the immediate intertidal zone, SST data extracted from local modern instruments were used to interpolate mid-Holocene SST values in this study. Due to timing and accessibility constraints to Mazie Bay during different seasons, seawater samples were not collected. There are 4 Cooperative Research Centre (CRC) Great Barrier Reef Marine Park-Australian Institute of Marine Science (GBRMPA-AIMS) *in situ* Odyssey Temperature Loggers (OTS) deployed in the Mazie Bay lagoon. The OTS collect day-time and night-time readings which capture sub-hourly SST data within the lagoon at different depths (0m, ~5m, ~6m and~8m). Large gaps are present in each dataset posing difficulties for calculating annual and monthly averages. Moreover, despite consistency in logger calendar date and time between each logger, it is likely that SST values collected from different depth intervals show fluctuating results (see Sadler et al. 2014). Therefore, it is assumed that logger data >5m depth would not provide accurate SST values for conditions present in shallow intertidal mollusc habitats (i.e. species depth ranges in this study are restricted to ~0-5m). Satellite data on the other hand, only provide values from the sea's surface (Sadler et al. 2014) which is where, in this case, the mollusc species under investigation mostly reside.

Night-time SST values recorded once per calendar night by the CRC GBRMPA-AIMS satellite were used in these analyses. These data were taken within a ~4km radius over the Keppel Bay Island area which includes Mazie Bay. Data captured by the satellite over a 34-year window between the years 1985 and 2018 were used to calculate monthly and annual averages. The area is exposed to ~12 hours sunlight per day - sunrise varies between 05:00-06:30hrs and sunset between 17:15-18:30hrs depending on the season (Geoscience Australia 2020). As the mollusc species under investigation do not frequent subsurface water depths ~>5m, SST satellite data did not require recalibrating for bulk SST estimates (i.e. satellite data do not record subsurface temperature values, see Sadler et al. 2014:299). Due to inconsistencies in the OTS logger data, comparisons between monthly and annual averages were not possible. Annual (24ºC), monthly (range: 19.9-27.6ºC), and seasonal (wet season 27.1ºC, dry season 22.4ºC) SST averages calculated from night-time satellite readings between 1985 and 2018 are similar to other modern predictions made for the broader region (see Lough 2007). Table 7.1 presents average SSTs recorded for annual, monthly and seasonal intervals using night-time satellite data (and see Figures 7.7, 7.8, 7.9 and 7.10).

Table 7.1 Sea surface temperature averages at annual, monthly and seasonal intervals, between 1985 and 2018, for the Mazie Bay area (data source, AIMS 2019).

Interval Type	Interval	Average SST (ºC)
Annual	34-year average	24.0
Monthly	January	27.4
	February	27.6
	March	26.7
	April	25.2
	May	23.2
	June	21.2
	July	19.9
	August	20.0
	September	21.5
	October	23.4
	November	25.1
	December	26.6
Seasonal	Summer	27.2
	Autumn	25.0
	Winter	20.4
	Spring	23.3
Seasonal	Wet	27.1
	Dry	22.4

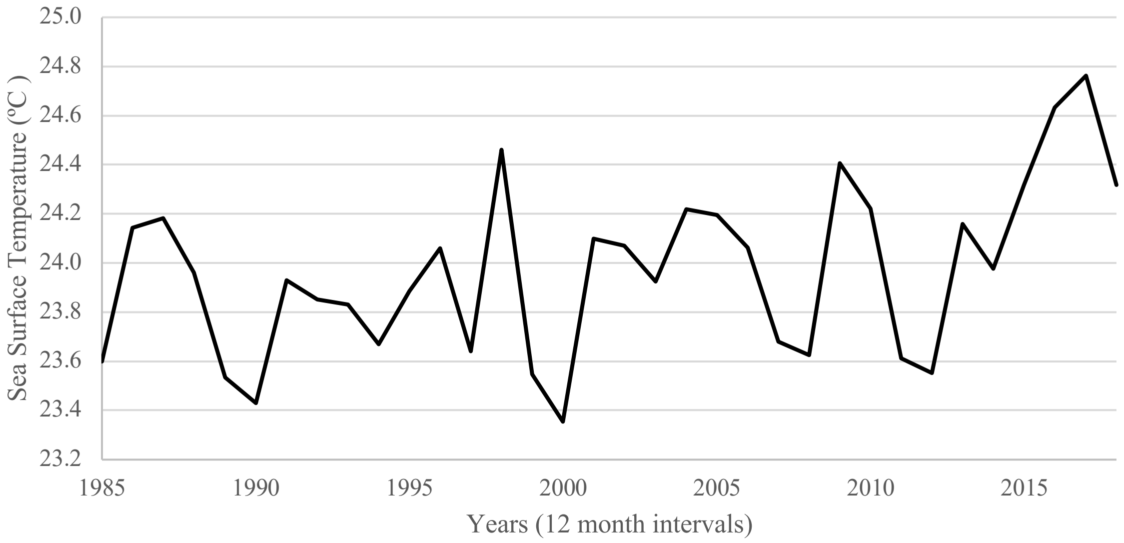


Figure 7.7 Annual sea surface temperature trends (1985-2018), Mazie Bay area (data source, AIMS 2019).

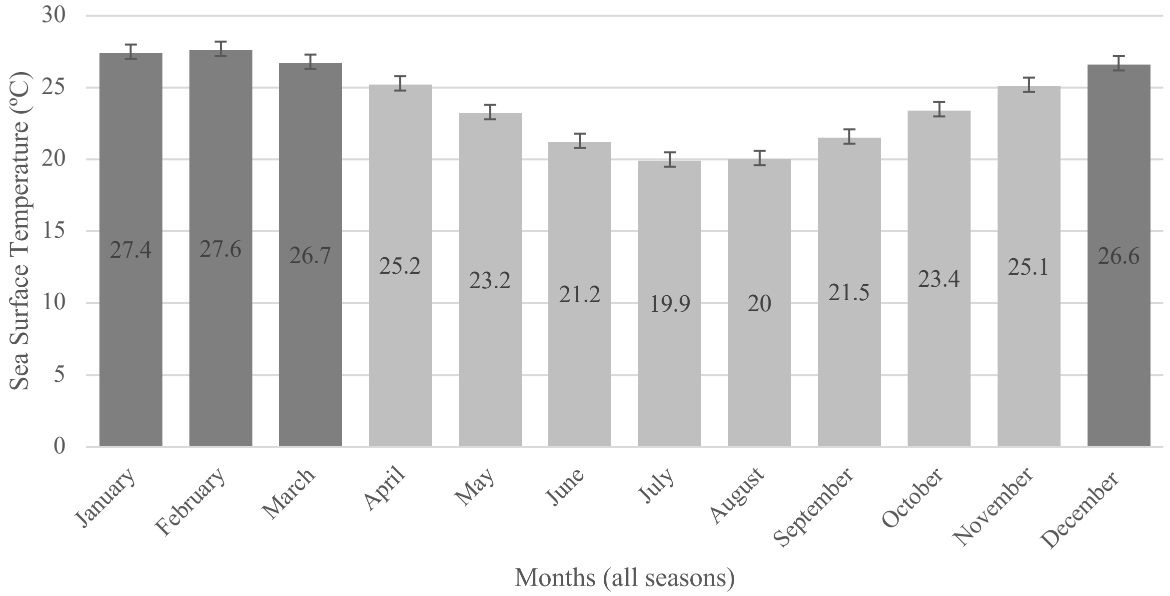


Figure 7.8 Monthly sea surface temperature averages (1985-2018), Mazie Bay area. Error bars represent standard deviations (all months ±0.5ºC) (data source, AIMS 2019).

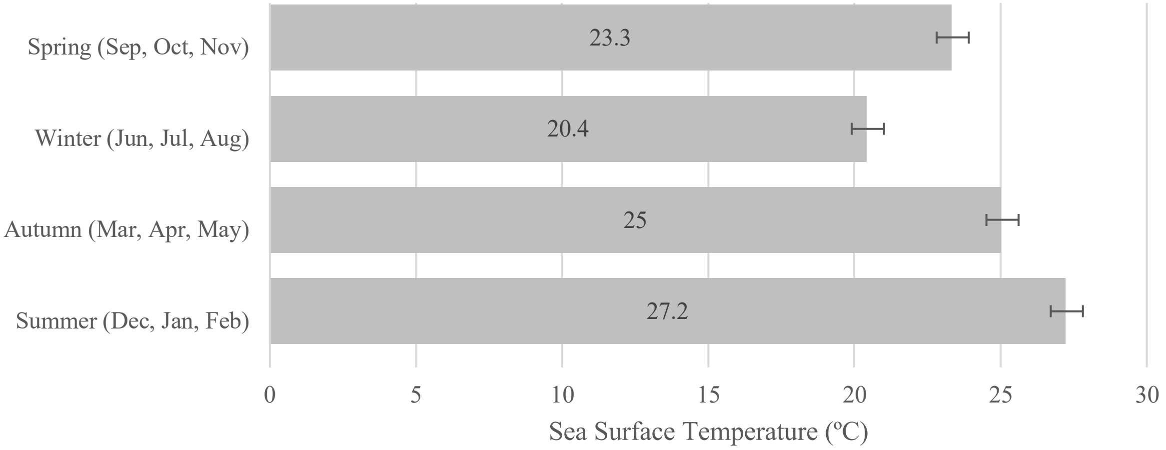


Figure 7.9 Seasonal sea surface temperature averages (1985-2018), Mazie Bay area. Error bars represent standard deviations (spring ±0.5 ºC, winter ±0.5ºC, autumn ±0.5ºC, summer ±0.6ºC) (data source, AIMS 2019).

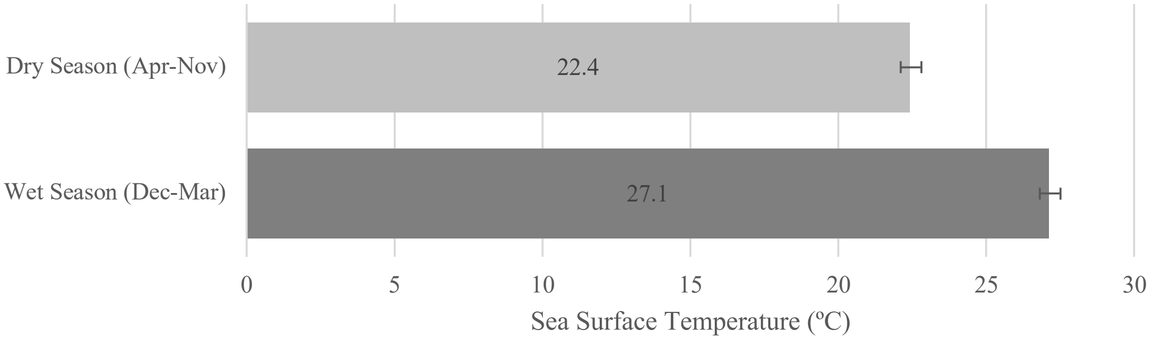


Figure 7.10 Wet and dry season sea surface temperature averages (1985-2018), Mazie Bay area. Error bars represent standard deviations (dry season ±0.3ºC, wet season ±0.4ºC) (data source, AIMS 2019).

A note on seasonality

The following assessments identify annual and sub-annual mollusc shell growing periods and Woppaburra resource use scheduling trends. An important objective of this research is to communicate findings through a common frame-of-reference suitable to practitioners working within the resource management and heritage spheres (see Figure 7.11). However, applying appropriate statistical tests to biogeochemistry data according to the 7 overlapping seasonal changes in the Woppaburra seasonal resource use calendar is challenging. This is because Woppaburra seasonal changes and resource use scheduling is based on climatic, environmental, cosmological and spiritual understandings. A translation of the Woppaburra seasons which best resemble the 12 months included in the Western Gregorian calendar year is available (see Chapter 3, Table 3.1). I therefore approach each case by isolating stable isotope data into wet and dry season analogies and the 4 temperate seasons defined in the Western Gregorian Calendar (summer, winter, autumn and spring) to explain when key changes are occur. Chapter 8 discusses the results using the seasons defined in the Woppaburra seasonal resource use calendar at length.

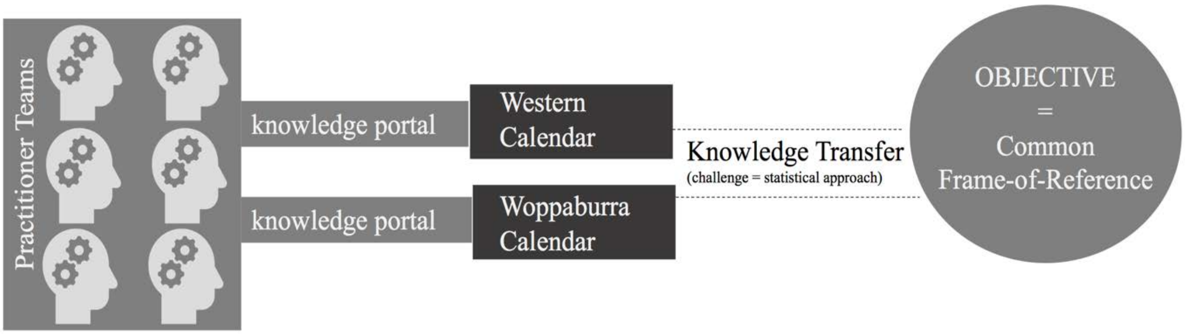


Figure 7.11 Knowledge transfer approach for directing biogeochemistry data into a common frame-of-reference.

7.4 Stable Isotope Analyses

Oxygen isotope ratios from shell powder samples were obtained from the GIs of each shell-section using a Rexim Minmo (1mm bit and 0.6mm bit) microdrill mounted under a binocular microscope (detailed below). Powdered carbonate samples were weighed to the nearest µg using a micro balance, placed into sterile exetainer vials and sealed. Samples >400 µg were analysed in an Analytical Precision AP2003 Mass Spectrometer. An automated MultiPrep device was used to inject and flush each exetainer with helium gas. Orthophosphoric acid, 0.5-1mg of 100%, was hand-injected using a syringe and then left to react with the sample at 70ºC for 30 minutes. The remaining CO_2 gas was analysed against in-house standards NEW-1 and NEW-12, and international standard NBS-18. All stable isotope results are reported using the delta (δ) notation and in units per mil (‰) relative to Vienna Pee Dee Belemnite (VPDB) where:

$\delta = 1000 * (R\ sample - R\ standard) / R$
$R\ oxygen = {}^{18}O / {}^{16}O$
$R\ carbon = {}^{13}C / {}^{12}C$

Average reproducibility for samples run on the AP2003 Mass Spectrometer is 0.11‰ for oxygen and 0.07‰ for carbon. For samples weighing <400µg, a Nu Perspective dual inlet isotope ratio mass spectrometer (DI-IRMS) connected to a NuCarb carbonate preparation system was used. Calibrations using in-house and international standards, NBS-18 and NBS-19, are better than 0.05‰ and 0.1‰ (1σ) for $\delta^{13}C$ and $\delta^{18}O$ respectively.

The Grossman and Ku (1986) equation was used to predict SSTs from the $\delta^{18}O$ values in shell samples. A thermometry function for biogenic aragonite adjusted to factor a correction conversion from VSMOW to VPDB by Dettman et al. (1999) was also used. An $\delta^{18}O$ sea water value for Mazie Bay is currently unknown and therefore, this value was kept at 0‰ in equation (1):

$$SST^{o}C = 20.6 - 4.34\,(\delta^{18}O_{shell}\,(VPDB) - (\delta^{18}O_{water\ (VSMOW)} - 0.27)) \tag{1}$$

The following results are therefore treated as an estimate and future work should incorporate a measured $\delta^{18}O$ sea water values collected directly from Mazie Bay and on a seasonal basis ($\delta^{18}O$ sea water data could not be collected from Mazie Bay due to financial constraints owing to fieldwork costs). Note: seawater $\delta^{18}O$ is not known for Mazie Bay therefore, results are not directly comparable with modern SSTs. The following analyses are suggestive only.

Sample Preparation and Resolution

Unstained shell-sections of *S. cuccullata*, *L. cinerea* and *A. gemmata*, were used for isotopic analyses. Sample preparation of unstained shell-sections and live-collection data for samples obtained from Mazie Bay in September 2018 can be consulted in Chapter 6. *Lunella cinerea* shells were utilised to extract full life-history growth records and season-of-collection indices for individuals. Long-sequence drilling enabled complete *L. cinerea* lifespans to be analysed (i.e. drill holes extended from the growing edge at the apertural lip and along length of the entire body whorl with ~2mm spacing between each powder sample). Short-sequence drilling (i.e. 5 drill holes from the edge of the apertural lip and back along the body whorl with ~2mm spacing between each powder sample) enabled the season-of-collection to be determined. Full life-history records for all deep time samples were not possible due to time and budget constraints. The same approach was adopted for *S. cuccullata* and *A. gemmata* samples, however due to sub-annual growth features being tightly spaced (i.e. sometimes <1mm wide), only powder samples averaged across entire annual GIs was possible. Due to the tight incremental layering of growth features in each section, powder samples were extracted using a 'milling' technique whereby each GI was carved away from each growing edge.

Contamination was avoided in each sample by firstly removing shell areas posing risk with a sterile drill. For example, organic outer shell layers which had traces of microboring organisms or lodged sediments were removed. For *S. cuccullata* 'chalk' was removed between each GI (despite previously reported isotope ratios between chalk and nacre being equivalent - see section 7.3 above); for *A. gemmata* GLs were removed (believed to have a slightly higher organic content than GIs in the articulamentum layer, see discussion in Peebles et al. 2017); and for *L. cinerea* a thin layer (~0.1mm) on the inner edge of the body whorl was light abraded to free samples of grit. In addition, at the time of sampling *S. cuccullata* samples 130-135cm#1 and 220-230cm#1, clear separation between GIs and GLs were apparent. It cannot be assumed if separation between these features occurred pre- or post-mortem. It did appear however, that they did not resemble 'cavities' as described above - complete sheets of shell were almost evenly separated along entire growth axes. Sheets of shell from each GI were carefully extracted by hand with a pair of tweezers and ground to a fine powder in an agate mortar and pestle.

From the deep time assemblage, an example of each species was selected from 5 successive excavation units (XUs) (i.e. from the bottom of the cultural deposit to the top). For consistency with terminology adopted in Chapter 6, I refer to disturbance anomalies as disturbance lines or DLs. When referring to the outer notches in *L. cinerea* shells, the term DL is used even though an outer notch will not always be associated with a GL.

7.4.1 δ^{18}O Stable Isotope Results, *Saccostrea cuccullata*

Live-Collected *Saccostrea cuccullata*

Oxygen isotope values from (n=3) live-collected *S. cuccullata* individuals were examined. Powder samples were taken from the GI widths of each shell sample at annual resolutions (Figure 7.12 and Table 7.2). Descriptive statistics and plotted δ^{18}O values show a high degree of variability between and within each individual (Table 7.3 and Figure 7.13). Two anomalies appear in LC#6 (δ^{18}O 0.58‰ and δ^{18}O 4.43‰) at sample sites 1 and 5 which correspond to the years 2018 and 2014 respectively. Apart from these anomalies, all δ^{18}O values are negative, indicating that each year shell was mostly precipitated during periods of lower salinity (i.e. either through rainfall or infiltration from other freshwater or brackish influences). This finding indicates high growth during the wet season. Using equation (1), live-collected *S. cuccullata* δ^{18}O values were then used to calculate predicted annual SST averages. Total offsets between instrumental SST averages and predicted SST averages are provided in Table 7.4, descriptive statistics in Table 7.5 and plotted values in Figures 7.14, 7.15 and 7.16.

Using equation (2), linear regressions were run to test the relationship strength between annually averaged instrumental SSTs and predicted annual SSTs.

$$Y = a + b(X) \qquad (2)$$

Histograms and P-P plots versus residual plots indicated normally distributed data and therefore satisfied the conditions required for regression analyses. Poor predictive power between instrumental SSTs and predicted SSTs were found where ≤ 47% of the variations can be explained (Table 7.6 and see Appendix K for scatter plots).

Figure 7.12 A) Live-collected *Saccostrea cucullata* example LC#2. B) Showing the annual growth increment areas milled for obtaining long-sequence $\delta^{18}O$ powder samples. Note grey outline is the epoxy resin.

Table 7.2 $\delta^{18}O$ values for live-collected *Saccostrea cucccullata* samples.

Year	$\delta^{18}O_{shell}$ ‰ LC#2	$\delta^{18}O_{shell}$ ‰ LC#4	$\delta^{18}O_{shell}$ ‰ LC#6
2018	-0.39	-1.04	0.58
2017	-1.28	-0.98	-0.89
2016	-0.72	-1.05	-1.02
2015	-0.19	-1.61	-0.10
2014	-0.35	-0.97	4.43
2013	-1.29	-1.32	-0.81
2012		-0.87	-0.11
2011		-1.22	-0.11
2010		-1.28	-0.15
2009		-1.67	
2008		-1.41	
2007		-1.39	
2006		-1.36	
2005		-1.70	
2004		-2.81	

Table 7.3 Descriptive statistics for live-collected *Saccostrea cuccullata* δ18O values. Edges = combined site 1 descriptive statistics.

				δ^{18}Oshell ‰			
Sample	**n=**	**Mean**	**Median**	**SD**	**Range**	**Min**	**Max**
Edges	3	-0.28	-0.39	0.81	1.62	-1.04	0.58
LC#2	6	-0.7	-0.55	0.48	1.1	-1.29	-0.19
LC#4	15	-1.37	-1.32	0.47	1.94	-2.81	-0.87
LC#6	9	0.2	-0.11	1.66	5.45	-1.02	4.43

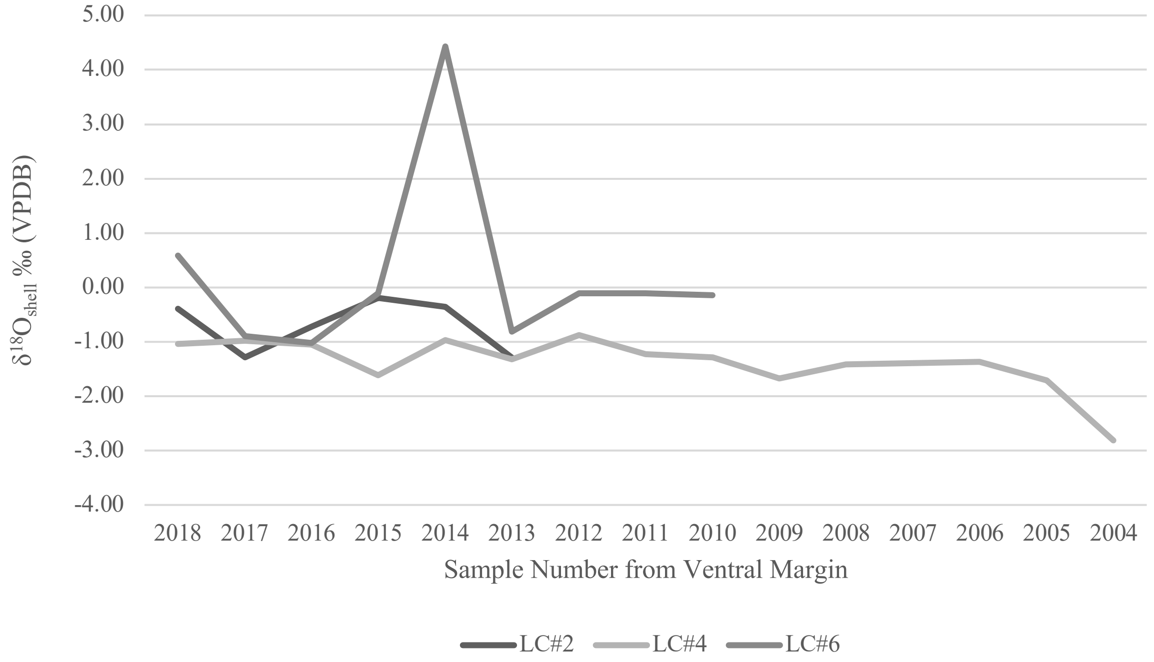


Figure 7.13 Plotted δ^{18}O values, live-collected *Saccostrea cuccullata* samples LC#2 (n=6), LC#4 (n=15), LC#6 (n=9) per year of growth.

Table 7.4 Offsets between annual instrumental sea surface temperatures and predicted annual sea surface temperatures from live-collected δ^{18}O *Saccostrea cuccullata* samples. Note LC#6 years 2018 and 2014 anomalies are not included and marked with an x.

Year	Inst. SST (ºC)	Pred. SST (ºC)				Offset SST (ºC)		
		LC#2	LC#4	LC#6		LC#2	LC#4	LC#6
2018	24.3	21.1	23.9	x		+3.2	+0.4	x
2017	24.8	25	23.7	23.3		-0.2	+1.1	+1.5
2016	24.6	22.6	24	23.9		+2	+0.6	+0.7
2015	24.3	20.3	26.4	19.9		+4	-2.1	+4.4
2014	24	21	23.6	x		+3	+0.4	x
2013	24.2	25	25.2	22.9		-0.8	-1	+1.3
2012	23.6		23.2	19.9			+0.4	+3.7
2011	23.6		24.7	19.9			-1.1	+3.7
2010	24.2		25	20.1			-0.8	+4.1
2009	24.4		26.7				-2.3	
2008	23.6		25.6				-2	
2007	23.7		25.5				-1.8	
2006	24		25.3				-1.3	
2005	24.2		26.8				-2.6	
2004	24.2		31.6				-7.4	
					Total Offset SST (ºC)	**1.9**	**-1.3**	**2.8**

Table 7.5 Descriptive statistics for annual instrumental sea surface temperatures and predicted sea surface temperatures from live-collected *Saccostrea cuccullata* δ^{18}O values.

			Pred. SST (ºC)				
Sample	**n=**	**Mean**	**Median**	**SD**	**Range**	**Min**	**Max**
Inst. SSTs (2018-2004)	15	24.1	24.2	0.36	1.2	23.6	24.8
Pred. SSTs LC#2	6	22.5	21.85	2.07	4.7	20.3	25
Pred. SSTs LC#4	15	25.4	25.2	2	8.4	23.2	31.6
Pred. SSTs LC#6	7	21.4	20.1	1.85	4	19.9	23.9

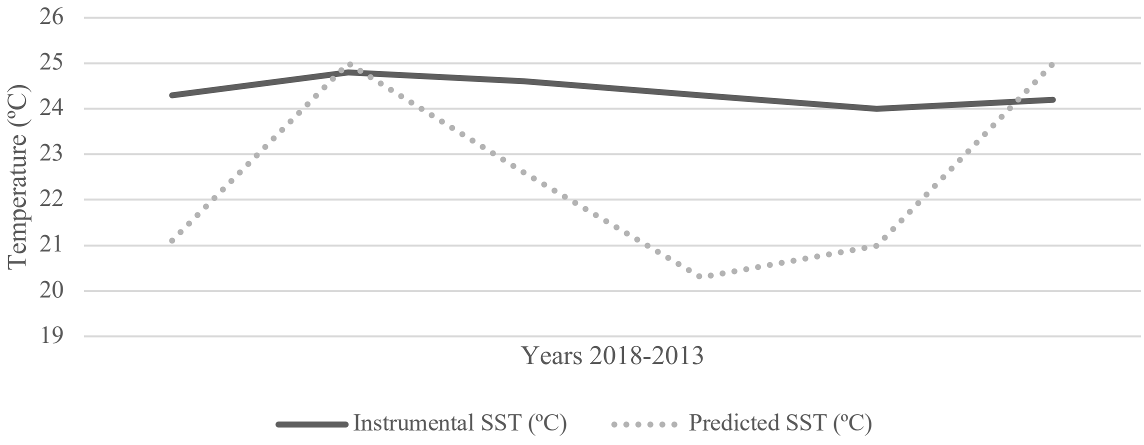


Figure 7.14 Plotted annual instrumental sea surface temperatures and predicted annual sea surface temperatures for *Saccostrea cuccullata*, LC#2 (n=6).

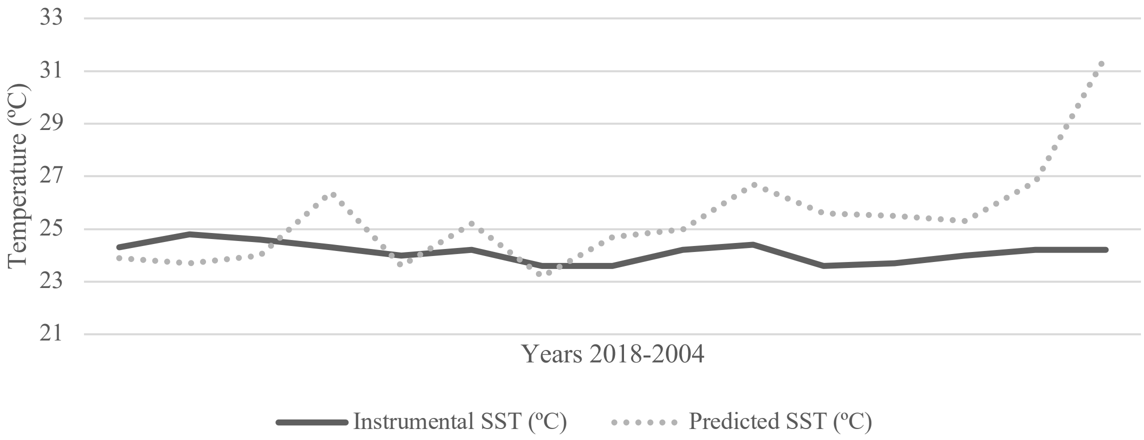


Figure 7.15 Plotted annual instrumental sea surface temperatures and predicted annual sea surface temperatures for *Saccostrea cuccullata*, LC#4 (n=15).

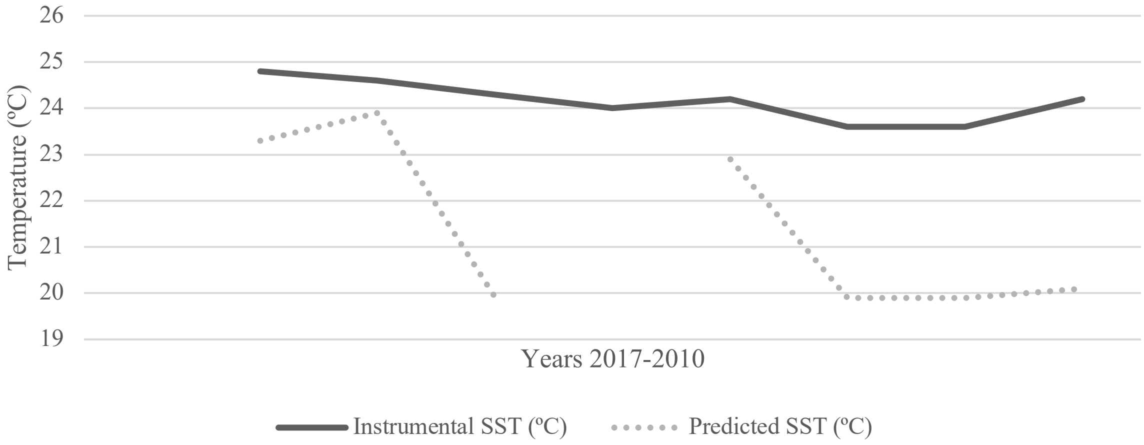


Figure 7.16 Plotted annual instrumental sea surface temperatures and predicted annual sea surface temperatures for *Saccostrea cuccullata*, LC#6 (n=9). Note: year 2018 and year 2014 predicted sea surface temperature anomalies are not represented.

Table 7.6 Summary of linear regression results for instrumental sea surface temperatures versus predicted sea surface temperatures, live-collected *Saccostrea cuccullata*.

	Pearson Correlation		Linear Regression			ANOVA			Equation
Sample/Years (n=)	***r***	***p***	r^2	***A***	***b***	***F***	**df**	***p***	
LC#2 2018-2013 (n=6)	0.246	0.159	0.057	22.822	0.069	1.304	1	0.317	$y = (22.82)+(x*0.07)$
	r	***p***	r^2	***A***	***b***	***F***	**df**	***p***	
LC#4 2018-2004 (n=15)	0.003	0.42	-0.073	23.856	0.01	0.042	1	0.841	$y = (23.86)+(x*0.01)$
	r	***p***	r^2	***A***	***b***	***F***	**df**	***p***	
LC#6 2017- (n=7 not incl. x)	0.560	0.026	0.472	20.235	0.185	6.371	1	0.053	$y = (20.23)+(x*0.18)$
LC#6 2018- (n=9 incl. x)	0.091	0.215	-0.039	23.866	0.017	0.7	1	0.43	$y = (23.87)+(x*0.02)$

Deep Time *Saccostrea cuccullata*

Predicted annual SSTs for deep time *S. cuccullata* (n=5) were calculated from annually averaged δ^{18}O values taken from GI widths. Similar to the live-collected *S. cuccullata* δ^{18}O values, deep time *S. cuccullata* δ^{18}O values are mostly negative, indicating that shells were predominantly precipitated during periods of lower salinity. Descriptive statistics and δ^{18}O values for each sample can be consulted in Appendix K. Sample 5-10cm#1 has the lowest predicted SST mean (17.8ºC) and sample 220-130cm#1 has the highest predicted SST mean (22.7ºC). Samples 60-65cm#1, 130-135cm#1, and 190-200cm#1 show consistency in predicted SST means (20.7ºC-20.8ºC) (Table 7.7). Figure 7.17 presents a box and whisker plot using predicted SSTs for *S. cuccullata* samples.

Table 7.7 Descriptive statistics for predicted annual sea surface temperatures from deep time *Saccostrea cuccullata* δ^{18}O values.

		Pred. SST (ºC)					
Sample	**n=**	**Mean**	**Median**	**SD**	**Range**	**Min**	**Max**
Edges	5	19.9	19.6	1.9	5.2	17.9	23.1
Pred. SSTs 5-10cm#1	4	17.8	17.3	1.6	3.6	16.5	20.1
Pred. SSTs 60-65cm#1	8	20.7	19.8	2.8	7.2	17.7	25
Pred. SSTs 130-135cm#1	15	20.7	20.6	2.3	6.6	17.4	24.1
Pred. SSTs 190-200cm#1	6	20.8	20.7	1.2	2.8	19.4	22.2
Pred. SSTs 220-230cm#1	8	22.7	22.2	2.2	5.8	20.1	25.9

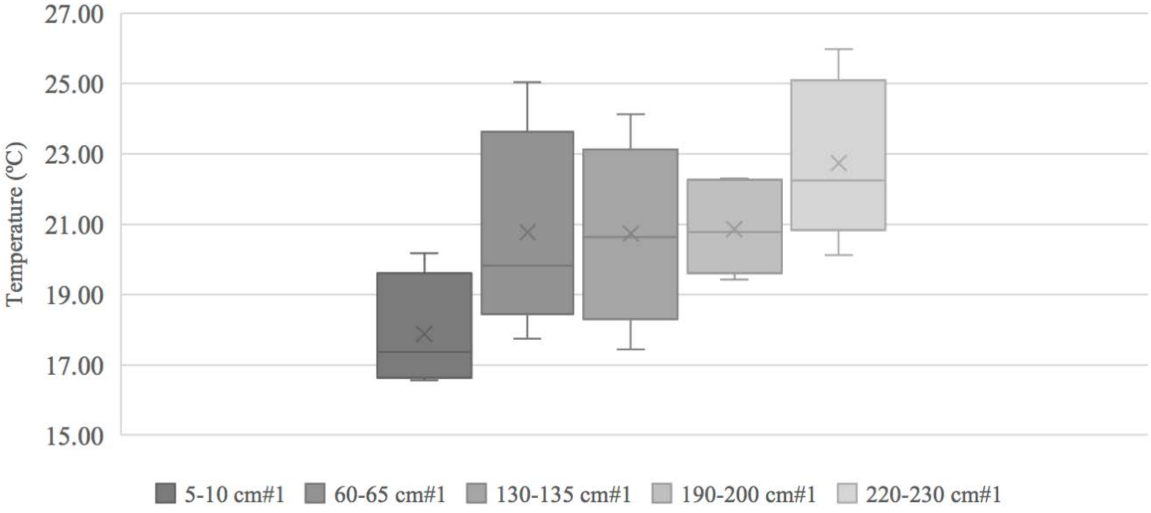


Figure 7.17 Box and whisker plot of deep time *Saccostrea cuccullata* predicted annual sea surface temperatures from $\delta^{18}O$ values, samples 5-10cm#1 (n=4), 60-65cm#1 (n=8), 130-135cm#1 (n=15), 190-200cm#1 (n=6), 220-230cm#1 (n=8).

7.4.2 $\delta^{18}O$ Stable Isotope Results, *Lunella cinerea*

Live-collected *Lunella cinerea*

Oxygen isotope values from (n=3) live-collected *L. cinerea* individuals were examined. Long-sequence $\delta^{18}O$ powder samples were collected for samples LC#3 and LC#4, and short-sequence $\delta^{18}O$ powder samples from LC#5 (Figure 7.18 and Table 7.8). Analyses of *L. cinerea* individuals are based on sub-annual resolutions. Slight variability in $\delta^{18}O$ values exist between LC#3 and LC#4 (means = LC#3 -0.53‰ and LC#4 -0.58‰; range = LC#3 2.73‰ and LC#4 2.06‰). Variability in $\delta^{18}O$ values exist between LC#5 and, LC#3 and LC#4 (mean = -0.37‰, range = 0.52‰). A single anomaly in LC#3 ($\delta^{18}O$ -1.62‰), appears at sample site 1 (year 2018) where, at the time of drilling the powder sample, the tip of the apertural lip broke. For consistency, this sample (LC#3 $\delta^{18}O$ -1.62‰, site 1) is included in the descriptive statistics (Table 7.9) and plotted in Figure 7.19 but excluded in all other analyses.

When *L. cinerea* $\delta^{18}O$ values are plotted, a ‘saw tooth’ pattern reveals distinctly warmer temperatures and cooler temperatures over the life-history of each individual (Figure 7.19). It can be concluded that the highest rate of growth in *L. cinerea* occurs during the wet season. These periods of shell growth show consistently low (negative) $\delta^{18}O$ values meaning that shell is precipitated during periods of lower salinity. High (positive) $\delta^{18}O$ values appear at dry season intervals which correlate with annual GLs. In samples LC#3 and LC#4 double GLs appear at life-stage intervals within their shell microstructures. Interpretation of this finding is challenging without measuring shell growth rates and microstructural patterning in live-specimens (i.e. *in situ* life-cycle measurements using live individuals). It does appear, however, that double GLs might indicate a period of spawning which is observed to appear after 2 years of age (see example Figure 7.18 for LC#3, and sample LC#4 in Appendix K). LC#3 show disturbance anomalies or 'DLs', which are observed as notches or grooves in the outer layer of the shell. Corresponding δ^{18}O values taken from the adjacent inner shell layer of LC#3 show low (negative) values equivalent to cool SST temperatures. This point is returned to below.

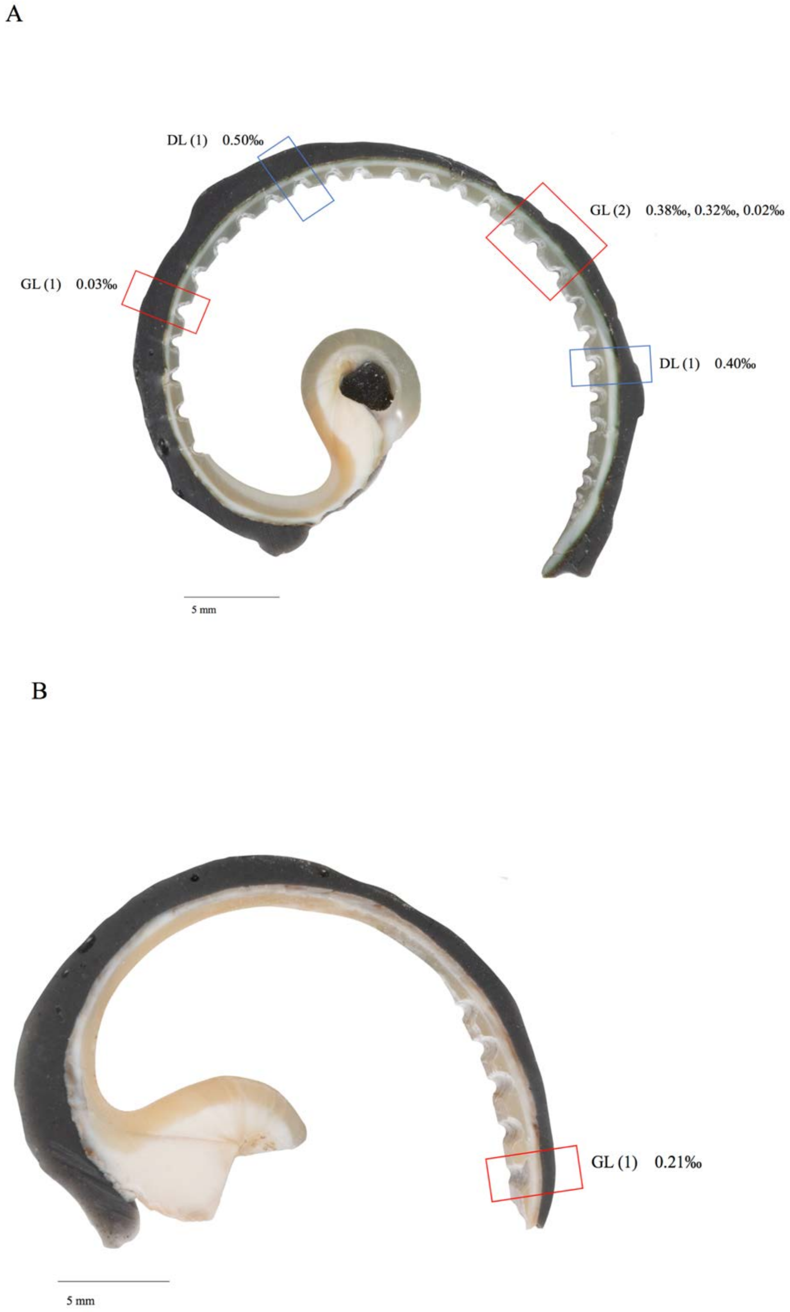


Figure 7.18 A) Example of a long-sequence drilled live-collected *Lunella cinerea* shell, LC#3. B) Example of a short-sequence drilled deep time *Lunella cinerea* shell 55-60cm#1. Note grey outline is the epoxy resin. GL = growth line, DL = disturbance line or notch, corresponding isotope value in corresponding feature areas (1 = one GL or DL, 2 = two GLs or DLs).

Table 7.8 $\delta^{18}O$ values of live-collected *Lunella cinerea*.

	$\delta^{18}O_{shell}$ ‰		
Year	**LC#3**	**LC#4**	**LC#5**
2018 (edge)	-1.62	-0.46	-0.50
	-0.96	-0.30	-0.67
	-0.88	-0.53	-0.38
	-0.32	-0.66	-0.16
	-0.90	-0.81	-0.15
	-0.68	0.09	
	-0.69	0.89	
	0.40	-0.94	
	-0.19	-0.67	
	1.10	-0.41	
	0.38	-0.79	
	0.32	-0.80	
	0.02	-1.09	
	-1.63	-1.08	
	-0.21	0.04	
	-0.19	-0.98	
	-0.79	-0.98	
	-1.13	-1.17	
	-1.57	-0.95	
	0.50	-0.98	
	-0.57	0.31	
	-0.19	-0.51	
	-1.58		
	-0.96		
	0.03		
	-0.28		
	-0.41		
	-1.17		
	-1.48		

Table 7.9 Descriptive statistics for live-collected *Lunella cinerea* $\delta^{18}O$ values. Edges = combined site 1 descriptive statistics.

				$\delta^{18}O_{shell}$ ‰			
Sample	**n=**	**Mean**	**Median**	**SD**	**Range**	**Min**	**Max**
Edges	3	-0.86	-0.5	0.65	1.16	-1.62	-0.46
LC#3	29	-0.53	-0.57	0.71	2.73	-1.62	1.1
LC#4	22	-0.58	-0.73	0.52	2.06	-1.17	0.89
LC#5	5	-0.37	-0.38	0.22	0.52	-0.67	-0.15

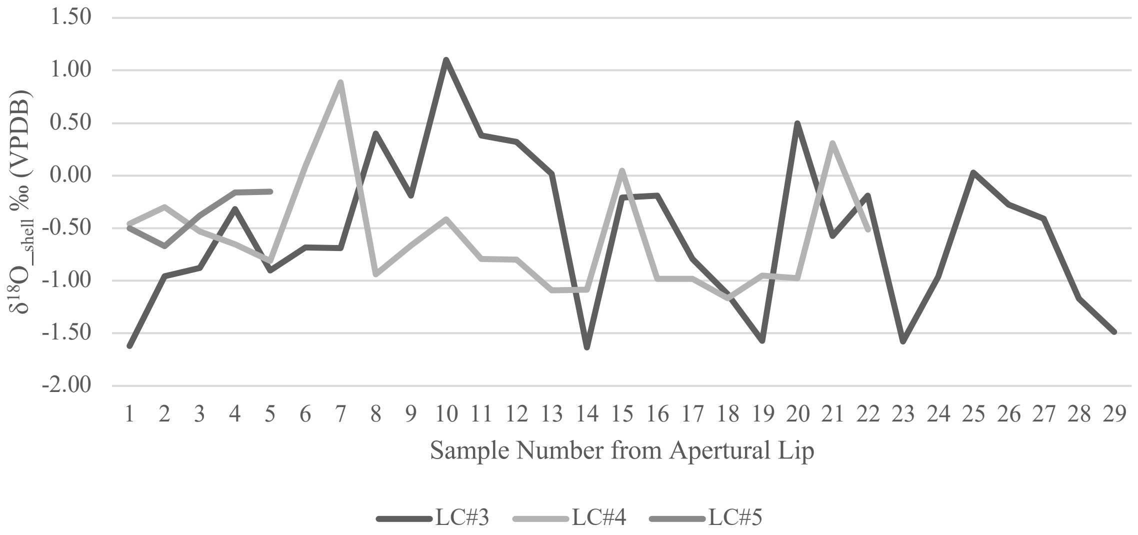


Figure 7.19 Plotted $\delta^{18}O$ values for live-collected *Lunella cinerea* LC#3 (full life-history, n=29), LC#4 (full life-history, n= 22) and LC#5 (edge sample, n=5).

Using equation (1), live-collected *L. cinerea* $\delta^{18}O$ values were used to predict SSTs for LC#3, LC#4, and LC#5. Table 7.10 summarises the descriptive statistics for each sample and for all sample edges. Results for sample LC#3 are given twice - including and excluding the $\delta^{18}O$ values which correspond to DLs. Slight differences exist in the predicted SST means, medians, and standard deviations when comparing LC#3 values (i.e. when including DL anomaly data and excluding DL anomaly data).

All predicted SST means have a value of ~21-23ºC showing overall low variability in sub-seasonal conditions or minimal differences in microhabitat conditions (for e.g. tidal regimes or availability of food and nutrients). When edge values for LC#3, LC#4 and LC#5 are used to calculate the predicted September 2018 SST mean, this point is further highlighted. The instrumental SST mean for September 2018 is 21.7ºC. The calculated SST mean for September 2018 using predicted SST values from sample LC#5 is 21ºC (Table 7.10). Calculated SST means for the September 2018 LC#3 and LC#4 edges are

22.7ºC (n=5 from the lip edge) and 22.9ºC (n=5 from the lip edge) respectively. Differences between the instrumental September 2018 SST mean and predicted SST means is ≤ 1ºC (Table 7.11).

Table 7.10 Descriptive statistics for predicted sea surface temperatures from live-collected *Lunella cinerea* δ^{18}O values. Edges = combined site 1 descriptive statistics.

	Pred. SST ºC						
Sample	**n=**	**Mean**	**Median**	**SD**	**Range**	**Min**	**Max**
Edges	3	22.5	22.4	1	2	21.6	23.6
LC#3	28	21.6	21.5	3	11.8	14.6	26.5
LC#3 (without DLs)	26	21.9	22.1	2.9	11.8	14.6	26.5
LC#4	22	23	23.6	2.2	8.9	16.6	25.4
LC#5	5	21	21	0.9	2.2	20	22.3

Table 7.11 Comparison of instrumental September 2018 SST mean with predicted SST means calculated from LC#5 δ^{18}O edge values.

Year / Month	**Mean Inst. SST (ºC)**	**Pred. SST (ºC)**		**Offset SST (ºC)**
		LC#5		**LC#5**
2018 / September	21.7	21.6		+0.1
		22.3		-0.6
		21.1		+0.6
		20.1		+1.6
		20.1		+1.6
	Total Sample Mean Pred. SST (ºC)	**21.0**	**Total Offset Mean SST (ºC)**	**0.66**

As the plotted δ^{18}O values suggest (Figure 7.19), *L. cinerea* shell microstructures record distinct wet season and dry season SST fluctuations. Figures 7.20, 7.21 and 7.22 demonstrates this finding again by plotting the predicted SST values for LC#3, LC#4, LC#5 with the location of growth features. Although wet season and dry season values can be easily determined, deciphering other seasonal changes typically identified in the Western Gregorian calendar (i.e. summer, winter, autumn, spring) or indeed the local Woppaburra seasonal resource use calendar, is challenging.

This is especially the case since seasonal δ^{18}O values are accurately presented in *L. cinerea* microstructures but appear within inconsistent growth increment widths (i.e. ~2mm powder subsampling might have missed an increment with autumn values or, autumn growth for that particular individual was short. Note: in future analyses an automated micro-milling procedure might assist in exact 2mm spacings rather than approximated spacing achieved with a handheld drill). Predicted SST anomalies, calculated from $\delta^{18}O$ values, in sample LC#3 correlate with DL sites along the shell growth axis. Details of these anomalies are discussed first before detailing an approach for deciphering seasonal indices from deep time *L. cinerea* shells.

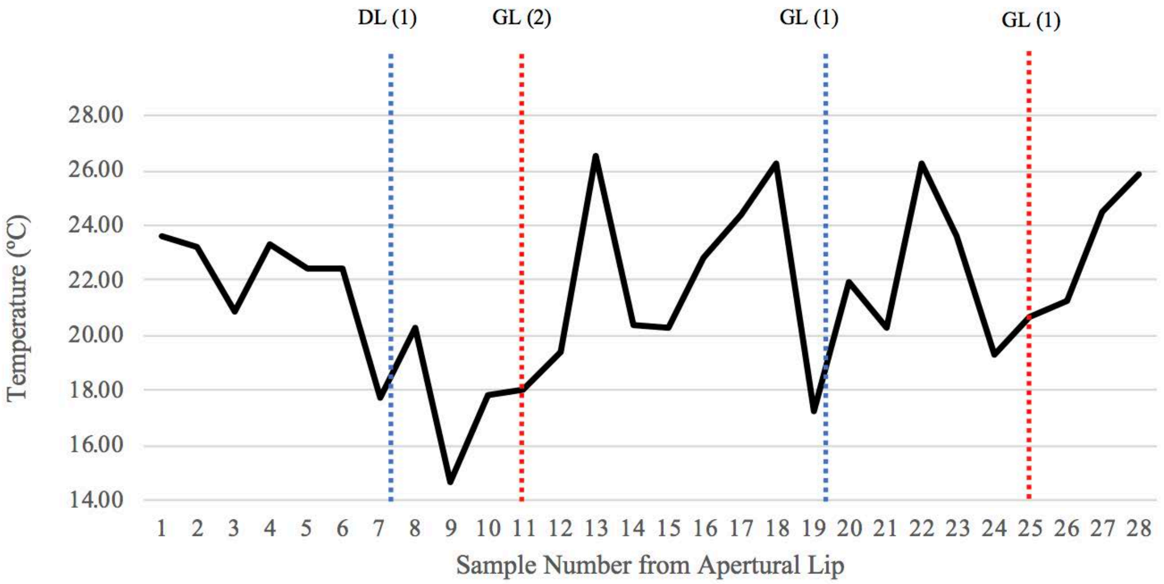


Figure 7.20 Plotted sub-annual predicted sea surface temperatures for *Lunella cinerea* LC#3 (full life-history, n=28). Blue dotted lines indicate the approximate location of disturbance anomalies (DL) (site 7, temperature 17.71ºC and site 19, temperature 17.27ºC). Red dotted lines indicate the approximate location of growth lines (GL). The number of observable features per site is indicated in brackets.

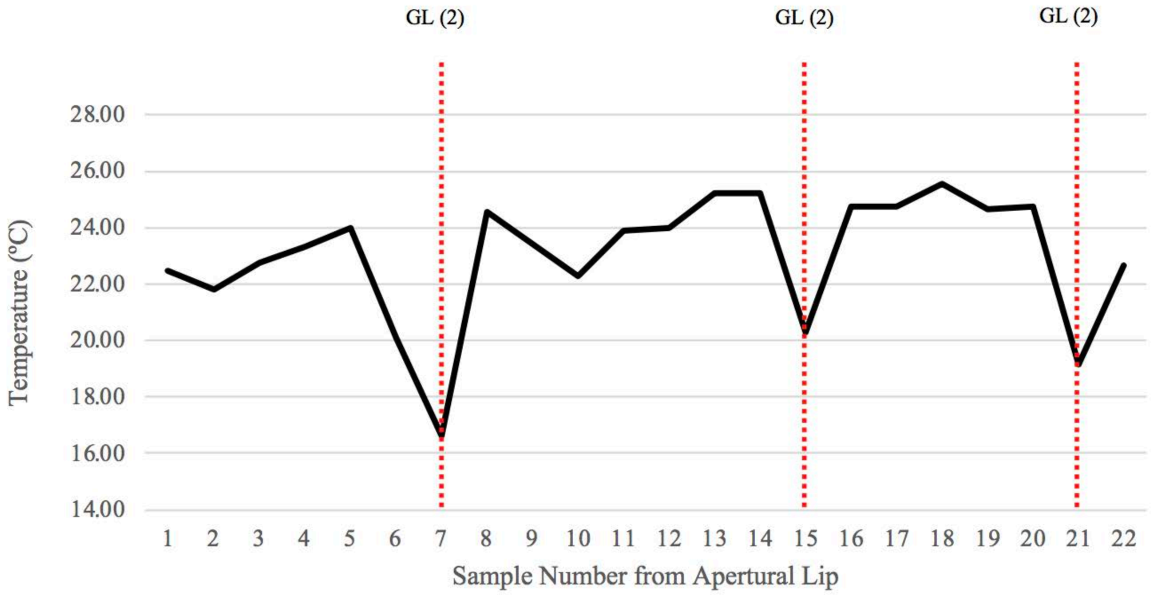


Figure 7.21 Plotted sub-annual predicted sea surface temperatures for *Lunella cinerea* LC#4 (full life-history, n=22). Red dotted lines indicate the approximate location of growth lines (GL). The number of observable features per site is indicated in brackets.

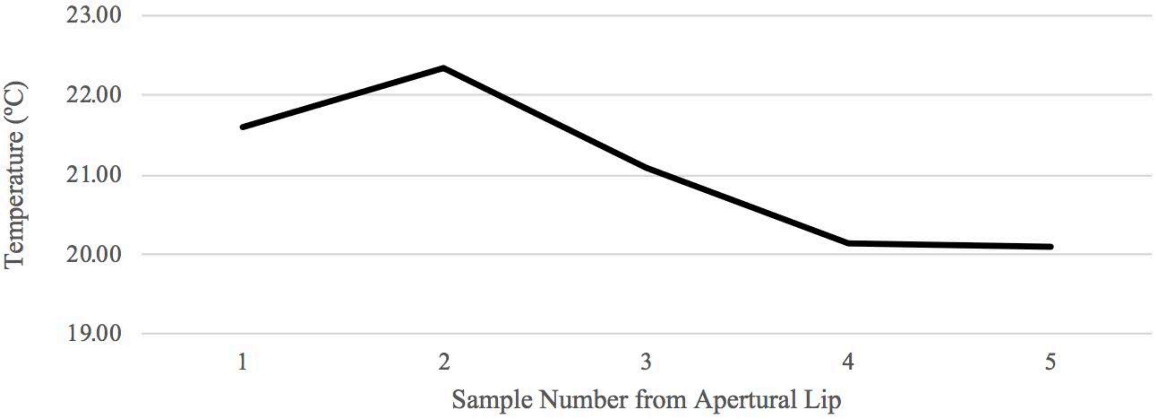


Figure 7.22 Plotted sub-annual predicted sea surface temperatures for *Lunella cinerea* LC#5 (edge sample, n=5). Growth features in the apertural lip area were not observed.

Disturbance Anomalies

Disturbance anomalies (DLs) appearing as notches in the outer shell layers of *L. cinerea* shells correlate well with high (positive) δ^{18}O values. For instance LC#3 sample site 7 has a predicted SST of 17.71ºC and sample site 19 has a predicted SST of 17.27ºC. Although it appears 17ºC could be at the temperature threshold for the species, and which might offer an explanation for when DLs are formed in outer shell layers, other sampled sites along the growth axes of individuals have SST values of ~17ºC but no DL feature. For instance, LC#3 site 11 has a predicted SST of 17.78ºC and LC#4 site 7 has a predicted SST of 16.64ºC, but no DL is present. GLs with no association to a DL, are instead assumed to represent these periods of growth during the coolest months of the dry season (i.e. winter). A sudden change in temperature is a more likely explanation for the formation of DLs in *L. cinerea*. Located immediately before the DLs in LC#3, an average ~4ºC temperature difference is present and immediately after, an average ~7ºC temperature difference is present. It is therefore anticipated that when *L. cinerea* experience a sudden change in temperature, a DL or notch is formed in the outer shell layer. These anomalies are likely to occur when individuals cannot reach a suitable temperature threshold within their microhabitats. Figure 7.23 below plots the predicted SST values again for LC#3 excluding the corresponding DL predicted SST values.

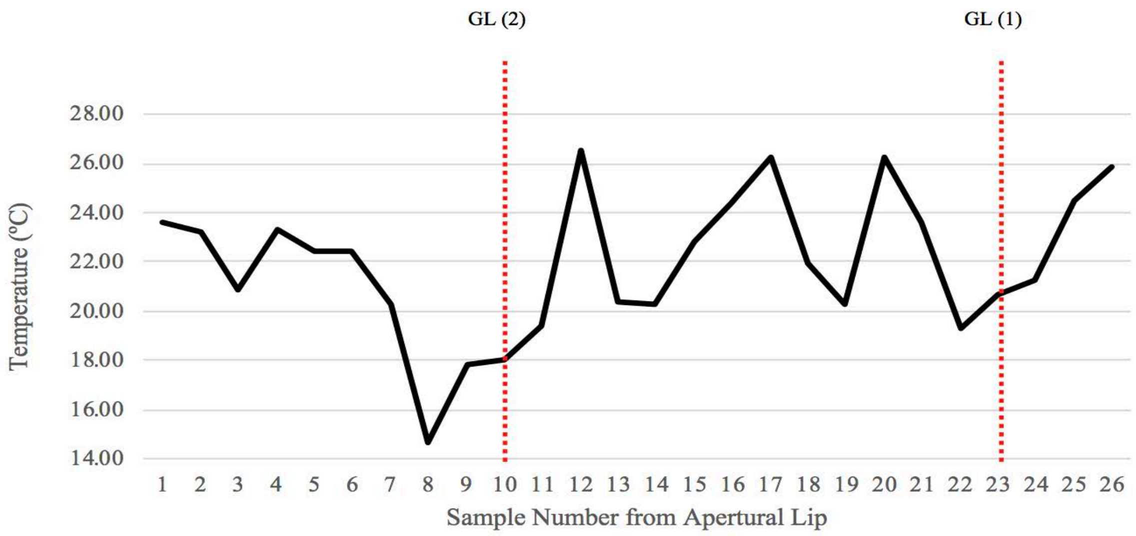


Figure 7.23 Plotted sub-annual predicted sea surface temperatures for *Lunella cinerea* LC#3 excluding disturbance anomalies (full life-history, n=26). Red dotted lines indicate the approximate location of growth lines (GL). The number of observable features per site is indicated in brackets.

A refined approach for interpreting seasonal growth indices from *L. cinerea* shells was made by using a statistical approach explained in Prendergast et al. (2016) and Mannino et al. (2003). Predicted SST values from shells LC#3 and LC#4 (full life-history data) were assessed by visualising data separated into quartiles, in a box and whisker plot. Quartiles were interpreted to represent different seasons. The upper quartile/maximum value (>75%) represents summer, the lower quartile/minimum value (<25%) represents winter and autumn, and the middle quartiles (25-75%) represents spring (Figure 7.24). Figure 7.25 shows the full life-history predicted SSTs in a box and whisker plot for each sample, confirming that shell was mostly precipitated during warmer temperatures. Figure 7.26 shows each sample plotted again using only the edge samples, to determine which season the shell died in. Samples LC#3 and LC#4 show good agreement that the season-of-death was indeed during the spring months. Sample LC#5 shows slightly cooler temperatures but still falls within the spring SST temperature range. These differences are suspected to be reflective of microhabitat conditions (e.g. position on rocky substrate).

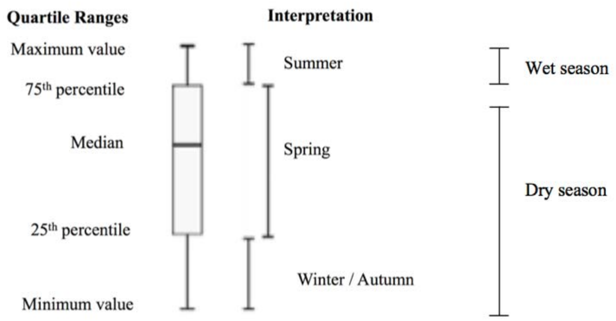


Figure 7.24 Quartile ranges and seasonal interpretations used in assessing predicted sea surface temperature values from *Lunella cinerea* shells.

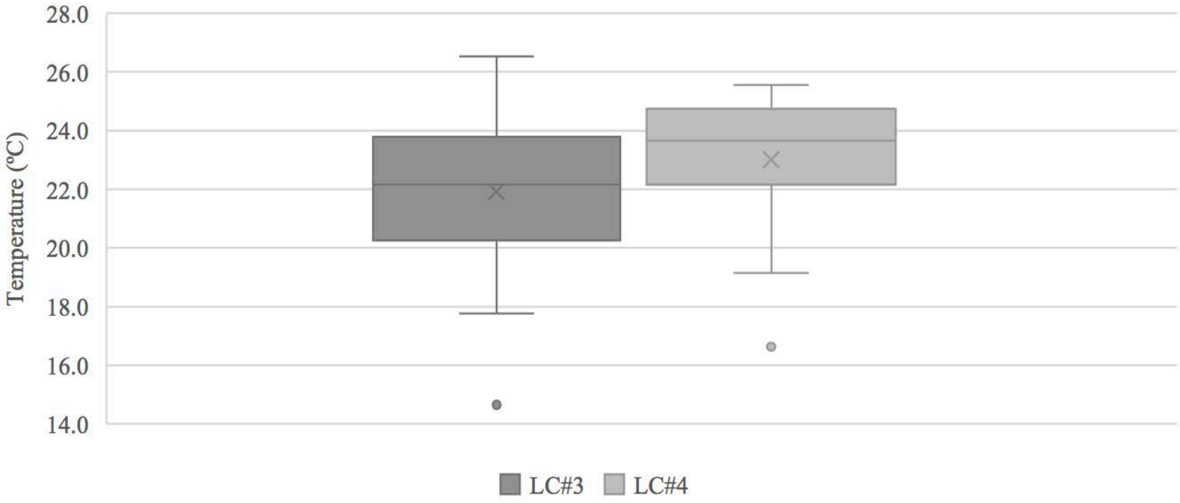


Figure 7.25 Box and whisker plot for full life-history sea surface temperatures, predicted from δ^{18}O values, live-collected *Lunella cinerea*.

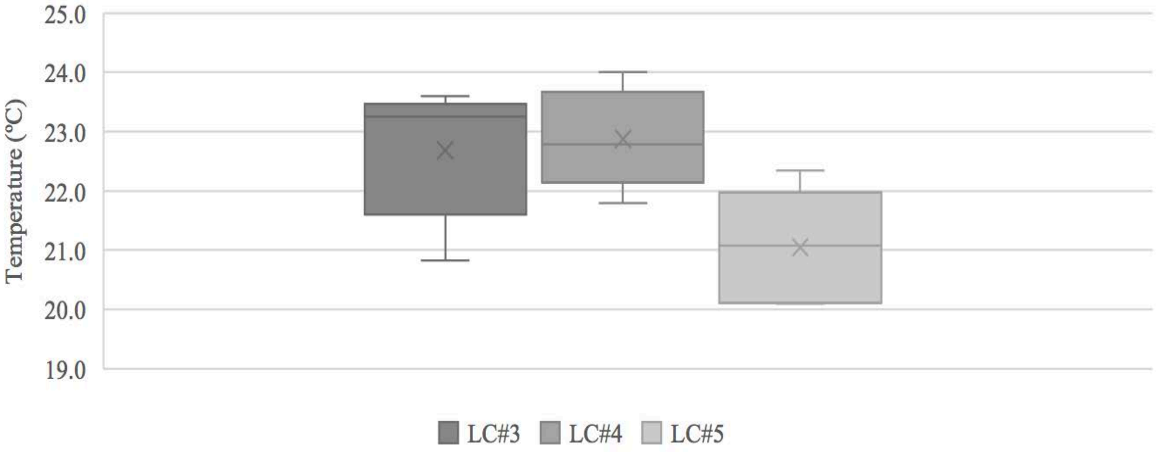


Figure 7.26 Box and whisker plots to determine the season-of-collection in live-collected *Lunella cinerea* shells.

Deep Time *Lunella cinerea*

The quartile approach was used to interpret growing seasons of deep time *L. cinerea* shells (n=5) from Mazie Bay. Almost all samples, except where annual GLs are present, show low (negative) δ^{18}O values (Appendix K) indicating that throughout deep time, *L. cinerea* shells were precipitated during periods of lower salinity. All samples except 170-180cm#2, were subsampled along short-sequence growth axes (Figures 7.27, 7.28, 7.29, 7.30 and 7.31). No DLs were present along the apertural lips of these samples (except sample 110-115cm#1) or present in the long-sequence 170-180cm#2 sample. The DL anomaly in sample 110-115cm#1 does not correlate with a low SST (~17ºC) value and is therefore assumed to have been formed another way (e.g. predator attack and subsequent shell regrowth at the site). Equation (1) was used to calculate the predicted SSTs from δ^{18}O values.

A summary of the descriptive statistics for predicted SSTs is presented in Table 7.12 (descriptive statistics for δ^{18}O values are included in Appendix K). Sample 5-10cm#2 has the lowest predicted SST mean (20.6ºC) and sample 255-265cm#2 has the highest predicted SST mean (24.1ºC). Samples 5-10cm#2, 55-60cm#1, and 170-180cm#2 show ~1ºC difference in predicted SST means (20.6-21.8ºC); and samples 110-115cm#1 and 255-265cm#2 show a 1ºC difference in predicted SST means (23.1-24.1ºC).

Figure 7.32 provides the predicted SST edge values of each sample in a box and whisker plot. Results confirm the Woppaburra People were predominantly harvesting *L. cinerea* in the spring months of the dry season. Samples 55-60cm#2, 110-115cm#1, and 255-265#2cm signal temperatures conducive to the warmer part of spring, and samples 5-10cm#2 and 17-180cm#2 conducive to cooler parts of spring. These differences probably reflect the positioning of shells in their respective habitat locations (i.e. microhabitat conditions). A similar explanation might be supported for sample 255-265cm#2, that has the highest predicted SST mean (24.1ºC). Alternatively, in comparison to proceeding periods, warmer SSTs might have been present at Mazie Bay.

Table 7.12 Descriptive statistics for predicted sea surface temperatures from deep time *Lunella cinerea* δ^{18}O values. Edges = combined site 1 descriptive statistics. Edge samples for 170-180cm#2 (n=5) is included for comparisons.

		Pred. SST ºC					
Sample	**n=**	**Mean**	**Median**	**SD**	**Range**	**Min**	**Max**
Edges	5	20.4	18.6	3.4	7.8	16.8	24.7
5-10cm#2	5	20.6	20	1.8	4.2	18.6	22.8
55-60cm#1	5	21.8	23.2	2.6	5.9	18.5	24.4
110-115cm#1	5	23.1	23.5	1.1	2.8	21.2	24.1
170-180cm#2	24	21.2	21.9	2.4	7.9	16.8	24.8
170-180cm#2 (edge only)	5	20.5	19.9	3.1	7.9	16.8	24.7
255-265cm#2	5	24.1	24.7	1.6	3.9	21.3	25.2

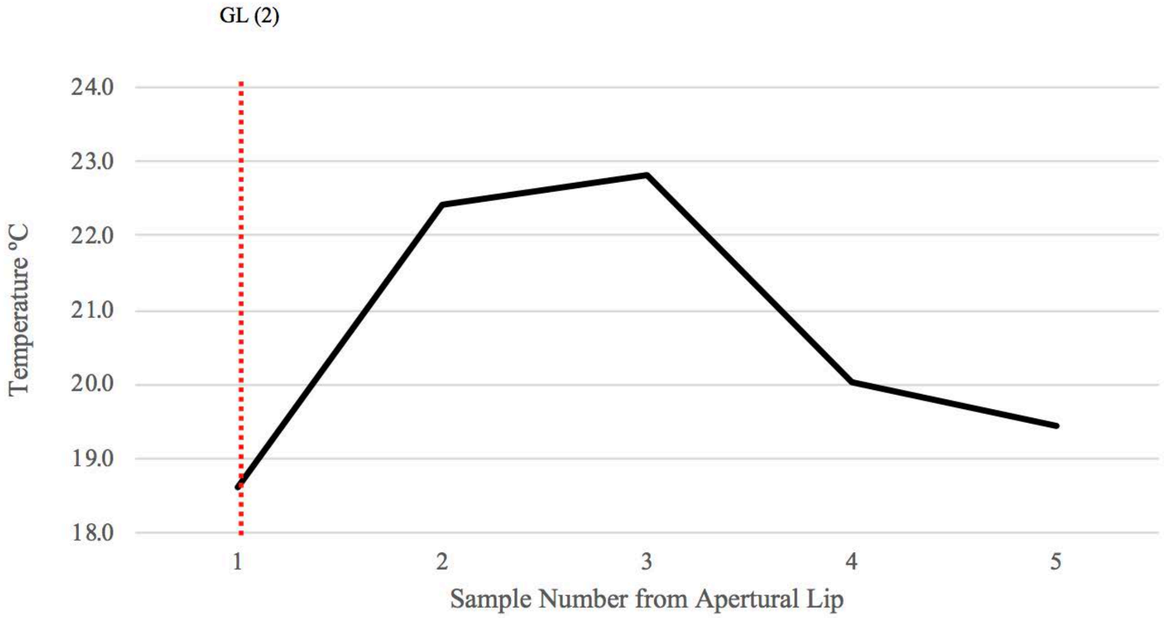


Figure 7.27 Plotted sub-annual predicted sea surface temperatures for *Lunella cinerea* 5-10cm#2 (edge sample, n=5).Red dotted lines indicate the approximate location of growth lines (GL). The number of observable features per site is indicated in brackets.

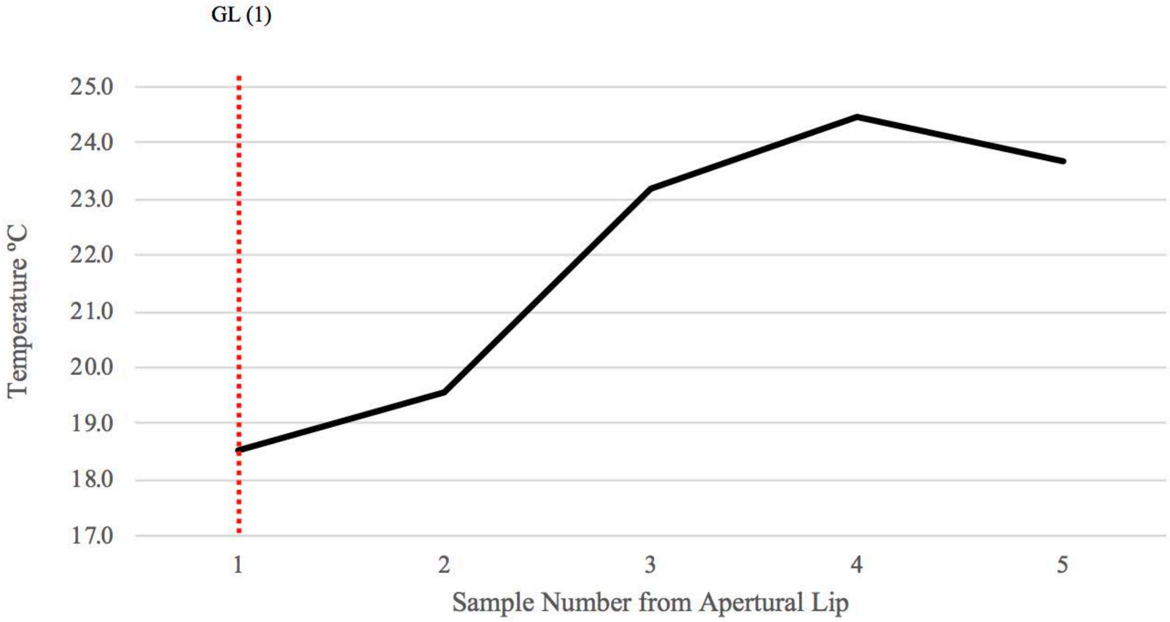


Figure 7.28 Plotted sub-annual predicted sea surface temperatures for *Lunella cinerea* 55-60cm#1 (edge sample, n=5). Red dotted lines indicate the approximate location of growth lines (GL). The number of observable features per site is indicated in brackets.

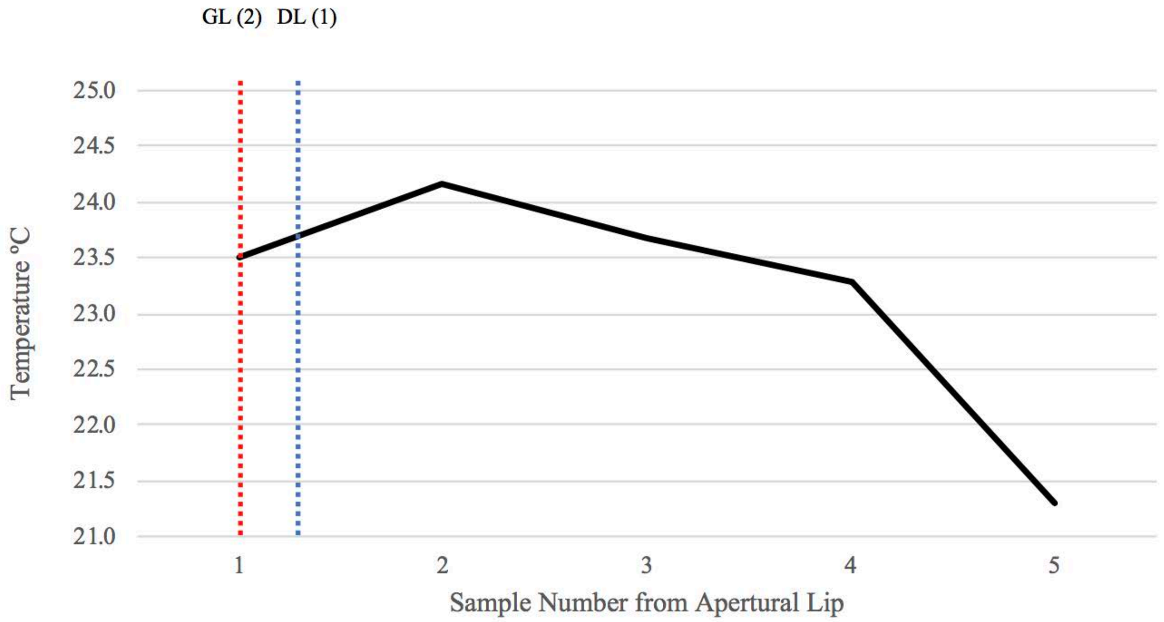


Figure 7.29 Plotted sub-annual predicted sea surface temperatures for *Lunella cinerea* 110-115cm#1 (edge sample, n=5). Red dotted lines indicate the approximate location of growth lines (GL). Blue dotted lines indicate the approximate location of disturbance anomalies (DL). The number of observable features per site is indicated in brackets.

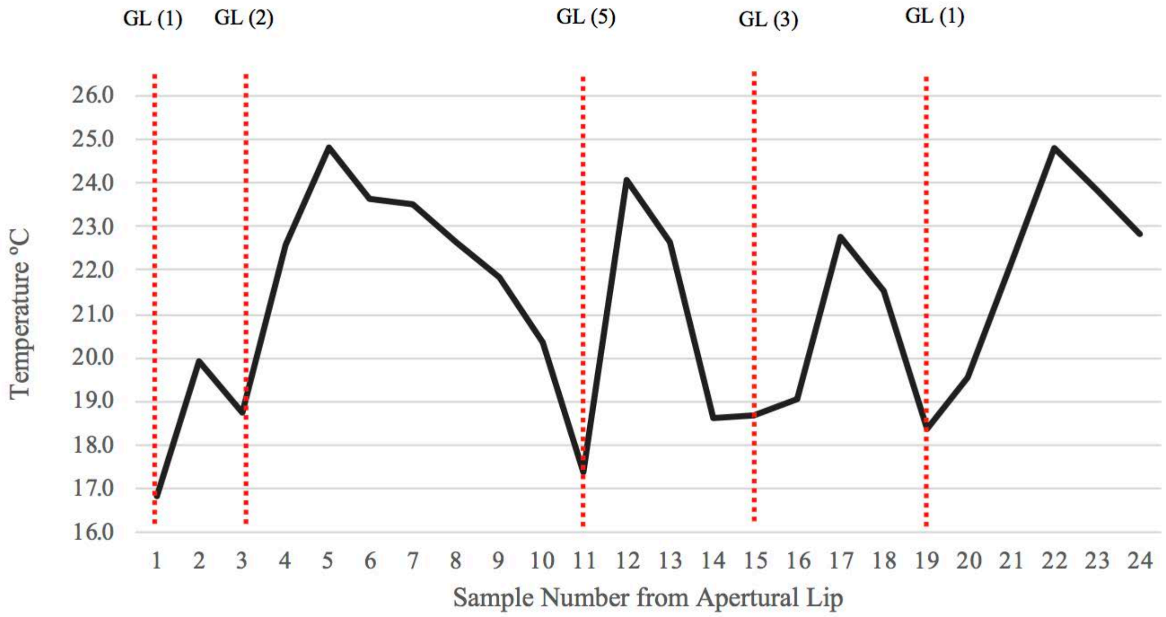


Figure 7.30 Plotted sub-annual predicted sea surface temperatures for deep time *Lunella cinerea*, 170-180cm#2 (full life-history, n=24). Red dotted lines indicate the approximate location of growth lines (GL). The number of observable features per site is indicated in brackets.

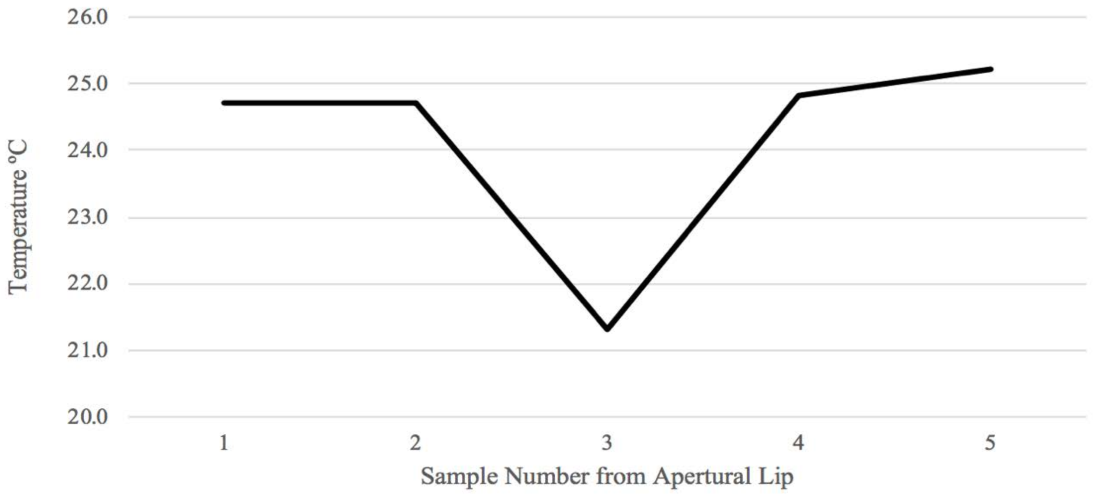


Figure 7.31 Plotted sub-annual predicted sea surface temperatures for *Lunella cinerea* 255-265cm#2 (edge sample, n=5). Growth features in the apertural lip area were not observed.

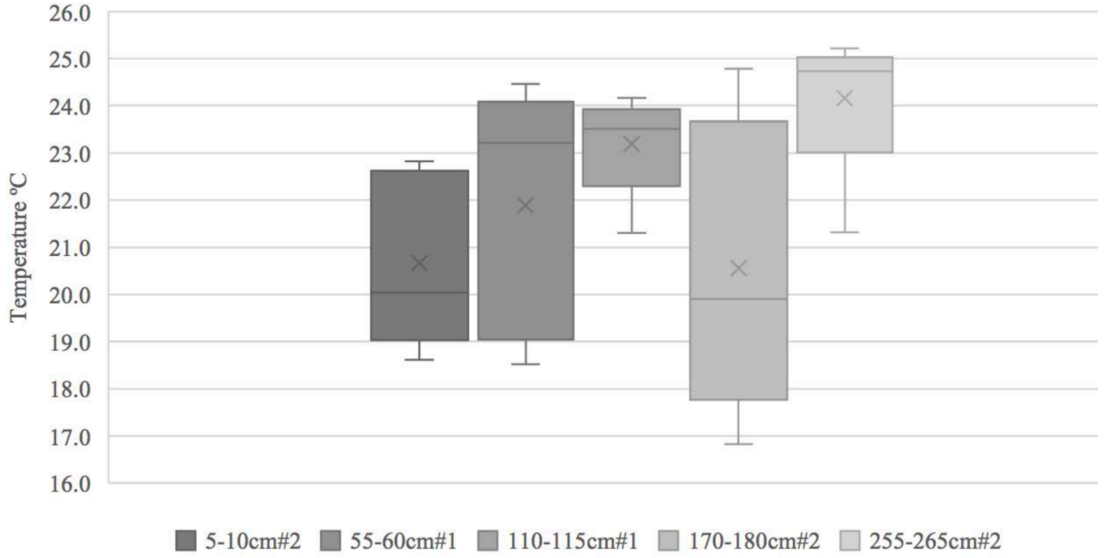


Figure 7.32 Box and whisker plots of edge values to determine the season-of-collection in deep time *Lunella cinerea* shells, 5-10cm#2 (n=5), 55-60cm#1 (n=5), 110-115cm#1 (n=5), 170-180cm#2 (n=5), 255-265cm#2 (n=5).

7.4.3 Stable Isotope Results, *Acanthopleura gemmata*

Live-collected and Deep Time *Acanthopleura gemmata*

Complications with mass spectrometer instruments arose throughout these analyses, resulting in powder samples being contaminated by leaked gas. Sample re-runs were planned however, the laboratory was closed due to COVID-19 restrictions in early 2020. Subsequently, any meaningful analysis of *A. gemmata* stable isotope results could not be completed. Figure 7.33 shows where powder samples were milled from in the articulamentum areas of *A. gemmata* shell valves.

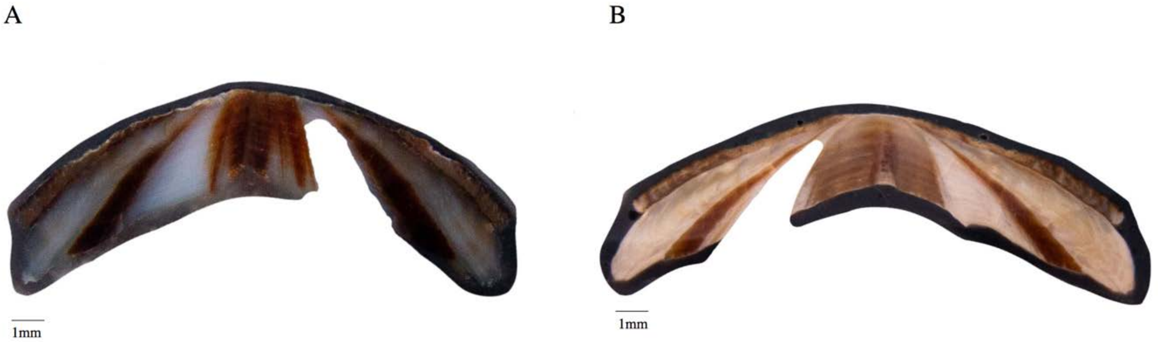


Figure 7.33 A) Live-collected *Acanthopleura gemmata* example LC#5 milled in the right articulamentum area for obtaining long-sequence δ^{18}O powder samples. B) Deep time *Acanthopleura gemmata* example 5-10cm#1 milled in the left articulamentum area for obtaining long-sequence δ^{18}O powder samples. Note grey outline is the epoxy resin.

7.4.3 δ^{13}C Stable Isotope Results: *Saccostrea cuccullata* and *Lunella cinerea*

Isotopes ^{13}C-enriched and ^{13}C-depleted are contained within mollusc shells. The δ^{13}C values of live-collected and deep time *S. cuccullata* and *L. cinerea* shells are provided in Appendix K, along with descriptive statistics. Figures 7.34, 7.35, 7.36 and 7.37 below compare δ^{13}C and δ^{18}O results using examples from the live-collected and deep time assemblages for each species. To test if a relationship exists between SSTs and carbon uptake, linear regressions were run for δ^{18}O and δ^{13}C values for *S. cuccullata* (annual resolution) and *L. cinerea* (sub-annual/seasonal resolution) using equation (2). Histograms and P-P plots versus residual plots indicated normally distributed data and therefore satisfied the conditions required for regression analysis. For cases *L. cinerea* LC#4 (full life-history), 190-200cm#1 (full life-history) and 255-265cm#2 (full-life history), none of the variability around the means of the for δ^{18}O and δ^{13}C values could be explained. Overall, poor predictive power between δ^{18}O and δ^{13}C values were found where ≤ 29% of the variations can be explained for live-collected S. *cuccullata*, ≤ 49% for live-collected *L. cinerea*, ≤ 39% for deep time *S. cuccullata*, and ≤ 56% for deep time *L. cinerea*. Two cases showing moderate to strong predictive power between δ^{18}O and δ^{13}C values (samples *S. cuccullata* 220-230cm#1 and *L. cinerea* 170-180cm#2) are highlighted below (Tables 7.13 and 7.14). Appendix K includes the linear regression scatter plots for each sample.

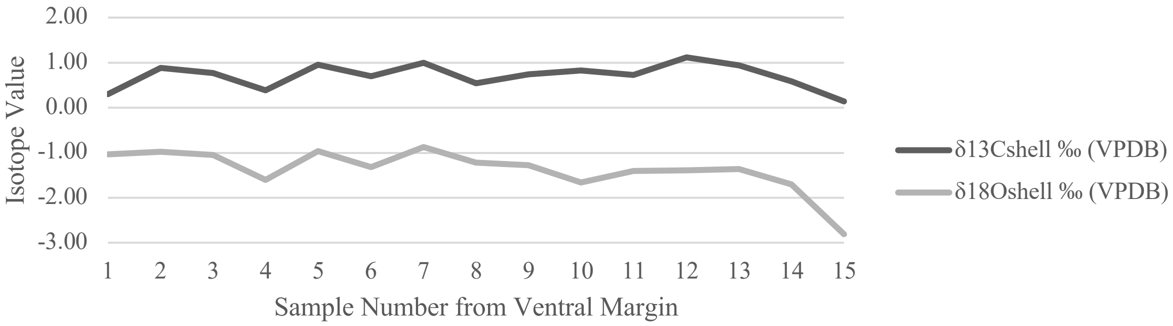


Figure 7.34 Live-collected *Saccostrea cuccullata* sample LC#4 (full life history). Comparison between δ^{13}C and δ^{18}O results.

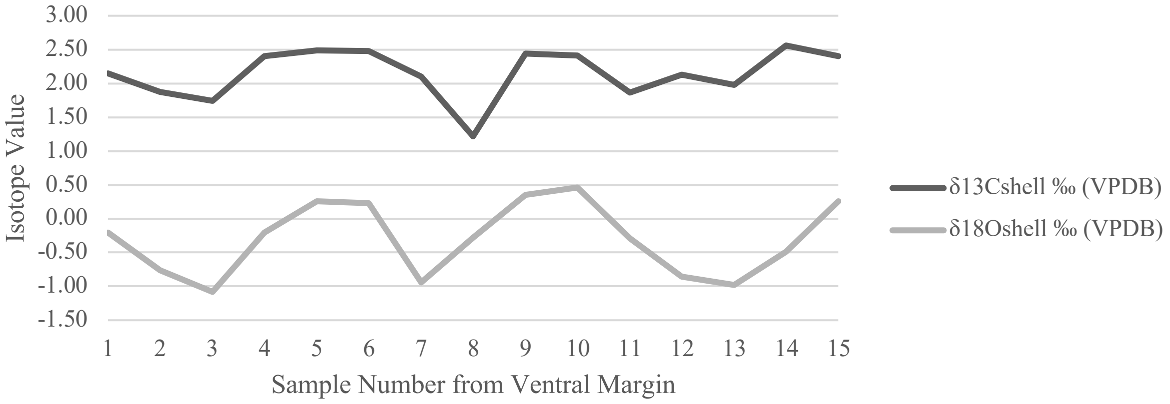


Figure 7.35 Deep time *Saccostrea cuccullata* sample 130-135cm#1 (full life history). Comparison between δ^{13}C and δ^{18}O results.

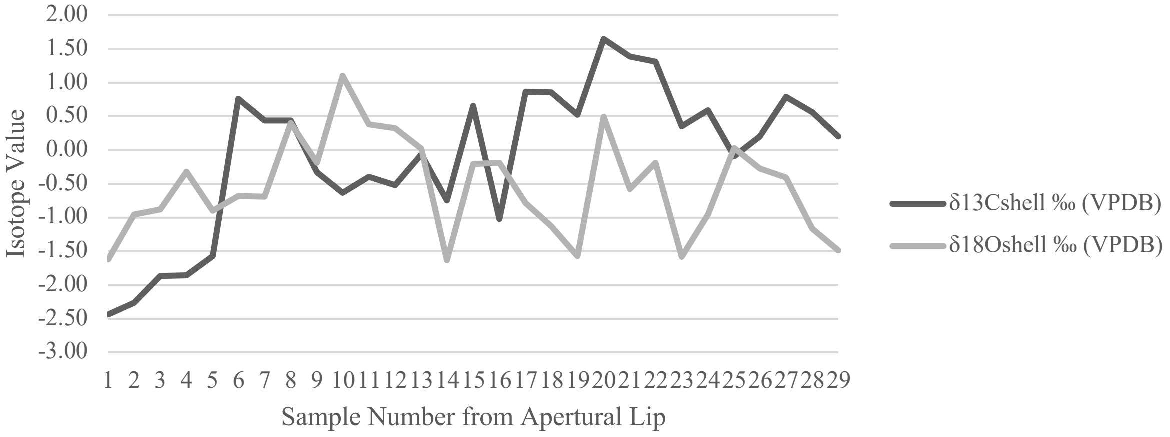


Figure 7.36 Live-collected *Lunella cinerea* sample LC#3 (full life history). Comparison between δ^{13}C and δ^{18}O results.

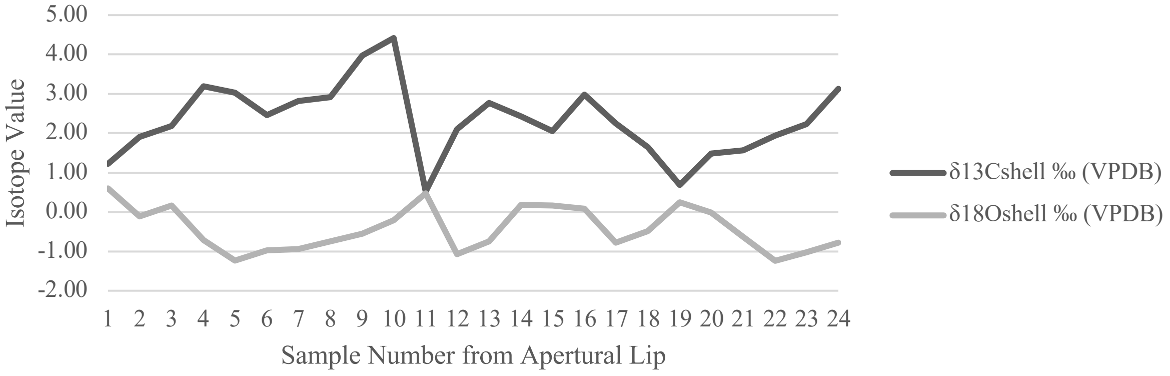


Figure 7.37 Deep time *Lunella cinerea* sample 170-180cm#2 (full life history). Comparison between δ^{13}C and δ^{18}O results.

Table 7.13 Summary of linear regression results for δ^{18}O versus δ^{13}C, live-collected *Saccostrea cuccullata* and *Lunella cinerea* samples.

LIVE-COLLECTED	**Pearson Correlation**		**Linear Regression**			**ANOVA**			**Equation**
S. cuccullata									
Sample (n=)	***r***	***p***	$\boldsymbol{r^2}$	***A***	***b***	***F***	**df**	***p***	
LC#2 (n=6)	0.145	0.228	-0.068	1.282	0.292	1.68	1	0.456	y = (1.28)+(x*0.29)
LC#4 (n=15)	0.346	0.011	0.296	1.179	0.341	6.877	1	0.021	y = (1.81)+(x*0.34)
LC#6 (n=9 incl. x)	0.141	0.16	0.018	0.821	0.122	1.148	1	0.32	y = (0.82)+(x*0.12)
	Pearson Correlation		**Linear Regression**			**ANOVA**			**Equation**
L. cinerea									
Sample (n=)	***r***	***p***	$\boldsymbol{r^2}$	***A***	***b***	***F***	**df**	***p***	
LC#3 (n=29) full life-history	0.02	0.234	-0.017	0.038	0.216	0.542	1	0.468	y = (0.04)+(x*0.22)
LC#3 (n=5) edge sample	0.424	0.117	0.232	-1.547	0.488	2.206	1	0.234	y = (-1.55)+(x*-0.49)
LC#4 (n=22) full life-history	0	0.469	-0.05	-0.297	-0.021	0.006	1	0.939	y = (-0.3)+(x*-0.02)
LC#4 (n=5) edge sample	0.314	0.163	0.085	-1.582	-0.62	1.373	1	0.326	y = (-1.58)+(x*-0.62)
LC#5 (n=5) edge sample	0.622	0.056	0.496	-0.78	1.157	4.935	1	0.113	y = (-0.78)+(x*1.16)

Table 7.14 Summary of linear regression results for δ^{18}O versus δ^{13}C, deep time *Saccostrea cuccullata* and *Lunella cinerea* samples.

DEEP TIME	**Pearson Correlation**		**Linear Regression**			**ANOVA**			**Equation**
S. cucculata									
Sample (n=)	***r***	***p***	**r^2**	***A***	***b***	***F***	**df**	***p***	
5-10cm#1 (n=4) full life-history	0.033	0.409	-0.451	2.308	0.262	0.068	1	0.819	$y = (2.31)+(x*0.26)$
60-65cm#1 (n=8) full life-history	0.477	0.029	0.39	1.828	0.554	5.483	1	0.058	$y = (1.83)+(x*0.55)$
130-135cm#1 (n=15) full life-history	0.276	0.022	0.22	2.259	0.364	4.956	1	0.044	$y = (2.26)+(x*0.36)$
190-200cm#1 (n=6) full life-history	0	0.487	-0.25	1.154	-0.009	0.001	1	0.975	$y = (1.51)+(x*0.001)$
220-230cm#1 (n=8) full life-history	0.704	0.005	0.655	2.643	0.715	14.3	1	0.009	$y = (2.64)+(x*0.71)$

	Pearson Correlation		**Linear Regression**			**ANOVA**			**Equation**
L. cinerea									
Sample (n=)	***r***	***p***	**r^2**	***A***	***b***	***F***	**df**	***p***	
5-10cm#2 (n=5) edge sample	0.006	0.452	-0.326	2.618	-0.092	0.017	1	0.904	$y = (2.62)+(x*-0.09)$
55-60cm#1 (n=5) edge sample	0.127	0.278	-0.164	2.2573	-0.26	0.437	1	0.556	$y = (2.57)+(x*-0.26)$
110-115cm#1 (n=5) edge sample	0.677	0.044	0.569	1.341	-2.002	6.286	1	0.087	$y = (1.34)+(x*-2.0)$
170-180cm#2 (n=24) full life-history	0.173	0.021	0.136	2.034	-0.687	4.618	1	0.043	$y = (2.03)+(x*-0.69)$
170-180cm#2 (n=5) edge sample	0.831	0.015	0.775	2.192	0.444	14.801	1	0.031	$y = (2.04)+(x*-1.02)$
255-265cm#2 (n=5) full life-history	0	0.492	-0.333	3.072	0.005	0.001	1	0.983	$y = (3.07)+(x*0.001)$

7.4.4 The Suess Effect and Broad $\delta^{13}C$ Interpretations

Further interpretations of $\delta^{13}C$ values in live-collected and deep time *S. cuccullata* and *L. cinerea* are challenging. This is mainly due to uncertainties regarding physiological responses in species to climatic and environmental changes, and the Suess Effect (i.e. the burning of fossil fuels since the Industrial Revolution) (see Dombrosky 2020). No standard southern GBR region Suess Effect curve exists to correct $\delta^{13}C$ values in modern and deep time mollusc shell samples. Global corrections for the Suess Effect exist but these do not consider historical or deep time fluctuations which usually offer corrections between 1.0‰ to 2.0‰ (see Dombrosky 2020). A further complication exists as Suess Effect corrections offer calibrations for either fully marine or fully terrestrial systems. Given the habitat zone of *S. cuccullata* and *L. cinerea* – upper intertidal rocky shores – they can be influenced by both marine and terrestrial carbon sources. With this in mind, only very broad uncorrected observations of the modern and deep time *S. cuccullata* and *L. cinerea* $\delta^{13}C$ values can be made at this time. The observations below are only time sensitive between modern and deep time periods and do not account for potential carbon fluctuations throughout the mid-Holocene or between seasons. If any meaningful conclusions are to be drawn in future, trace element analysis is recommended. I return to this point in section 7.6.2 below.

Saccostrea cuccullata

Live-collected *S. cuccullata* $\delta^{13}C$ values show an average $\delta^{13}C$ value of 0.87‰ (n=3) over their full life histories (annual resolution). Deep time *S. cuccullata* samples show an average $\delta^{13}C$ value of 1.96‰ (n=5) (annual resolution). Both time periods show a predominantly marine carbon source for *S. cuccullata*.

Lunella cinerea

Live-collected *L. cinerea* $\delta^{13}C$ values show an average $\delta^{13}C$ value of -0.52‰ (n=3) (sub-annual resolution). Deep time *L. cinerea* samples show an average $\delta^{13}C$ value of 2.76‰ (n=1 full life history, n=4 edge sample only) (sub-annual resolution). For *L. cinerea*, terrestrial carbon sources appear to dominate in the modern period, in comparison to predominantly marine carbon sources in deep time.

7.5 Discussion

Southern GBR SSTs fluctuate throughout the year and these fluctuations can be seasonally predicted. The dry season and the wet season are the most dominant seasons per calendar year. Dry season SST averages are approximately 6ºC cooler than wet season averages which approach ~27ºC for most of December, January and February each year. Dry season mid-winter SSTs reach ~19ºC. Two culturally and ecologically important mollusc taxa to the Woppaburra People and the Mazie Bay area, *S. cuccullata* and *L. cinerea*, show different shell growth trends in response to changing SSTs. Despite both taxa deriving from upper intertidal rocky shore habitats, only *L. cinerea* appears to grow in close isotopic equilibrium with ambient SSTs. The reason for this difference is attributed to the locomotion ability of *L. cinerea* individuals who can manoeuvre themselves to more suitable conditions within their habitat ranges. Conversely, *S. cuccullata* are sessile organisms, affixed to intertidal rocks and unable to manoeuvre themselves when met with unfavourable conditions. *Saccostrea cuccullata* exhibit highly variable year-to-year growth and cannot be used as a reliable palaeothermometer. Isotopic disequilibrium might be triggered by food sources, stored or expelled energy, or other kinetic or metabolic effects (Gutiérrez-Zugasti et al. 2017:49; Mannino et al. 2003:668).

Lunella cinerea show high growth sensitivity to SSTs and can be used as an accurate palaeothermometer. SST predictions are within a ≤ 1ºC error range, showing excellent agreement between instrumental SST averages and predicted SST averages for the Mazie Bay area. Very clear 'saw tooth' patterning in δ^{18}O values demonstrate distinct wet season and dry season periods for both modern and deep time samples. This species experiences a growth hiatus period in the coldest temperatures, coinciding with the appearance of annual growth lines within their shell microstructures. Double growth lines, seemingly appearing after 2 years of age might be indicative of sexual maturity and the first instance of a spawning period; however, more work on live individuals would need to be undertaken for confirmation. Disturbance notches on the outer shell layer probably occur when an individual is exposed to abrupt temperature changes (i.e. very cold to very hot) and finds difficulty in manoeuvring to suitable conditions (e.g. wedged between rock cervices or upside-down in ponded environments). Although modern *L. cinerea* shells reliably record seasonal SST signatures in their shells, GI widths are highly variable. This is likely a consequence of variations in microhabitat conditions, sub-seasonal fluctuations (e.g. tidal regimes), or other physiological responses to changes which might or might not be dependent on ontogenetic age (e.g. availability of food and nutrients, light, salinity).

7.5.1 Season-of-Collection, *Lunella cinerea*

Lunella cinerea δ^{18}O shell edge values for samples appearing in the deep time Mazie Bay assemblage fall within the 25th percentile and 75th percentile ranges. This result demonstrates slight variability in the spring-time collection during the mid-Holocene where early spring (cooler spring-time SSTs) and late spring (warmer spring-time SSTs) values are shown. Nonetheless, all predicted SST means from deep time derived *L. cinerea* samples fall close to modern spring-time instrumental SST averages (~23ºC ±3ºC), with only 2 samples showing low predicted SST means (samples: 55-60cm#1 20ºC, and 170-180cm#2 19.9ºC). These low predicted SST values would appear representative of winter-time SSTs by modern instrumental SST average standards. However, modern instrumental averages for the month of September (rather than the 3-month seasonal average 23ºC) measures SSTs at 21ºC. This result falls within a ≤ 1ºC error range for what we might expect for early spring-time temperatures. I suggest these shells, samples 55-60cm#1 and 170-180cm#2, were collected at the end of winter during the onset of spring. Sample 255-265cm#2 signals slightly warmer SST conditions during the mid-Holocene period (~5000 BP to 4000 BP); however, it is unknown if this finding is reflective of microhabitat conditions or possibly larger regional temperature trends. Roche et al. (2014) and Gagan et al. (1998) suggest regional temperatures were warmer during this period by 1ºC.

The Woppaburra People adopted a sustained dry season harvesting strategy for *L. cinerea* since the mid-Holocene at Mazie Bay. Although this finding is based on just 5 *L. cinerea* samples, results are indicative of sustained seasonal use of the site during the time of year corresponding to spring on the Western Gregorian calendar. Whether other species were seasonally harvested in deep time remains to be clarified; however, this early result is in agreement with a long-term and sustained seasonal resource use approach as expressed in the Woppaburra cultural map/seasonal resource use calendar. A synthesis of stable isotope results with knowledge communicated in the Woppaburra seasonal resource use calendar is presented next in Chapter 8.

7.5.2 Scales and Resolutions: Broader Implications

Stable isotope data from coral cores report little difference between modern and deep time SSTs. Comparisons between modern and deep time predicted SST ranges from *L. cinerea* shells agree with this observation. A cautionary approach however, would include the possibility that slight changes in temperature could influence the growth of taxa. Between the modern and deep time periods, the highest shell precipitation rates occurred during periods of lower salinity during the wet season. This finding is consistent across both *S. cuccullata* and *L. cinerea* samples. Extreme versus less extreme freshwater influxes to Mazie Bay during the deep time and modern phases are not yet certain but it is assumed to have profound influences on faunal growth. Further examination of the carbon uptake cycles of these species is therefore recommended. Indeed, the $\delta^{13}C$ values measured here could be reflective of both dietary carbon and atmospheric carbon. Dietary carbon is of importance due to the proximity of the Fitzroy River (i.e. flood plumes and sediment loads carry plant and other organic debris).

Early speculation, based on preliminary findings from linear regression analyses, posits that the availability of dietary carbon to *S. cuccullata* and *L. cinerea* shells operates independently from SSTs. Severe tropical storms initiating flooding of the Fitzroy River and delivering a strong supply of dietary carbon, might be occasionally signalled by a correlation between $\delta^{13}C$ and SSTs (because tropical storms most often but not explicitly occur in the summer monsoon months). To assist in teasing out these complexities further, trace element analyses should be undertaken. Another control which would determine the rates of precipitation would be to examine SSS values. The examination of SSS values was not possible in this study due to an absence of Mazie Bay sea water samples. If intraseasonal precipitation patterns were a dominating influence in deep time, perhaps delivered by the MJO, we would expect more varied SSS signatures in the shell properties of *L. cinerea* samples. Results might also distinguish between the delivery of dietary carbon via Fitzroy River flood plumes or marine upwelling events. Comparisons between other key molluscan taxa are recommended. In this study *S. cuccullata* shells proved inadequate as a comparative species.

7.6 Summary

This chapter contributes the first stable isotope analyses on deep time-derived mollusc shells from a GBR cultural resource use site. Stable isotope analyses have been key to refining understandings about Woppaburra resource use and seasonal conditions since the mid-Holocene. Other studies have attempted biogeochemical assessments on oyster shells using the hinge and left valves but with limited results. This study confirms that the right valves of *S. cuccullata* are inadequate for deducing climate proxy data. Although *L. cinerea* is also a rocky shore intertidal species that occupies a similar habitat zone to *S. cuccullata*, it is an ideal candidate to use as a palaeothermometer. Unique behavioural traits of *L. cinerea*, and its ability to record $\delta^{18}O$ signatures in near isotopic equilibrium with ambient sea water temperatures, allows for reconstruction of mid-Holocene sea temperatures and insight into seasonal resource use trends. *Lunella cinerea* is therefore, strongly recommended for further biogeochemical assessments of deep time and modern samples appearing in tropical locations.

8

Conclusion

8.0 Introduction

Long-term socio-ecological interactions at the Keppel Bay Islands can be expressed as dynamic and ongoing. A multi-perspective approach to understanding the complexities underlying this dynamic system can be drawn from both tangible and intangible sources of knowledge. Compellingly, the socio-ecological trajectory at Mazie Bay confirms at least ~5000-years for the sustained seasonal use of at least one species, *Lunella cinerea*. Although only the dominant molluscan species recovered from Woppaburra's deep time cultural resource use site at Mazie Bay could be analysed in this research, the scope and significance of information derived from these findings have important implications for fisheries and heritage planning. After a synthesis of results are provided, as guided by the tenets of an Historical Ecology framework, the next discussion situates how findings can be used in conservation management initiatives.

8.1 Contribution of Multiple Perspectives and Non-Linearity

Total phenomena are formed by human, environmental and climatic mechanisms (Balée 1998; Head 2012; Head 2008; Ingold 2000). One or more variables can operate on varying spatial and temporal scales which determine short-term or long-term outcomes. As Balée (1998), Ingold (2000) and others have pointed out, all landscapes have been interacted with by humans to some extent, but the total degradation of environments or resource populations should not be assumed. Indeed, in some instances, the use of resources and changes in climatic and environmental variables has been shown to accelerate population growth rather than initiate population decline (for e.g. *Nerita tessellata* in Giovas et al. 2013 and see Giovas et al. 2010). Identifying the interplay of variables which amount to an outcome (e.g. food intake and temperature regimes owing to an organism's growth) is critical for understanding the complexities underlying large-scale socio-ecological patterns. Only when sufficiently high-resolution data are accumulated and examined can larger, and often non-linear patterns, be discriminated from linear or isolated events. Because variables operating over short or long terms are cumulative processes which could still be in operation today, knowledge collected from projects situated within Historical Ecology can make substantial contributions to management initiatives, particularly at the planning stages. Indeed, forecasting and planning for cultural and ecological resilience using baseline understandings, and together with practitioner teams, is key to securing successful futures (Figure 8.1).

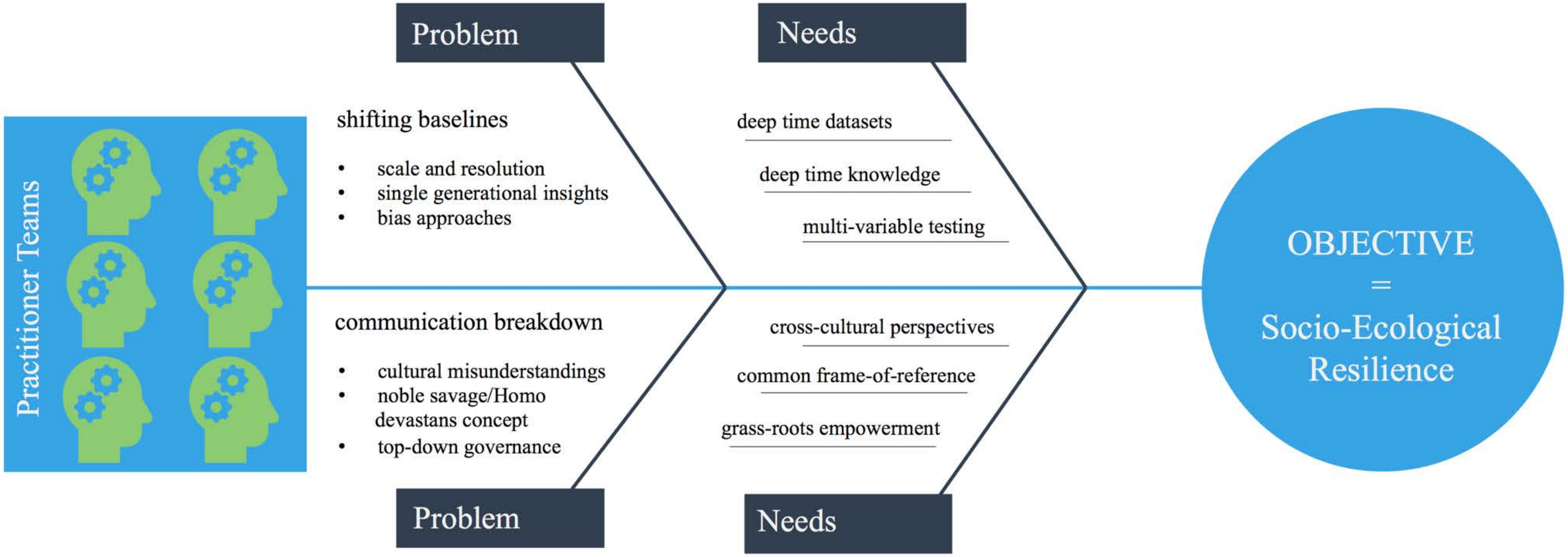


Figure 8.1 Challenges and objectives in resource and heritage management spheres (concepts taken from Faulkner et al. 2019, Pauly 1995 and Tengö et al. 2014).

Practice-based and collaborative stewardship for cultural heritage and fisheries management in the Keppel Bay Island has been underway for some time. A recent example showcasing the planning and implementation of measures to secure fish resources at Great Keppel Island was the launch of *Balban Dara Guya* (Leekes Creek) fish habitat area in 2017. Collaborations between the Woppaburra Traditional use of Marine Resources Agreement (TUMRA) steering committee, the Great Barrier Reef Marine Park Authority (GBRMPA), local government representatives and local community members, made use of Traditional Ecological Knowledge (TEK) and Western Scientific Knowledge (WSK) in this instance to achieve common goals – to set a geographical boundary intended for the conservation of commercially and recreationally important fish and crustaceans. Continuation of transboundary negotiations in initiatives such as these base decisions making processes on known and available information, but also uncover potential areas needing consideration. Refined assessments of the deep time fish and crustacean record within the Keppel Bay Islands does not yet exist despite the recovery of some deep time materials from cultural sites. Although the protective measures put in place to secure the future of marine resources at Leekes Creek, for example, represent a positive and successful initiative, it could be improved by the contribution of baseline data extracted from deep time materials. In most locations across the Great Barrier Reef (GBR) World Heritage region, beneficial conservation initiatives such as these do exist but rarely is an Historical Ecology framework adopted to take advantage of communicating and documenting socio-ecological processes through a common frame-of-reference.

The collation of socio-ecological understandings using material evidence from the deep past at the Keppel Bay Islands has been afforded by the work of the Woppaburra People and A/Prof. Michael Rowland. Beginning in the 1970s, archaeological survey and excavation work was no small feat. Numerous places of significance were recorded along with observations and preliminary quantifications for the use of many plant and animal resources. Most, if not all of these sites appear on heritage registers which are known places of significance to the Woppaburra People and wider community members. Numerous sites, except for Mazie Bay, show evidence for human occupation from at least ~1500 years ago (Rowland 2007). Only at Mazie Bay is a deeper human occupation record indicated by radiocarbon dating undertaken by Rowland (see 1999a) and the research presented in this thesis. Reasons for the differences in occupational histories at each site within the Keppel Bay Islands might be indicative of a few things. Considerations include: the inundation of earlier sites from rising sea-levels or removal by other natural processes (i.e. wind), more sites may exist but have not yet been located, or limitations in sampling and excavation techniques (i.e. depth limitations) (Rowland 1992). Another possibility might be that Mazie Bay was utilised by the Woppaburra People on a longer and more continual basis due to its positioning (e.g. access to freshwater, food, and/or shelter from prevailing winds at certain times of the year) or other reasons (e.g. cosmological beliefs).

The deep time resource use site at Mazie Bay is a rich archive of Woppaburra TEK and cultural materials which occupies the matrices of an extensive sand dune system. Large marine animal remains (e.g. turtle), fish, crustaceans and molluscs were among the most dominant materials recovered from the site by Rowland in 1979. Since his earliest enquiries, the observation of geomorphological changes in each stratigraphic unit and expansion and contraction of faunal remains, suggested to Rowland that environmental and climatic changes played a major role in the courses of socio-ecological outcomes. Since high-resolution techniques to assess materials recovered from the site have become available, and in pursuit of contributing a well-informed body of knowledge to management practitioners, improvements to Rowland's existing data has been improved using a multiple evidence based (MEB) approach. Components include:

- the Woppaburra seasonal resource use calendar and documented oral histories,
- a critique of existing palaeoenvironmental datasets and hypotheses offering explanations for change,
- revisiting data from early ethnographic records and Rowland's archaeological excavations,
- deployment of additional quantification measures to understand the expansion and contraction in representation of selected mollusc species,
- grounding an understanding of mollusc species growth, ecology, and behavioural traits,
- reconstructions of selected mollusc species shell sizes using biometric techniques,
- reconstructions of selected mollusc species ontogenetic ages and growth trends using sclerochronological techniques; and,
- reconstructions of selected mollusc species stable isotope signatures to build palaeoenvironmental proxies and to identify Woppaburra seasonal harvesting trends.

8.2 Synthesis of Existing Knowledge

The Woppaburra cultural map or seasonal resource use calendar is a representation of cultural identity. Seven overlapping seasons depicted in the calendar are conceptualised in such a way as to go beyond simple differences in annual climatic rhythms. The attribution of language names and songlines connecting places, resources, objects, and people, is an illustration of culture being deeply imbedded into land and seascapes. Waterways and song lines link important places across sea Country where the Woppaburra People engage in ceremony and honour cosmological and spiritual beliefs. Van Issum (2016) provides the most detailed analogy of cultural aspects imbued in the Woppaburra seasonal resource use calendar which articulates the significance of flora and faunal resources. Although all of Woppaburra sea Country is represented in the seasonal resource use calendar, *Konomie* or North Keppel Island is given special significance. The name *Konomie*, belonging to an important ancestor 'Grandmother *Conomie*', is also the name given to one of the 7 seasons depicted in the Woppaburra calendar. The humpback whale, *Mugga Mugga* being at the centre of Woppaburra cosmology, is portrayed within *Konomie* (see Figure 8.2 below).

Oyster shells appear as a dominantly featured resource in the calendar which is illustrated across more than a single season. Details for the use of mollusc meat as a food source and use of mollusc shells (e.g. body scarring and fishhooks) are included in ethnographic and oral history accounts (see Chapter 3, section 3.2.2). Shallow surface scatters and deeply deposited shell lenses at cultural sites within the Keppel Bay Islands are evidence of long-term use by the Woppaburra People. Rowland's (see 1999a) geomorphological observations and weight quantifications for taxa recovered from Mazie Bay showed evidence of changes in the abundances of species through time. These data coincided with what Rowland (1999a) defined as the 'pre-3500 buried soil event' and 'post-3500 buried soil event'. Sea-level rise and fall and regionally-scaled climatic oscillations were subsequently hypothesised by Rowland as key drivers of change (Rowland 1999a; 1999b). Met with a limited ability to retrieve high-resolution data from the geomorphological profile and molluscan remains in the 1980s and 1990s, only broad parallels between palaeoenvironmental changes and the representation of faunal remains in the Mazie Bay deposit could be drawn (Rowland 1999a; 1999b).

Opportunities to refine these understandings have since become available to the project through the application of new and accessible analytical techniques, ultimately assisting in 'cross-checking' datasets contained within resource material assemblages and regional explanations for socio-ecological changes. Concurrently, improvements to regional environmental and climatic modelling for the southern GBR region have also become available. Regional sea-level models show relative stability over the past 6000 years (~1-1.5m fluctuations) (see Leonard et al. 2016; Lewis et al. 2013; Wolanski 1994), while sea surface temperature (SST) data deduced from coral cores generally show limited variations (~1-2ºC fluctuations) (see review in Chapter 7). However, consensuses on precipitation patterns driven by interannual and intraseasonal oscillations are not yet clear. Adding a further challenge to any interpretations is river run-off and delivery of sediments from the adjacent Fitzroy and Burdekin Rivers. Exactly how flood plumes impacted the coastal geomorphology, faunal populations and human activities at Mazie Bay since the mid-Holocene is unknown. On a similar note, despite some research on sand dune and beach ridge formation processes on the adjacent mainland coast (see Brooke et al. 2008), no direct assessments for the Mazie Bay sand dune complex have been made.

Variables which have operated at Mazie Bay since the mid-Holocene and that are perhaps still in operation today, are numerous. Indeed, environmental and climatic conditions within species habitats, and their exposure to predation from humans or other predators are compelling reasons for why changes in species population structures might have occurred. A breakdown of key variables which could be directly tested and within the scope of this study was provided in Chapter 4. Targeting information about the conditions under which molluscs lived and died, and as a way for deducing human harvesting patterns, are best retrieved through the application of biometrics, sclerochronology and biogeochemistry techniques. International studies using these analytical techniques generally report the most success in defining the life histories of taxa in cases where there are strong correlations between ontogenetic age and shell size, in regions where distinct seasonal cycles can be determined (according to Western calendar systems), and in species that occupy fully marine or terrestrial environments (Andrus 2011; Jones and Quitmyer 1996). In studies situated within applied zooarchaeological contexts, foundational understandings for the growth of faunal species are usually drawn from already available ecological and biological information. In the context of the Mazie Bay mollusc species available for analytical testing, growth data from independent studies and for GBR populations more specifically, are scarce.

A further challenge considering the growth of mollusc species and Woppaburra resource use patterns was the known boundaries defining seasonal changes across different calendrical systems. In the Western calendar system, 2 distinct seasons (wet and dry) for tropical regions or 4 distinct seasons (summer, spring, autumn, winter) for temperate regions are typically acknowledged. These boundaries are constructed differently in the Woppaburra seasonal calendar as 7 overlapping phases (*Konomie*, *Tang-go-I*, *Garimal*, *Yamal*, *Yamal/Dana*, *Bapam*, *Giru*). Seasonal changes in the Woppaburra calendar are based on spiritual and cosmological understandings as well meteorological and resource availability patterns. Complexity arose when statistical testing of the datasets took place due to a limited ability to confidently assign species growth characteristics to each of the Woppaburra seasons – because each Woppaburra season is loosely overlapping and intricately linked with other criteria (e.g. the presence of indicator species and cultural meanings). Despite differences between the Western and Woppaburra seasonal calendars, 2 constant variables, temperature and precipitation, are features of both knowledge systems. These variables are identified as underpinning the growth of all living organisms. Because the dominant mollusc species represented in Woppaburra's Mazie Bay cultural site live at the crossroads of marine (saltwater) and terrestrial (freshwater) spaces in rocky shore habitats, defining each increment of shell growth against a generally coarse time-series template (because spawning cycles and growth curves for these species did not previously exist), delivered another major challenge to interpretations. These hurdles were overcome using an amalgamation of information derived from both TEK and WSK which purposefully informed each other throughout the undertaking of each analysis.

8.3 Synthesis of Analytical Results

Newly available AMS radiocarbon dates and calibration of Rowland's (1999a) conventional radiocarbon dates confirm Woppaburra occupation at Mazie Bay from at least 5000 years ago. Geomorphological assessments of Mazie Bay were not undertaken as part of this research; however, insights into sand dune building phases and sand dune hiatus phases do appear coincidental with Rowland's (1999a) observations of sediment deposition to some extent. Phase 2 (3800 cal BP to 2500 cal BP), coinciding with Rowland's (1999a) '3500 BP buried soil event', is representative of the time when the Woppaburra People harvested the highest volumes of mollusc taxa from the intertidal zone. Keeping in mind that only the relative abundance of the dominant species were quantified using minimum number of individual (MNI), number of individual specimens (NISP), and weight, most were found to come from upper intertidal rocky shores. Mangroves and estuarine habitats were also visited to harvest key species and to lesser extents sandy-mud flats and coral reefs. Despite Phase 2 assemblages having the highest MNI counts, the expansion and contraction of species rank orders confirmed slight changes in Woppaburra harvesting patterns through time. This finding was further explored by using biometric assessments to understand species shell size differences through time.

8.3.1 Biometrics

Mollusc shells comprising the cultural deep time Mazie Bay assemblage are highly fragmented. Regression analyses was therefore employed to reconstruct the maximum shell sizes of individuals. This method is routinely applied to gastropod and bivalve species recovered from deep time cultural contexts; however, no studies have reported on the application of this technique to *Acanthopleura gemmata* valves or other species comprising the family Chitonidae. Linear regression equations for *Asaphis violascens*, *Pinctada sugillata*, *Saccostrea cuccullata*, *Lunella cinerea*, *Nerita chamaeleon*, and *A. gemmata* were calculated from museum assemblages. In all assessed species, at least 3 attributes where ≥ 85% of variations could be explained, were used to estimate maximum shell sizes. Linear regression equations were subsequently used to increase the number of testable cases in the deep time species assemblages. One species in the deep time assemblage, *P. sugillata*, was highly fragmented in all cases and it was determined that biometric analysis was not feasible. While only minor changes in *A. violascens*, *S. cuccullata*, *L. cinerea* and *N. chamaeleon* deep time assemblages was found, *A. gemmata* shell sizes showed a moderate decline in size into the most recent phases of Woppaburra occupation. Biometric analyses of key species appearing in the Mazie Bay cultural resource use site ultimately showed that a non-random or size-selective harvesting approach was adopted by the Woppaburra People throughout time. Reasons for shell size changes and variability in species rank orders however, were not immediately obvious from the biometric dataset alone.

8.3.2 Sclerochronology

Three mollusc species were selected for sclerochronological analyses: *S. cuccullata*, *L. cinerea*, and *A. gemmata*. In all species, growth feature characteristics were defined in the cross-sections of shell samples as growth lines (GLs) and growth increments (GIs). The entire widths of GIs were determined to be representative of sub-annual or seasonal periods of growth with annual markers separating these periods identified as GLs. Daily and sub-daily growth characteristics appearing within each GI were not assessed but are likely to be present in these samples to varying degrees (i.e. in ontogenetically older samples or in samples that have been subjected to a range of taphonomic processes, growth characteristics at daily and sub-daily resolutions are hard to define). Ontogenetic ages in all species were successfully estimated using growth feature characteristics representing annual and seasonal growth periods. Despite small samples sizes from the deep time assemblages, findings showed no major differences in ontogenetic ages between modern and deep time *L. cinerea* and *A. gemmata*. In *S. cuccullata* however, older age classes were estimated in the deep time assemblages. Preliminary results testing the relationship between shell sizes and ontogenetic ages indicated weak correlations. Whether variability in GI widths in these species is reflective of local palaeoclimatic/palaeoenvironmental conditions, or the conditions present within each individual's microhabitat, was questioned. To explore these anomalies in more detail and to provide insight into Woppaburra resource use scheduling trends, stable isotope analyses was employed.

8.3.3 Stable Isotopes

Each mollusc species, despite being from similar rocky shore upper intertidal habitats at Mazie Bay, have unique behavioural traits and growing tolerances to variables. One variable, temperature, was tested from Mazie Bay shell samples using stable isotope analyses. A review of conditions potentially present within the microhabitats included the 'ponding' effect, whereby temperature values can be reflective of the water temperature of the pond rather than ambient SSTs. In most cases, ponded water values would be expected to be warmer than usual in tropical areas due to heating from the sun (i.e. direct penetration into shallow water pools and the heating of substrates). Ponding is often associated with *A. gemmata* which tend to rest in home scars at low tides. Home scars can be inundated with seawater at high tides, although a true ponding effect usually depends on the depth and angle in which the home scar is situated on rocky surfaces. Home scarring is not associated with *L. cinerea* although the species, similar to *A. gemmata*, has the ability to employ locomotion abilities to suitably situate themselves within their microhabitat. Species which have locomotion abilities have been found to be suitable candidates to build palaeoclimatic proxies in other studies because they often situate themselves in niche zones reflective of ambient SSTs (e.g. see *Phorcus turbinatus* study in Prendergast et al. 2013). This was certainly found to be the case for Mazie Bay *L. cinerea* shells, where δ^{18}O values successfully reflect ambient SSTs in both modern and deep time contexts. Accelerated growth occurs in *L. cinerea* during the wet season, while cooler dry season temperatures reflect periods of slowed growth. When individuals are exposed to extreme temperature changes, a growth anomaly or disturbance notch appears in their outer shell layer.

Oxygen isotope signatures retrieved from the last increments of growth in *L. cinerea* shell samples confirmed each individual died within spring (September, October, November) or the dry season according to the Western calendar system. Statistical methods using quartile percentages to deduce the seasons-of-death for each individual conveniently lend themselves well to seasonal correlations included in the Western seasonal calendar but not to the Woppaburra seasonal calendar. In the case of

L. cinerea, a sustained seasonal signature for collection during the dry season was determined. Two phases indicative of slightly cooler SST values are probably reflective of slightly earlier seasonal collection (i.e. during the change-over from winter to spring). There appears to be no change in dry season harvesting throughout time for *L. cinerea*. Furthermore, SST temperatures reconstructed from Mazie Bay *L. cinerea* shells broadly agree with the trends proposed from independent SST models situated within the marine sciences. These data agree that SST fluctuations since the mid-Holocene and prior to European occupation have been limited (fluctuations ranged between 1-2ºC). Despite the growth of *L. cinerea* appearing relatively unperturbed by these temperature changes, even slight SST changes might signal a change in growth for other species.

The seasons-of-collection for *S. cuccullata* could not be determined due to difficulties sampling within assumed increments of seasonal growth (i.e. increments are too narrow for milling with a handheld drill) and therefore only annual SST averages could be estimated. Oxygen isotope signatures from *S. cuccullata* shells showed high annual temperature variability. Because *S. cuccullata* grow affixed to rocky substrates, they do not possess the mechanism to relocate if they find themselves to be within or close to their thermal thresholds. δ^{13}C results demonstrate the potential for further examinations testing dietary carbon and uptake of trace elements that could be key in distinguishing between influences from precipitation versus run-off from the Fitzroy River. Although findings are inconclusive for *S. cuccullata* but conclusive for *L. cinerea* at this time, further biogeochemical testing would provide a more refined picture for what climatic and environmental conditions were like at Mazie Bay since the mid-Holocene and particularly throughout the sand dune building and hiatus phases. Stable isotope values for *A. gemmata* could not be completed (due to reasons outlined in Chapter 7, section 7.3.3) but it is recommended that biogeochemistry techniques are also applied to the valves of this species. Comparisons between species signatures could assist in determining microhabitat conditions from regional trends.

8.4 Synthesis of Findings

Woppaburra resource use practices portray a dynamic and cyclical pattern whereby cultural and ecological knowledge ascriptions to seasonal cues have been relied upon for thousands of years. Woppaburra's use of molluscs establishes the dynamics in these types of cyclical processes well. Recurring resource use trends by the Woppaburra People across temporal phases at Mazie Bay demonstrate:

- repeated and sustained access to major mollusc habitats (e.g. rocky shores),
- repeated and sustained use of *A. violascens*, *P. sugillata*, *S. cuccullata*, *L. cinerea*, *N. chamaeleon* and *A. gemmata*,

- repeated sustained targeting of larger bodied/mature individuals per species, and,
- repeated and sustained harvesting of *L. cinerea*, on a defined seasonal basis.

Quite remarkably, since TEK is a non-linear entity believed to rarely hold true beyond a few hundred years, the Woppaburra seasonal calendar can be described as a type of palimpsest which explains the sustained seasonal use of *L. cinerea* (see Bailey 2007 for concept of palimpsest). Indeed, loosely corresponding Western calendar months for comparisons with the 7 Woppaburra seasons are available which confirm a sustained seasonal signature for collection of *L. cinerea* during *Konomie* (September and October) (Figure 8.2). Two phases indicative of slightly cooler *Konomie* SST values are probably reflective of early seasonal collection (i.e. during the change-over from *Giru* to *Konomie* and see overlap of oysters in *Giru*). The language name '*Konomie*' has immense significance in Woppaburra culture. Grandmother *Conomie*, an ancestral figure, is also the name used to address North Keppel Island. The season, coinciding with the representation of the Woppaburra clan group totem *Mugga mugga* (humpback whale) which is also an important time of year for ceremony, is named *Konomie*. Western ideology might view these attributions of the name *Konomie* (season, ancestor and place name) as prescribing to separate entities when in fact the very name *Konomie* might be better explained as a code which interlinks the Woppaburra People with Country – ultimately contributing to total phenomena.

An important point to make, also made by Quitmyer et al. (1997:826) is that any inference for seasonal resource use does not necessarily imply seasonal occupation. Rather, a continuous occupation trend might have occurred at the same time but with seasonal resource harvesting of certain species. Abandonment of the Mazie Bay site by the Woppaburra People during seasonal, annual, or larger scaled intervals is not yet clear. That said, further investigation posits that Mazie Bay could have been occupied since the mid-Holocene during the wet season. The name *Konomie* translates to 'North Wind'. The Woppaburra People identify this period as 'a time when winds change from the predominant south-east during the mornings to east to north-east in the afternoon' (Van Issum 2016:122). At the onset of the monsoon (*Garimal*, Heat) and during the monsoon/wet season (*Yamal-Dana*, Rain-Humid) northerly winds are common along the GBR coastline. Although, the monsoon season is defined as delivering higher rainfall, a direct translation of the term underlying Western scientific understandings posits that the monsoon 'refers to the seasonality of winds' (Suppiah 1992:284). Mazie Bay might have been used as a central locale during the wet season by the Woppaburra People. Indeed, as the Woppaburra resource use calendar and TEK presents, significant travel between other islands using swimming logs for the collection of resources took place just prior to the wet season during *Garimal* (see pandanus swimming log depicted during *Garimal* and review in Van Issum 2016:125).

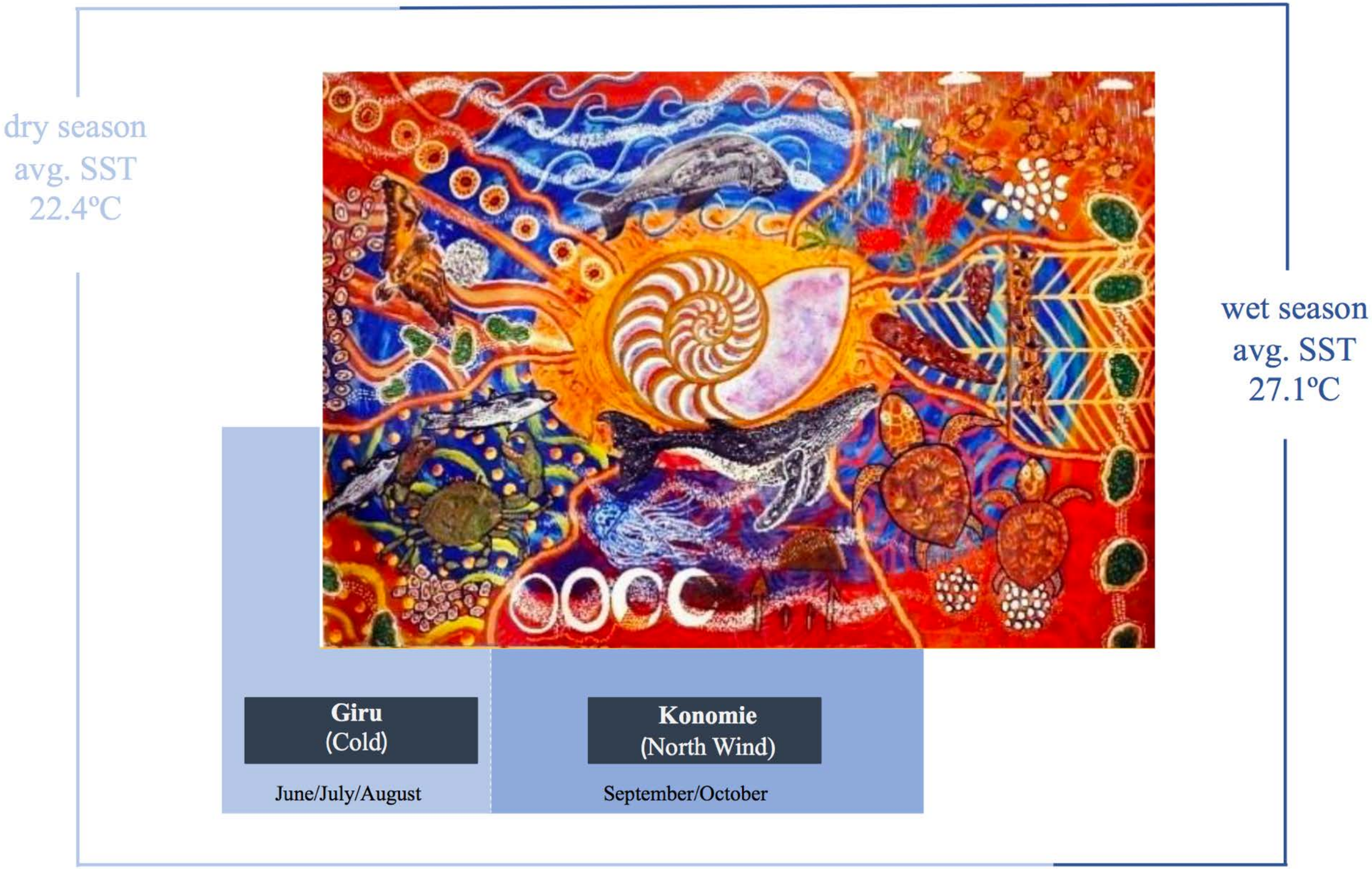


Figure 8.2 The Woppaburra cultural map (by artist Glenn Barry, in Van Issum 2016:113). Note that seasonal change occurs in an anti-clockwise rotation. Seasonal sea surface temperature averages (SST avg.) are provided for the dry season and the wet season (data source AIMS 2019).

Underlying the socio-ecological dynamics at Mazie Bay since the mid-Holocene, are multi-variable drivers resulting in non-linear changes to species rank orders and body sizes of *A. gemmata* per temporal phase. Changes in species rank orders cannot be explained by human overexploitation where the Woppaburra People opted to harvest alternate resources at the decline of a population or decrease in shell sizes (i.e. *A. gemmata*). Of further importance is that mid-Holocene Woppaburra resource use trends do not strictly fit Optimal Foraging Theory (OFT) criteria, but does illustrate a convincing case for the adoption of a long-term optimal resource procurement strategy. Body size changes in *A. gemmata* are speculated in this study to be in response to changed environmental and climatic conditions; however, geochemical testing is needed to confirm this notion. This finding is informed by relatively little difference in the estimated ontogenetic ages of *A. gemmata* despite shell sizes becoming smaller into the most recent phases of Woppaburra occupation. The inverse is true for *S. cuccullata* where ontogenetic ages are estimated to increase but with little difference in shell sizes. Changes in shell sizes, but with no detrimental change in population structure (i.e. age classes), is likely the result of changed environmental and climatic conditions. Although *A. gemmata* and *S. cuccullata* both occupy rocky shore habitats and overlapping tidal zones, the results of this study suggest that each species likely has different growth tolerances in response to a range of influencing variables.

Temperature proxies extracted from *L. cinerea* shells shows a small degree of change in SSTs through time, yet in all sclerochronologically assessed species incremental growth is highly variable. Intraseasonal oscillations such as the Madden-Julian Oscillation, delivering rainfall and/or a range of sediments and nutrients via flood plumes, is suspected to have contributed to variability in the incremental growth indices of *S. cuccullata*, *L. cinerea*, and *A. gemmata* shells sampled in this study. Given the Fitzroy and Burdekin Rivers are estimated to contribute ~70% of sediments and nutrients into the GBR lagoon (Brooke et al. 2008; Radke et al. 2010; Ryan et al. 2007), the next logical phases of examinations should encompass trace element analyses to build upon the results presented here. Indeed, Tynan et al. (2017b) report successful interpretation of Mg/Sr values in other Ostreidae species from other locations in Australia. A further complexity in the variability of *S. cuccullata* growth might be due to the inability of the species to escape intense heat exposure from the sun (i.e. directly to shells and via prolonged heating of rocky substrates). Any changes to the incremental growth of other dominant species recovered from the Woppaburra deep time site including *A. violascens*, *P. sugillata* and *N. chamaeleon* are currently unknown. Sclerochronological and biogeochemical testing of modern and deep time *A. violascens* and *N. chamaeleon* would add further insight into the growth tolerances of these species and perhaps the conditions present between upper intertidal habitats and deeper subtidal habitats at Mazie Bay. Although the habitat type representative of where *P. sugillata* populations might exist was observed during fieldwork in 2018, no live individuals were seen and none are reported to have been observed for quite some time (Creighton 1984; pers. comm. Rowland 2017; pers. obs. Aird 2017, 2018). Slight changes in climatic and environmental conditions since the mid-Holocene might have influenced their demise, or human predation might have contributed to population declines, or indeed a combination of these variables could have contributed (i.e. during deep time and/or during the historic commercial shellfish fishery period).

8.5 Applicability of the Research in Conservation Management

A common finding in many coastal locations across the globe is the unprecedented decline of natural marine resources (Pauly and Zeller 2015; Pauly et al. 1998; Worm 2016; Worm et al. 2006). Decline of resource populations often has devastating effects on human communities who rely on the ocean for survival and cultural prosperity. In several regions of the world, urgent attention is being given to the loss of biodiversity and consequent challenges faced by human communities whether in the case of overfished Atlantic Cod (*Gadus morhua*) populations in Canada (see for e.g. Norin et al. 2019; Rose 2004; Rose and Rowe 2018), or overfished Queen Conch (*Strombus gigas*) populations in the Caribbean and the Bahamas (see for e.g. Baker et al. 2016; Kough et al. 2017; Hernandez-Lamb et al. 2012). In response to threats to the resilience of the GBR, many initiatives target the monitoring of marine resources as a way of attempting to secure the ongoing survival of populations. No take areas or restricted fishing access areas are governed by the GBRMPA and in association with TUMRA agreements. Areas prioritised as needing the greatest attention are often selected based on the ecological and biological significance of an area or resource population. This point becomes obvious when we consider that most datasets utilised as baselines fail to incorporate socio-ecological practices extending back into deep time. This is not to say that datasets used to evaluate modern and historical periods have no value but rather, baseline understandings could be enriched through incorporation of archaeological datasets.

Comprehensive accounts detailing the complexities in resource use and cultural heritage can be afforded through the documentation and perhaps comparison (with appropriate cultural permissions) of long-time series datasets (e.g. comparative oyster catch records for the Holocene, historic, and modern phases) (see discussions and other examples in Aswani and Allen 2009:614; Erlandson and Rick 2008; Reitz 2004; Rick and Lockwood 2013; Steneck et al. 2002). While only one cultural deep time record could be assessed here, it forms the first baseline for the long-term use of molluscan resources within the southern GBRs 'high nutrients coastal strip'. None of the assessed species appear on the International Union for Conservation of Nature / Convention on International Trade in Endangered Species of Wild Fauna and Flora (ICUN CITES) list; however 1 taxon, *Pinctada* spp., is recognised as having undergone heavy exploitation throughout the GBR since European occupation (see overview in McPhee 2004). Strong representation of *P. sugillata* in Woppaburra's cultural deep time site, provides some insight into the range distribution of the species. Moreover, this preliminary enquiry questions if and why *P. sugillata* population ranges might have shifted through different temporal periods. Since Creighton's survey in the mid-1980s (see Creighton 1984), only a single sighting of a few *P. sugillata* shells were recorded during an Australian Museum fieldtrip to the area during 2002 (see collection photograph in Chapter 5, Figure 5.12). Although, *P. sugillata* might have been regarded as a low-grade pearl shell by commercial standards, the taxon is nonetheless important in Woppaburra culture and in the ecological structure of Keppel Bay Island reefs. Additional survey work, throughout different seasons, might reconfirm the presence or absence of *P. sugillata* populations in the region.

Live populations of *S. cuccullata*, *L. cinerea*, *N. chamaeleon* and *A. gemmata* are present at Mazie Bay and the Keppel Bay Islands today. Although there is no immediate concern for the health of these populations in the area, a 'tight feedback response' (Steinhardt et al. 2016:3) for the monitoring of these culturally important species is necessary. Should they be needed, timely resilience measures could then be put in place at the earliest stages of any identifiable risks. In this light, when undertaking examinations on live *S. cuccullata*, *L. cinerea* and *A. gemmata* in future, shell sizes should not be relied upon as a measure for population health (because, as demonstrated in this study, ontogenetic age is not reflected in maximum body sizes). Furthermore, long-lived slow growing species such as *S. cuccullata* and *A. gemmata*, would perhaps need more recovery time than short-lived fast-growing species such as *L. cinerea* should intense predation occur. Of course, this will depend on the types of variables capable of accelerating or impeding their growth. For instance, 1-2ºC temperature differences in *L. cinerea* populations will not impede their growth, however cool temperatures ≤ 19ºC, can cause a growth stoppage or in more extreme cases death (which are posited to be unlikely given Mazie Bay temperature predictions). At this time, maximum thermal tolerances for *L. cinerea*, and other species appearing in Woppaburra's cultural deep time deposit are unknown.

As other internationally based case studies have demonstrated (e.g. assessments of oysters in the Chesapeake Bay Historical Ecology project), these types of data can also be utilised to inform fishing zones, catch limits, appropriate catch seasons, and TUMRAs immediately applicable to the study area and in neighbouring localities. Indeed, major molluscan species recovered from the deep time cultural site at Mazie Bay exist to varying degrees at other coastal GBR locations, which also hold unique and intrinsic socio-ecological values (e.g. the Whitsunday Island Group, see Barker 2004). Cautionary approaches to possible differences existing between cultural values and knowledge sets on these occasions must be exercised by practitioners. In the case of the Woppaburra People, responding to land and sea management responsibilities can be described as 'caring for Country' (see Austin et al. 2018:377 for explanation of this concept in other cases) which directly maintains the 'trinity between human, physical and spiritual worlds' (Van Issum 2016:109, 131).

8.6 Recommendations for Future Research

Prior to the development of this research, no projects situated within Historical Ecology had attempted to provide a MEB approach for explaining long-term socio-ecological trajectories in a GBR setting. Rowland's work with the Woppaburra People in the 1980s and 1990s was indeed a collaborative effort; however, the completion of archaeological surveys and excavations was needed before a refinement of details used to explain long-term socio-ecological interactions could be translated into a common frame-of-reference. Without neglecting the unique significances of TEK and WSK in their respective forms, this research demonstrates how situating both knowledge systems in a communicative feedback loop during the undertaking of research enquiries are advantageous. Western scientific methods for examining datasets using statistical approaches, for example, do not always lend themselves well to testing interrelated criteria communicated via TEK. This is perhaps due to differences in how Western versus non-Western comprehension of phenomena are approached (i.e. Western scientific approaches typically adopt structured deductive measures to assess conditions whereas non-Western approaches might group different ways of knowing based on alternate types of boundaries) (see Berkes 1993:4-5, and see Table 1.1, Chapter 1).

At this intersection, statistical approaches for assessing quantitative data retrieved from the physical remains of cultural objects might seem less than an ideal approach. Although, in this particular instance, use of multi-knowledge sets have been evidently suitable for returning to details provided through TEK and for revealing a new subset of co-informed knowledge to practitioners. One immediate example that comes to mind, is the assessment of molluscan growth indices and challenges met with defining seasonal boundaries according to Western and Woppaburra seasonal calendars. This research used both deductive and non-deductive methods to suitably co-inform a new subset of knowledge, and thereby allowing the communication of findings to be explained through a common frame-of-reference. Further development of the theoretical underpinnings of this approach could explore Systems Theory, drawing together a discussion on the topic of knowledge, ways of knowing, and binary oppositions in the context of TEK and WSK (see Systems Theory in Bateson 1991).

Although this is the first project adopting a MEB approach and situated within Historical Ecology for the GBR, it does not neglect the significance of research undertaken using WSK techniques. The application of biometrics to mollusc shells has yielded valuable insights into the human use of resources in other case studies situated in the central and northern GBR in the past. Yet, these inferences cannot be used to explain the underlying complexities driving changes in socio-ecological trajectories and therefore do not lend themselves well to practical applications in conservation management. In retrospect, only after sclerochronological and biogeochemical assessments have been made to the hard skeletal structures of faunal remains, can shell size data be more informative for speculating what variables could have driven changes in resource populations. Use of sclerochronological and biogeochemistry techniques in this research has afforded direct evaluations with TEK and eliminated socio-cultural and environmentally deterministic arguments. Future research avenues might employ morphological assessments to oyster shells to understand maricultural practices potentially adopted by the Woppaburra People and, to understand environmental influences which perhaps changed shell thickness and shape (e.g. nutrient supplies and turbidity).

It is recommended that the next phase of analyses target morphological assessments of mollusc shells in combination with additional biogeochemical testing of samples. Information for sediment transportation, disease and foreign contaminants, and the delivery of nutrients to resource habitats from rainfall and/or run-off from the Fitzroy River is needed. These results could directly inform clean waterway management projects as well as providing insights into changed socio-ecological conditions since the mid-Holocene. Geomorphological examinations of the Mazie Bay complex could confirm sand dune building and hiatus phases specific to the conditions present during Woppaburra occupation and compared with adjacent mainland models. Findings could then be compared with region-wide models for sedimentation regimes since European settlement (e.g. using coral coring and coral rubble datasets e.g. McCulloch et al. 2003). Refined assessments detailing geomorphological changes and precipitation patterns since the mid-Holocene might indicate why *P. sugillata* has not been easily observed within the Keppel Bay Island area in modern times. Lastly, examinations of the breadth of economic resources comprising other deep time sites at North Keppel Island and on other Woppaburra islands using a combination of TEK and WSK techniques might confirm why site occupation is signalled from within the last ~1500 years.

8.7 Contribution of the Research

This research project was developed to directly support efforts aiming to secure resilient socio-ecological futures within the Keppel Bay Islands. An important aim has been to communicate the value of Woppaburra cultural heritage and its inseparability with sea Country. By offering a collation of knowledge for the long-term use of molluscs, findings resulting from this work can be applied within the resource and heritage management sphere. Each of the major findings are translatable at the TEK and WSK interface for practitioners to reasonably understand common frames-of-reference when working in cross-cultural contexts (i.e. including researchers, the Woppaburra community, policymakers and members of the public). Another critical point in successful negotiations and planning is the realisation that human interactions within the environment do not necessarily result in negative 'impact' (see Head 2008). Indeed, the Woppaburra's sustained and cyclic use of important mollusc resources throughout deep time is a good example showcasing the maintenance of major species populations. Customary management of sea Country, including both cultural and ecological aspects, is evident in the Woppaburra resource use calendar. Whether the maintenance of resource populations was intended in deep time, or if outcomes were epiphenomenally driven, is not known. More pressingly, throughout the last 5000-years of human occupation at the site, approaches to past resource use by the Woppaburra People (i.e. whether sustainability was intended or met epiphenomenally) might have varied through time. In either case, with a sound knowledge of the operation of key variables and mechanisms, data derived from Woppaburra's cultural deep time site at Mazie Bay can be used as a tool to predict and forecast socio-ecological resilience using a MEB grass-roots approach.

MEB grass-roots approaches are useful for responding to the aims outlined in the *2050 Traditional Owner Aspirations* document (provided in Appendix A). Although all short and long-term aspirations outlined in the document can draw on findings in this research in some way, of immediate pertinence is the facilitation of recommendation 9 'Towards Research Partnerships'; and recommendation 10 which seeks to embed traditional owners in GBR monitoring. As previously discussed, the Woppaburra People have an ongoing partnership in sea Country management with the GBRMPA and other initiatives. A continued partnership between the Woppaburra People and A/Prof. Rowland has been in play for the past 40-years. This mutually agreed research project is an extension of those efforts. Communication of the dynamics in long-term use of faunal resources, especially those that are given lesser attention in routine modern ecological assessments (i.e. molluscs), lays foundations for risk minimisation to socio-ecological structures (e.g. potential loss of significant cultural sites and/or resources) and therefore directly supports the 'Strong-Country Strong-People' framework. Finally, the socio-ecological context at Mazie Bay and the Keppel Bay Islands more broadly is routinely used as an educational case study at the North Keppel Island Environmental Education Centre (NKIEEC) for local and international groups. Field-led education, such as visits to the Mazie Bay site, snorkelling excursions, and integration of aspects of Woppaburra culture are important components of the NKIEECs curriculum. Insights into deep time cultural resource use and the application of scientific techniques to marine fauna could be built into educational discussions and formal discourses referencing long-term Woppaburra connection to sea Country.

This research contributes the first detailed analyses of growth characteristics prevalent in GBR *S. cuccullata*, *L. cinerea*, and *A. gemmata* by using advanced high-resolution techniques. Biometrical assessments contribute the finding that shell size cannot be used as a proxy for ontogenetic age in these species, but is useful for speculating upon why body sizes might have changed through time. Linear regression analyses were successful for building biometric datasets using the shell fragments of 5 species recovered from the deep time cultural site (*A. violascens*, *S. cuccullata*, *L. cinerea*, *N. chamaeleon*, and *A. gemmata*). Experimental linear regression analysis on *P. sugillata* shells were successful, although due to the flakiness of fragments recovered from the deep time site the method could not be applied. Whether *P. sugillata* linear regression equations formulated in this research could be applied to other *P. sugillata* assemblages possibly existing in other deep time sites will depend on the integrity of those fragments. Given that the species and related taxa are an important resource to

Aboriginal and Torres Strait Islander people within Australia, detailed biometric assessments of *Pinctada* spp. recovered from deep time sites could contribute preliminary data for baseline fisheries datasets. Commercial catches of *Pinctada* spp., particularly within the northern parts of the GBR and the Torres Strait Islands has a long history where the most intense period of harvesting is currently believed to have taken place during the historic period (McPhee 2004). Perhaps just as prevalent in deep time sites within Australian and the broader Pacific are the remains of chitons. Although routinely documented to be an important food resource in coastal communities, chitons are seldom used in applied zooarchaeological assessments beyond routine quantifications (e.g. weight data).

Any meaningful applied zooarchaeological analysis using chiton valves has perhaps been limited in the past due to the initial challenge of distinguishing between valves in deep time assemblage contexts. To overcome this challenge in this research, the anterior and posterior valves of *A. gemmata* were identified to contribute minimum number of individual (MNI) and number of individual specimens (NISP) counts. Reconstructing maximum body sizes using linear regression equations was successful, but despite very preliminary findings testing for these relationships with ontogenetic age, only weak correlations were found. Given that only ~3% of chiton species microstructures have been examined in the literature to date (Peebles et al. 2017), inspections of *A. gemmata* internal valve growth features and mineralogy has contributed a significant amount of knowledge to current understandings. Few studies have applied sclerochronological techniques to chiton valves but never has this technique been applied to cultural deep time samples. A degree of experimental work assessing growing axes in the posterior valves of *A. gemmata* showed that ontogenetic ages could be estimated for the species. The fact that *A. gemmata* are made of strong aragonitic cross-lamellar structures, believed to have undergone little or no change over evolutionary time, makes the species an ideal candidate for the application of biogeochemical techniques. Thorough testing of the resilience of *A. gemmata* shell valves to taphonomic processes, however, is recommended for further analysis. These assessments should focus on how shell microstructures might change when subjected to intense anthropogenic sources of heat (i.e. dry or wet heating in camp fires).

In comparison with studies situated within temperate regions in Australia and internationally, not many applied zooarchaeology projects have attempted to understand how SSTs have influenced growth in tropical species (but see Parker et al. 2017 for a recent applications). Often flagged to be the most problematic of tropical mollusc species are those situated in upper intertidal contexts because they comprise both marine and terrestrial signatures. This research offers the first account of a GBR upper intertidal mollusc species suitable for deriving palaeotemperature proxies and for estimating seasons-of-death. *Lunella cinerea* has afforded this advantage by having the ability to manoeuvre across their microhabitat into suitable niches. Growth sensitivities and behavioural traits in *L. cinerea* were largely unknown prior to this study; however, this finding suggests that other tropical upper intertidal species which have the ability to manoeuvre across vertical tidal zones could also be useful in biogeochemical assessments. Because *L. cinerea* record ambient SST signatures in their shell microstructures, the first local proxies for palaeotemperatures existing since the mid-Holocene could be determined. These signatures agree with the notion that SST fluctuations were probably within the range of 1-2ºC relative to present temperatures, at which time the Woppaburra People maintained seasonal harvesting of the species throughout *Konomie* and *Giru* during the dry season.

GBR populations of *L. cinerea* are considered 'not in danger' at this time. Should socio-ecological conditions change, *L. cinerea* growth attributes indicate that the species might be a good candidate for surviving perhaps, a larger range of temperature extremes or influences from other variables. The importance of targeting assessments on species which appear to cope with stressors well, is discussed in Darling and Côte (2018) and further highlighted in Morrison et al. (2020). Indeed, when planning for future socio-ecological resilience, changes will often be forecasted to manifest differently in comparison with past and present contexts (i.e. resource populations will not always be able to be restored to their historical baselines). This insight is not a limitation but rather an advantage to forecast and plan for the interplay of complex socio-ecological variables in future trajectories.

The significance of these findings can be described as being at least two-fold. Firstly, these findings contribute to the documentation of important aspects in Woppaburra cultural heritage and secondly contribute to baseline palaeoenvironmental understandings. Both feed into objectives set by the Environment Protection and Biodiversity Conservation Act (1999), the Environment Protection and Conservation Regulations (2000), and other international guidelines such as the Nagoya Protocol and ACHI Convention on Biological Diversity. The GBR is a global icon recognised by United Nations Educational, Scientific and Cultural Organisation (UNESCO) criteria to have outstanding natural values. Conservation of the GBR can be enhanced by recognising the unique roles Aboriginal and Torres Strait Islander people contribute to this system. TEK and ways of managing for socio-ecological resilience is best utilised in management contexts when supported with baseline understandings derived from deep time archives. Co-informed re-articulation of the conditions and relationships developed between the Woppaburra People and the environment since deep time provides clarity on the types of complexities and significance of at least 1 GBR location representative of outstanding socio-ecological value (see original clause describing the seasonal use of resources by Indigenous peoples in the UNESCO World Heritage nomination in GBRMPA 1981:16). Indeed, post-Mabo contexts (see *Native Title Act 1993*) for the nomination of important heritage places, and particularly those within the GBR, must include the consideration of long-term cultural values and practices of first nations peoples. Combining MEB approaches with the addition of using deep time baselines, could be valuable to other national and international cases for streamlining conservation planning and heritage assessments on mutually agreed terms.

Use of Archaeological Data and Traditional Ecological Knowledge in Conservation Planning

The research generated in this thesis offers a considerably large baseline for practitioner groups to improve and implement future ecological and cultural heritage conservation strategies in the Keppel Bay Island region. The following points serve as a non-exhaustive guide for practitioner teams to pursue in future conservation planning.

- Use the Keppel Bay Islands case study and relevant data to adjust practitioner attitudes.
  The Keppel Bay Islands case study is a useful educational tool for communicating the importance and advantages of 'decolonising' conservation initiatives and attitudes (i.e. through the use of a MEB approach and equal integration of cross-cultural and cross-disciplinary data). Further, practitioner teams must recognise that human resource use does not necessarily imply, in past or present contexts, negative impact.

- Use the newly generated and co-collation of data to continue to inform existing and emerging Woppaburra TOs about how cultural resources from Mazie Bay have been assessed using archaeological techniques. Continue consulting with practitioners about how cultural heritage, linked to sea Country and marine species, would be best managed into the future.
  Continuing to make data and information available to practitioner teams and individuals allows for more informed and joint decision making processes. Indeed, land and sea responsibilities can be better planned for and communicated (see 'caring for Country') when 'top-down governance' barriers are eliminated.

- With improved understandings about species growth, use biogeochemistry data and cultural knowledge to model and negotiate sizes of species populations needed to maintain healthy stock levels within the Keppel Bay Island group.
  After modelling future population growth scenarios and resource use scheduling trends, use known species growth parameters to negotiate fishing zones, catch limits and appropriate catch seasons. Data could also be used to predict how population might be affected during, for example, tropical storms (i.e. cyclones) or how routine harvesting might improve rather than impede population health (e.g. oyster beds).

- Define the current status of *P. sugillata* in the region by comparing archaeological data and data collected in the near future (i.e. modern *P. sugillata* survey data).

Archaeological data demonstrates P. sugillata was present in deep time however current stock levels are not known.

- Action the use of biogeochemistry datasets and TEK in future monitoring of intertidal and deep water molluscan species across the GBR (i.e. both modern and deep time assemblages).
  Not all molluscan species will be favourable to biogeochemistry assessments; however, there are clear advantages for the application of such analyses on some species (aside from understanding species parameters, palaeoclimate modelling is necessary for any future conservation work).

8.8 Conclusion

Over the past century, a major decline in marine resources and health of marine environments in general, has been recorded across the globe. Implementing resilience measures to protect socio-ecological structures is critical for ensuring prosperous futures. Grass-roots approaches to assessing the complexities and dynamics in past socio-ecological interactions can uncover ways in which risks in present and future trajectories can be minimised. Information derived from both TEK and WSK bases are extremely useful avenues for compiling data, understanding perspectives, and integrating knowledge for holistic views. Importantly, as Fitzpatrick and Keegan (2007:40) suitably describe, archaeology is a ‘nexus’ where social science meets natural science, and is where cross-cultural and multidisciplinary efforts can combine to address common conservation goals (Armstrong et al. 2017; Peacock et al. 2012; Peacock and Seltzer et al. 2008; Peacock et al. 2018; Mitchell and Peacock 2014; for discussion see Rick and Lockwood 2013). A MEB approach afforded cross-cultural understanding for the types of conditions and changes present in Woppaburra’s deep history at Mazie Bay. Their use of marine resources extends to at least 5000-years ago and is a compelling example of many generations’ worth of TEK. It is hoped the Historical Ecology framework can be used to further inform Keppel Bay Island management initiatives, and the broader GBR region, through successful ongoing collaborations between practitioners.

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Appendix A – Traditional Owner 2050 Aspirations

Direct excerpt from:

Dale, A., L. Wren, D. Fraser, L. Talbot, R. Hill, L. Evans-Illidge, T. Forester, M. Winer, M. George, M. Gooch, L. Hale, S. Morris and J. Carmody 2018 *Traditional Owners of the Great Barrier Reef: The Next Generation of Reef 2050 Actions: Final Report from The Reef 2050 Traditional Owner Aspirations Project*, December 2018, Australian Government.

… as a consequence of deep discussions across the GBR and synthesis of the literature and global experiences, in order of priority (and timing), we explore key emerging ***recommendations and initiatives that reflect the stated aspirations of Traditional Owners*** *regarding the* ***specific and detailed changes (or pathways to progress)*** *needed if review of Reef 2050 Plan is to genuinely meet these aspirations:*

Statement/Recommendation 1:

Resolve Sea Country Claims: *Those responsible for the management of the Reef ensure, through collaboration between relevant Federal and State agencies, that adequate resources are available to support the longer term, fair and efficient resolution of Sea Country native title claims across the GBR estate over the coming decade.*

Statement/Recommendation 2:

Get the Foundations Right: *Formalising and supporting the foundational rights and responsibilities of Traditional Owners in Sea Country by enhancing the governance capacities of families, clans, tribes, sub-regions and regions.*

Statement/Recommendation 3:

Normalise Rights-Based Agreement Making: *Embed policy, procedures and ongoing participation and support to mobilise long term approaches for co-governance and co-management through agreement making, implementation and monitoring across the GBR at regional, sub-regional, and local scales.*

Statement/Recommendation 4:

Establish a GBR Traditional Owner Sea Country Alliance: *Resource and support Traditional Owners to establish a GBR-wide Sea Country Alliance and engagement framework as a basis for negotiating and implementing a Tripartite Agreement.*

Statement/Recommendation 5:

Negotiate a GBR-Wide Tripartite Agreement: *Australian and Queensland Governments (through Intergovernmental Agreement) to meet obligations for Free, Prior and Informed Consent (in accordance with UNDRIP) through the negotiation of a whole of GBR Tripartite Agreement with Traditional Owners.*

Statement/Recommendation 6:

Establish a GBR Traditional Owner's Funding Facility: *To underpin long term and sustainable support for achieving Traditional Owner aspirations (from local to regional scales), establish a GBR funding facility and support partnership arrangements to enable program delivery and investment leverage.*

Statement/Recommendation 7:

Immediate Traditional Owner Co-Design in Programs and Procurement: *Urgent interim action is required to ensure equitable and effective Traditional Owner involvement and influence in the co-design, procurement and delivery of all current programs and tenders of relevance to their Reef-related aspirations (e.g. Great Barrier Reef Foundation (GBRF), Indigenous Advancement Strategy, Closing the Gap, etc.).*

Statement/Recommendation 8:

Ensure Fit-For-Purpose Delivery Programs: *Through leveraging the Traditional Owner Funding Facility, establish stable delivery programs that particularly support social, cultural, environmental and economic aspirations (e.g. country-based planning, meaningful jobs, infrastructure, and business development).*

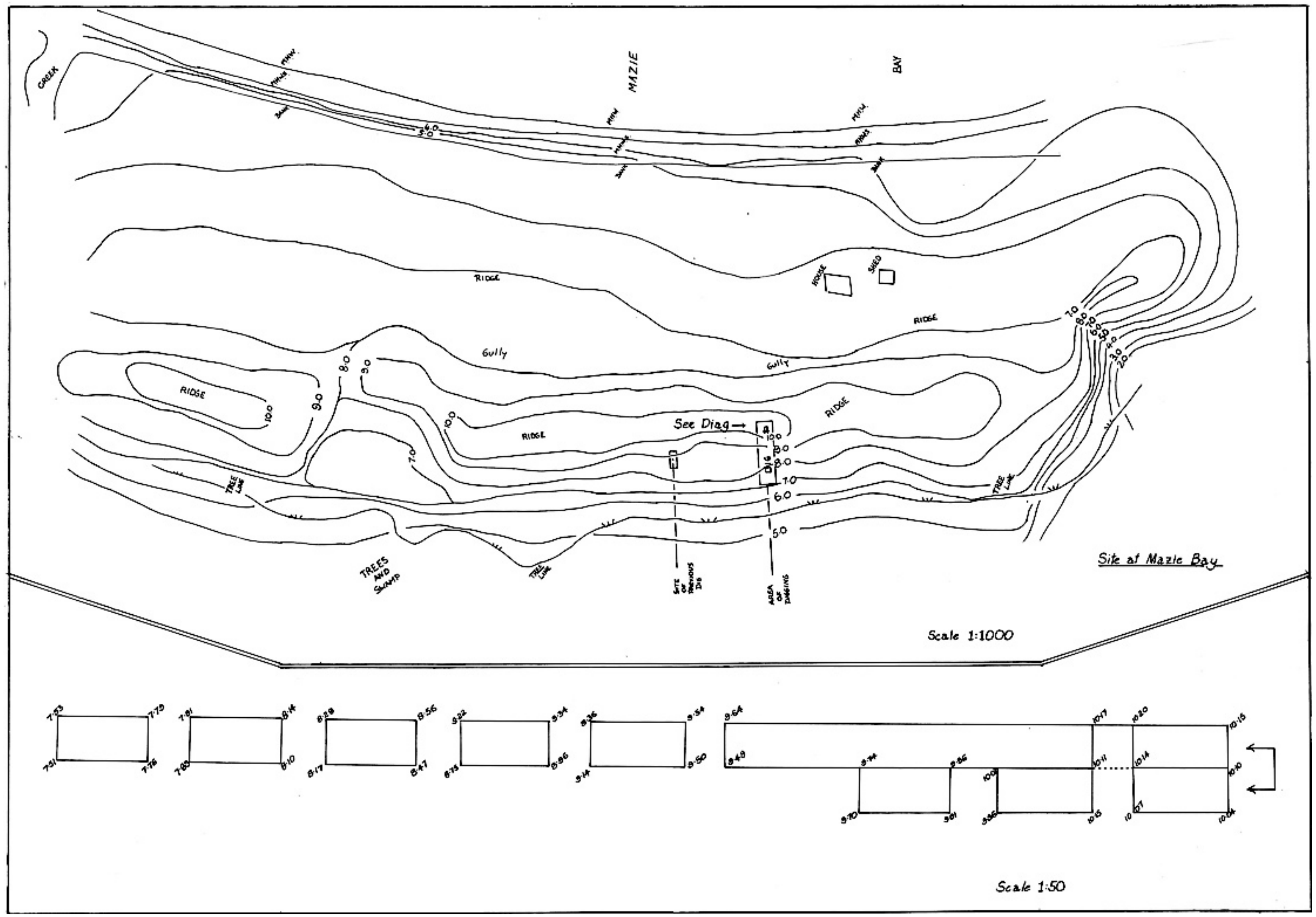
Statement/Recommendation 9:

Towards Research Partnerships: *The GBR's leading research institutions jointly collaborate with Traditional Owners to plan and negotiate a long term strategy for supporting their knowledge and research needs (e.g. data sharing agreements, etc.).*

Statement/Recommendation 10:

Traditional Owners Embedded in GBR Monitoring: *Embed Traditional Owners and cultural heritage in all aspects (e.g. turtle and dugong) and scales (from GBR-wide to local) of GBR monitoring and evaluation, using culturally appropriate approaches (e.g. Strong Country – Strong People Framework).*

Appendix B – Mazie Bay Site Plan and Summary of Weights



Site plan of Mazie Bay and location of archaeological excavations, from Rowland field notes 1981 (courtesy Rowland).

Site plan from Rowland field notes 1981 overlaid onto a Google Earth representation of Mazie Bay.

Table 3.2 Summary of weights for each taxon per excavation unit (XU), Square A1 and Square A5, Mazie Bay, from Rowland's 1979 analyses. Note: weight categories including 'rock oyster', '*Crassostrea*', '*commercialis*' and '*amasa*' from Rowland's 1979 laboratory notes is compiled here in Ostreidae category 1. Ostreidae category 2 is defined by 'light oyster' as defined by Rowland's 1979 laboratory notes. Neritidae includes shell and opercula weights, *Lunella cinerea* includes shell and opercula weights, 'chitons' from Rowland's 1979 laboratory analysis are referred to here as Polyplacophora, 'worm cases' are referred to as Polychaeta and 'pearl shell' as *Pinctada* spp.. Other nomenclature appearing in this table has not been updated from Rowland's original recordings (i.e. *Asaphis deflorata*, *Anadara trapezia*, *Turbo cinerea*).

Square	**A1**	**A1**	**A1**	**A1**	**A1**	**A1**	**A1**	**A1**
XU	**5-10cm**	**10-15cm**	**15-20cm**	**20-25cm**	**25-30cm**	**30-35cm**	**35-40cm**	**40-45cm**
BIVALVIA								
Anadara trapezia				82	22			2
Asaphis deflorata	46	83	183			73	108	168
Ostreidae ('rock oyster', '*Crassostrea'*, '*commercialis', 'amasa'*)	6060	14636	8203	1879	1206	3231	1663	2424
Ostreidae ('light oyster')		2	17	5	38	71	9	49
Pinctada spp. ('pearl shell')	3	25	359	463	782	1798	754	1884
GASTROPODA								
Dicathais orbita		21	15	45	6			
Monodonta labio		5	65	77	6	1	2	8
Neritidae	14	12	197	4	72	3	17	176
Turbo cinerea	448	62	356	147	43	69	104	652
POLYPLACOPHORA ('chiton')	505	164	238	72	459	706	77	13
POLYCHAETA ('worm cases')							12	19
CRUSTACEA								
Balanus sp.		111	72	25	9	13	12	32

Square	**A1**	**A1**	**A1**	**A1**	**A1**	**A1**	**A1**	**A1**
XU	**45-50cm**	**50-55cm**	**55-60cm**	**60-65cm**	**65-70cm**	**70-75cm**	**75-80cm**	**80-85cm**
BIVALVIA								
Anadara trapezia						48	28	
Asaphis deflorata	175	122	28	160	109	89	59	58
Ostreidae ('rock oyster', '*Crassostrea'*, '*commercialis', 'amasa'*)	2483	12497	154	14129	5854	4605	2542	2754

Ostreidae ('light oyster')	41	23	80	81	15	6	15	17
Pinctada spp. (‘pearl shell’)	1144	423	848	2015	504	671	69	106
GASTROPODA								
Dicathais orbita			3					
Monodonta labio	10	10	5	68	6	23	3	6
Neritidae	79	59	92	308	135	102	101	36
Turbo cinerea	358	195	98	561	701	285	187	206
POLYPLACOPHORA (‘chiton’)	22	29	12	56	35	27	15	43
POLYCHAETA (‘worm cases’)	20			18				
CRUSTACEA								
Balanus sp.	28	46	25	18	8	14	9	18

Square **XU**	**A1** **85-90cm**	**A1** **90-95cm**	**A1** **95-100cm**	**A1** **100-105cm**	**A1** **105-110cm**	**A1** **110-115cm**	**A1** **115-120cm**	**A1** **120-125cm**
BIVALVIA								
Anadara trapezia								
Asaphis deflorata	26	60	43	55	61		50	34
Ostreidae ('rock oyster', ‘*Crassostrea*’, ‘*commercialis*’, ‘*amasa*’)	1301	1436	643	481	1438	2694	3964	4612
Ostreidae ('light oyster')	2	3	13	7	17	18	10	3
Pinctada spp. (‘pearl shell’)	26	62	244	273	566	315	428	127
GASTROPODA								
Dicathais orbita		12				10		3
Monodonta labio	6	2	3		13	5	9	1
Neritidae	78	122	88	125	150	76	117	79
Turbo cinerea	119	110	199	181	266	169	131	107
POLYPLACOPHORA (‘chiton’)	26	19	18	20	23	46	31	28
POLYCHAETA (‘worm cases’)		5			3			
CRUSTACEA								

Balanus sp.	2	2	2		3	1		3

Square **XU**	**A1** **125-130cm**	**A1** **130-135cm**	**A1** **135-140cm**	**A5** **to 160cm**	**A5** **160-165cm**	**A5** **165-170cm**	**A5** **170-180cm**	**A5** **180-190cm**
BIVALVIA								
Anadara trapezia					18	41	83	
Asaphis deflorata	6	6		66	70	165	213	110
Ostreidae ('rock oyster', '*Crassostrea'*, '*commercialis', 'amasa'*)	1197	444	257	2038	1952	11561	11437	8371
Ostreidae ('light oyster')				23	46	457	721	1373
Pinctada spp. ('pearl shell')	49	27	22	89	824	7894	10601	14243
GASTROPODA								
Dicathais orbita	20				33	83	58	
Monodonta labio	1					9	23	24
Neritidae		11	13	225	63	1142		1000
Turbo cinerea	30	9	12	295	38	1179	1290	941
POLYPLACOPHORA ('chiton')	12	4	1	278	31	194	205	116
POLYCHAETA ('worm cases')						40	114	117
CRUSTACEA								
Balanus sp.	3	1		3	5	47	92	93

Square **XU**	**A5** **190-200cm**	**A5** **200-210cm**	**A5** **210-220cm**	**A5** **220-230cm**	**A5** **255-265cm**		Sub Totals
BIVALVIA							
Anadara trapezia							324
Asaphis deflorata	37	2	14		38		2517
Ostreidae ('rock oyster', '*Crassostrea'*, '*commercialis', 'amasa'*)	586	333	1052	12479	73		152669
Ostreidae ('light oyster')	74	5	11	106	50		3408

Pinctada spp. (‘pearl shell’)	1227	70	111	1482			50528
GASTROPODA							
Dicathais orbita				26			335
Monodonta labio	2	1	3	50	10		457
Neritidae	83	188	62	381	104		5514
Turbo cinerea	86	15	39	735	71		10494
POLYPLACOPHORA (‘chiton’)	2	3	7	76	5		3618
POLYCHAETA (‘worm cases’)			1		3		352
CRUSTACEA							
Balanus sp.	23	2	1	17	2		742
Grand Total							**230958**

Appendix C – Summary of Quantifications

Summary of taxa minimum number of individuals (MNIs) per excavation unit (XU), Square A1 and Square A5, Mazie Bay. Square A1 contains XUs between '5-10cm' and '135-140cm', with Square A5 containing XUs between 'to 160' and '255-265cm'. The unit described as 'to 160' is defined as a 20cm unit consisting of materials between 140cm and 160cm recovered from Square A5 only.

Square / XU	**A1 5-10cm**	**A1 10-15cm**	**A1 15-20cm**	**A1 20-25cm**	**A1 25-30cm**	**A1 30-35cm**	**A1 35-40cm**	**A1 40-45cm**
BIVALVES								
Asaphis violascens	3	2		4	1	3	4	
Saccostrea cuccullata	34	166	57	52	32	57	41	33
Pinctada sugillata	1	3	30	26	20	20	31	32
GASTROPODS								
Lunella cinerea	86	10	70	36	6	8	15	120
Nerita chamaeleon		20		2		6	8	3
POLYPLACOPHORA								
Acanthopleura gemmata	75	31	34	12	46	76	8	8
Sub Totals	199	232	191	132	105	170	107	196

Square / XU	**A1 45-50cm**	**A1 50-55cm**	**A1 55-60cm**	**A1 60-65cm**	**A1 65-70cm**	**A1 70-75cm**	**A1 75-80cm**	**A1 80-85cm**
BIVALVES								
Asaphis violascens	6	18	1	6	11	3	15	3
Saccostrea cuccullata	36	56	42	68	48	32	34	28
Pinctada sugillata	30	23	21	52	16	9	2	12
GASTROPODS								

Lunella cinerea	69	31	17	122	164	43	38	44
Nerita chamaeleon	24	14	17	117	46	32	20	16
POLYPLACOPHORA								
Acanthopleura gemmata	3	4	2	3	3	4	1	3
Sub Totals	168	146	100	368	288	123	110	106

Square / XU	**A1 85-90cm**	**A1 90-95cm**	**A1 95-100cm**	**A1 100-105cm**	**A1 105-110cm**	**A1 110-115cm**	**A1 115-120cm**	**A1 120-125cm**
BIVALVES								
Asaphis violascens	1	3	2	4	4		6	3
Saccostrea cuccullata	16	23	30	19	33	42	56	73
Pinctada sugillata	3	6	16	21	22	33	45	14
GASTROPODS								
Lunella cinerea	22	19	56	61	80	53	41	
Nerita chamaeleon	22	19	17		47	42	7	50
POLYPLACOPHORA								
Acanthopleura gemmata	4	3	3	6	5	6	6	4
Sub Totals	68	73	124	111	191	176	161	144

Square / XU	**A1 125-130cm**	**A1 130-135cm**	**A1 135-140cm**	**A5 to 160cm**	**A5 160-165cm**	**A5 165-170cm**	**A5 170-180cm**	**A5 180-190cm**
BIVALVES								
Asaphis violascens		1		4	3	8	8	7
Saccostrea cuccullata	47	22	23					
Pinctada sugillata	2	3	2	7	13	66	84	73

GASTROPODS								
Lunella cinerea	42	10	3	64	65	250	202	138
Nerita chamaeleon			8	60	12	213	331	260
POLYPLACOPHORA								
Acanthopleura gemmata	2	1	1	37	7	10	20	15
Sub Totals	93	37	37	172	100	547	645	493

Square / XU	**A5** **190-200cm**	**A5** **200-210cm**	**A5** **210-220cm**	**A5** **220-230cm**	**A5** **255-265cm**	Sub Totals
BIVALVES						
Asaphis violascens	3		2	8	2	149
Saccostrea cuccullata	27	12	28	37	9	1313
Pinctada sugillata	26	6	11	62	40	883
GASTROPODS						
Lunella cinerea	14	3	12	164	18	2196
Nerita chamaeleon	35	18	17	182	75	1740
POLYPLACOPHORA						
Acanthopleura gemmata		1	1	8		453
Sub Totals	105	40	71	461	144	6754
Grand Total				**6754**		

Summary of taxa number of individual specimens (NISPs) per excavation unit (XU), Square A1 and Square A5, Mazie Bay.

Square / XU	**A1 5-10cm**	**A1 10-15cm**	**A1 15-20cm**	**A1 20-25cm**	**A1 25-30cm**	**A1 30-35cm**	**A1 35-40cm**	**A1 40-45cm**
BIVALVES								
Asaphis violascens	44	64		71	31	47	102	
Pinctada spp.	14	106	364	443	469	417	781	1242
Saccostrea cuccullata	74	569	150	135	67	147	94	101
GASTROPODS								
Lunella cinerea	3	83	97	36	15	56	26	147
Nerita spp.		94	36	8	8	12	25	18
POLYPLACOPHORA								
Acanthopleura gemmata	826	306	374	106	466	791	89	58
Sub Totals	961	1222	1021	799	1056	1470	1117	1566

Square / XU	**A1 45-50cm**	**A1 50-55cm**	**A1 55-60cm**	**A1 60-65cm**	**A1 65-70cm**	**A1 70-75cm**	**A1 75-80cm**	**A1 80-85cm**
BIVALVES								
Asaphis violascens	89	212	28	78	49	35	111	23
Pinctada spp.	323	929	1409	1647	1368	103	455	568
Saccostrea cuccullata	116	143	95	150	124	74	117	61
GASTROPODS								
Lunella cinerea	79	53	47	180	230	51	39	59
Nerita spp.	44	86	57	301	143	68	53	53
POLYPLACOPHORA								
Acanthopleura gemmata	29	43	20	17	40	33	14	40

Sub Totals	680	1466	1656	2373	1954	364	789	804

Square / XU	**A1 85-90cm**	**A1 90-95cm**	**A1 95-100cm**	**A1 100-105cm**	**A1 105-110cm**	**A1 110-115cm**	**A1 115-120cm**	**A1 120-125cm**
BIVALVES								
Asaphis violascens	19	13	28	16	23		38	30
Pinctada spp.	424	293	737	712	324	1200	1420	499
Saccostrea cuccullata	40	55	64	82	112	135	139	131
GASTROPODS								
Lunella cinerea	39	43	45	73	91	83	54	
Nerita spp.	117	156	139	203	144	185	104	185
POLYPLACOPHORA								
Acanthopleura gemmata	30	22	26	36	41	73	49	29
Sub Totals	669	582	1039	1122	735	1676	1804	874

Square / XU	**A1 125-130cm**	**A1 130-135cm**	**A1 135-140cm**	**A5 to 160cm**	**A5 160-165cm**	**A5 165-170cm**	**A5 170-180cm**	**A5 180-190cm**
BIVALVES								
Asaphis violascens	10	3		48	26	26	128	71
Pinctada spp.	162	56	30	668	1192	1837	3115	1962
Saccostrea cuccullata	99	202	201					
GASTROPODS								
Lunella cinerea	88	10	3	85	72	625	73	279
Nerita spp.	92	40	41	437	137	1195	1440	848
POLYPLACOPHORA								

Acanthopleura gemmata	14	6	1	367	35	198	207	113
Sub Totals	465	317	276	1605	1462	3881	4963	3273

Square / XU	**A5 190-200cm**	**A5 200-210cm**	**A5 210-220cm**	**A5 220-230cm**	**A5 255-265cm**	Sub Totals
BIVALVES						
Asaphis violascens	8	3	4	37	20	1535
Pinctada spp.	580	373	293	1243	1674	29432
Saccostrea cucullata	85	149	148	121	88	4068
GASTROPODS						
Lunella cinerea	7	14	30	326	47	3288
Nerita spp.	208	106	199	371	249	7602
POLYPLACOPHORA						
Acanthopleura gemmata	7	5	11	95	8	4625
Sub Totals	895	650	685	2193	2086	50550
Grand Total						**50550**

Summary of taxa weights (g) per excavation unit (XU), Square A1 and Square A5, Mazie Bay.

Square / XU	**A1 5-10cm**	**A1 10-15cm**	**A1 15-20cm**	**A1 20-25cm**	**A1 25-30cm**	**A1 30-35cm**	**A1 35-40cm**	**A1 40-45cm**
BIVALVES								
Asaphis violascens	42	67		75	21	71	105	
Saccostrea cucullata	696	1775	866	612	583	802	650	584
Pinctada spp.	4	22	195	204	291	422	324	507
GASTROPODS								
Lunella cinerea	300	103	277	115	29	42	79	464
Nerita spp.		62	96	10	4	7	27	13
POLYPLACOPHORA								
Acanthopleura gemmata	496	159	233	70	488	700	75	50
Sub Totals	1538	2188	1667	1086	1416	2044	1260	1618

Square / XU	**A1 45-50cm**	**A1 50-55cm**	**A1 55-60cm**	**A1 60-65cm**	**A1 65-70cm**	**A1 70-75cm**	**A1 75-80cm**	**A1 80-85cm**
BIVALVES								
Asaphis violascens	172	304	26	95	86	86	222	56
Saccostrea cucullata	508	881	931	1342	1505	532	696	710
Pinctada spp.	337	219	344	713	232	115	71	104
GASTROPODS								
Lunella cinerea	293	155	73	466	623	198	165	189
Nerita spp.	63	116	33	314	112	55	71	49
POLYPLACOPHORA								
Acanthopleura gemmata	20	28	10	12	33	26	15	42

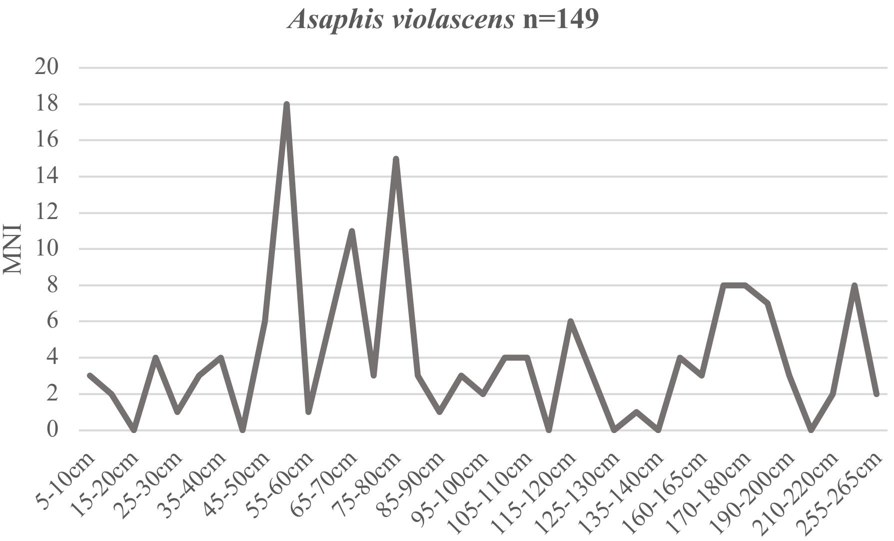
Sub Totals	1393	1703	1417	2942	2591	1012	1240	1150

Square / XU	**A1 85-90cm**	**A1 90-95cm**	**A1 95-100cm**	**A1 100-105cm**	**A1 105-110cm**	**A1 110-115cm**	**A1 115-120cm**	**A1 120-125cm**
BIVALVES								
Asaphis violascens	24	60	41	54	58		49	11
Saccostrea cuccullata	516	591	348	258	533	722	776	737
Pinctada spp.	24	60	243	277	184	287	405	116
GASTROPODS								
Lunella cinerea	108	95	178	156	234	141	129	1399
Nerita spp.	75	133	163	67	101	86	42	75
POLYPLACOPHORA								
Acanthopleura gemmata	25	17	16	18	5	23	29	25
Sub Totals	772	956	989	830	1115	1259	1430	2363

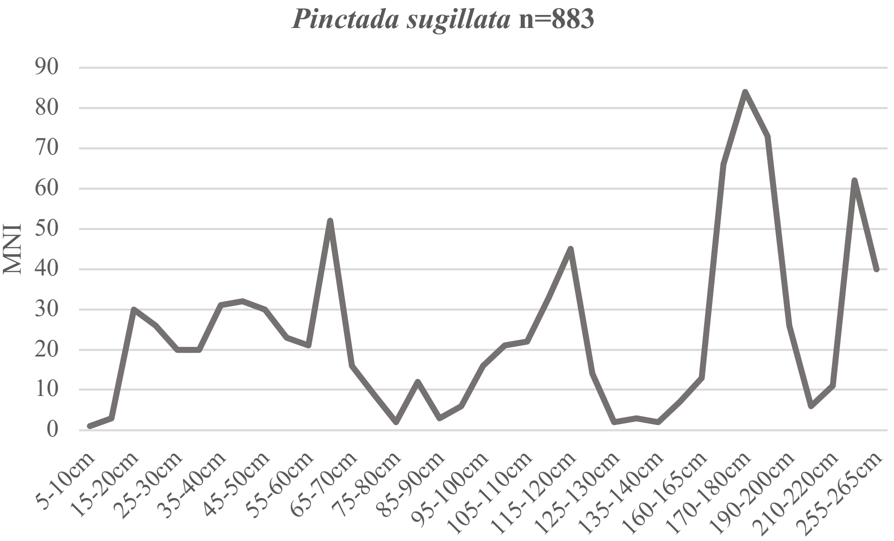
Square / XU	**A1 125-130cm**	**A1 130-135cm**	**A1 135-140cm**	**A5 to 160cm**	**A5 160-165cm**	**A5 165-170cm**	**A5 170-180cm**	**A5 180-190cm**
BIVALVES								
Asaphis violascens	6	6		111	69	126	102	108
Saccostrea cuccullata	493	418	253					
Pinctada spp.	49	35	18	85	358	761	689	887
GASTROPODS								
Lunella cinerea	118	6	9	236	205	1399	1055	852
Nerita spp.	37	8	39	285	78	1147	1096	1009
POLYPLACOPHORA								

Acanthopleura gemmata	10	3	1	272	32	200	172	108
Sub Totals	713	476	320	989	742	3633	3114	2964

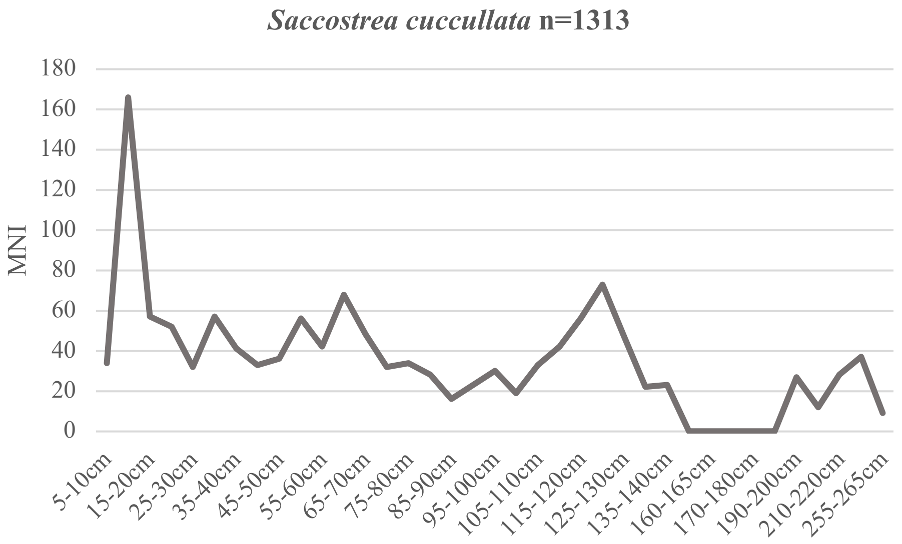
Square / XU	**A5 190-200cm**	**A5 200-210cm**	**A5 210-220cm**	**A5 220-230cm**	**A5 255-265cm**	Sub Totals
BIVALVES						
Asaphis violascens	36	107	14	53	37	2500
Saccostrea cucullata	391	332	586	645	71	21343
Pinctada spp.	322	68	111	522	493	10098
GASTROPODS						
Lunella cinerea	65	9	29	656	48	10698
Nerita spp.	128	50	76	474	132	6333
POLYPLACOPHORA						
Acanthopleura gemmata	1	1	6	78	4	3503
Sub Totals	943	567	822	2428	785	54475
Grand Total						**54475**



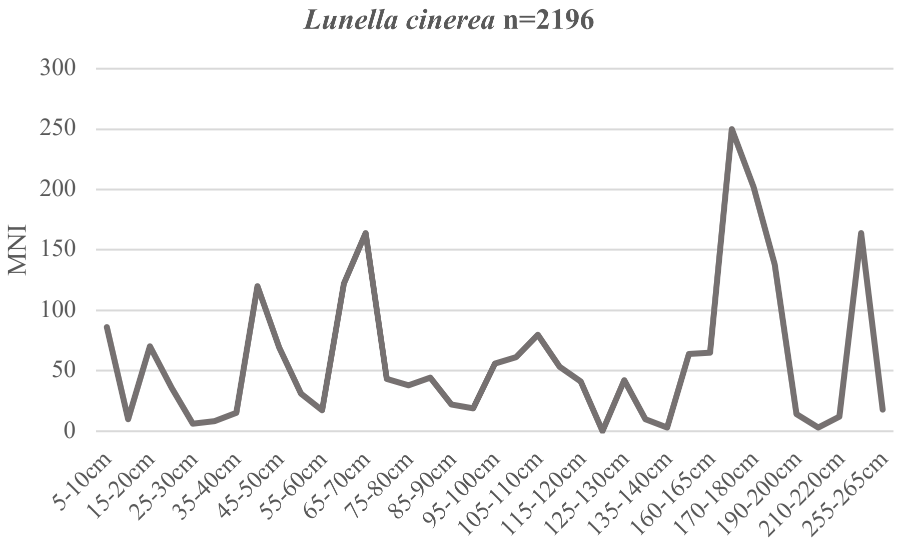
Asaphis violascens minimum number of individuals (MNI) per excavation unit (XU), Square A1 and Square A5, Mazie Bay.



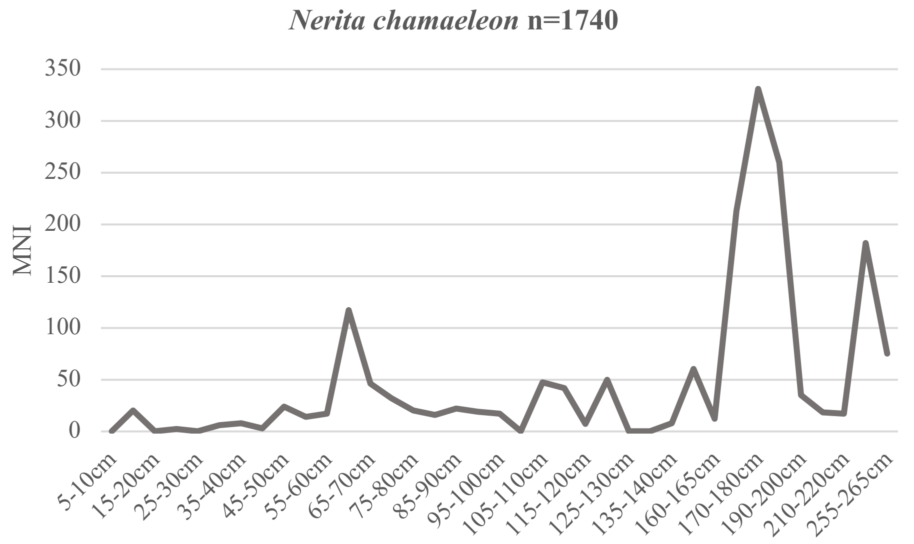
Pinctada sugillata minimum number of individuals (MNI) per excavation unit (XU), Square A1 and Square A5, Mazie Bay.



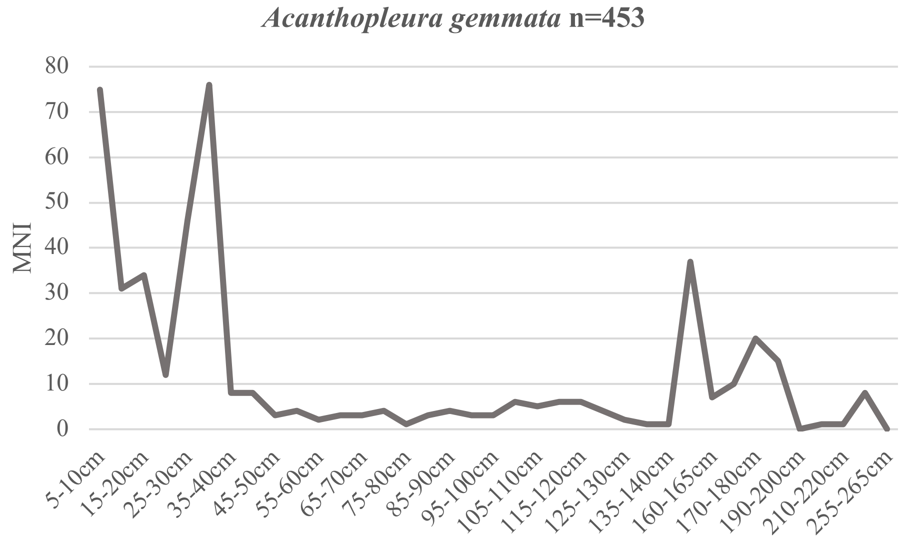
Saccostrea cuccullata minimum number of individuals (MNI) per excavation unit (XU), Square A1 and Square A5, Mazie Bay.



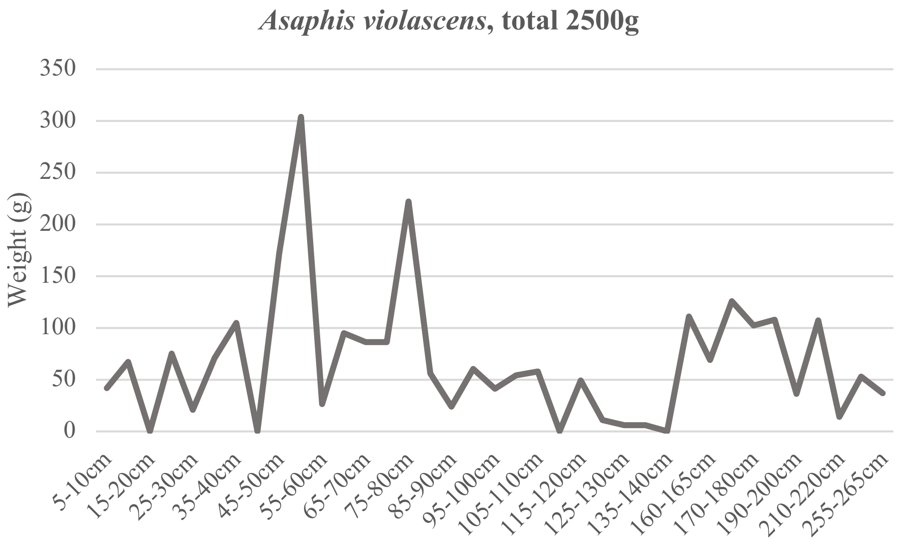
Lunella cinerea minimum number of individuals (MNI) per excavation unit (XU), Square A1 and Square A5, Mazie Bay.



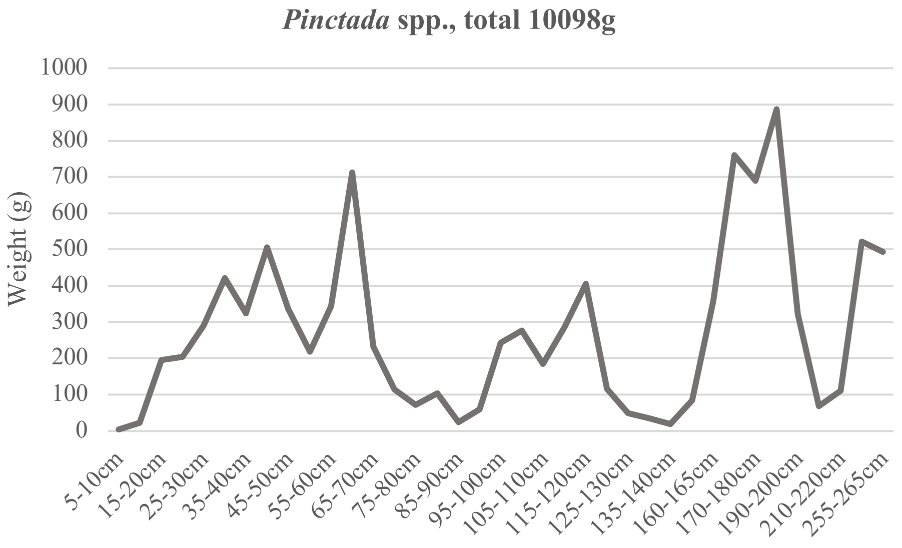
Nerita chamaeleon minimum number of individuals (MNI) per excavation unit (XU), Square A1 and Square A5, Mazie Bay.



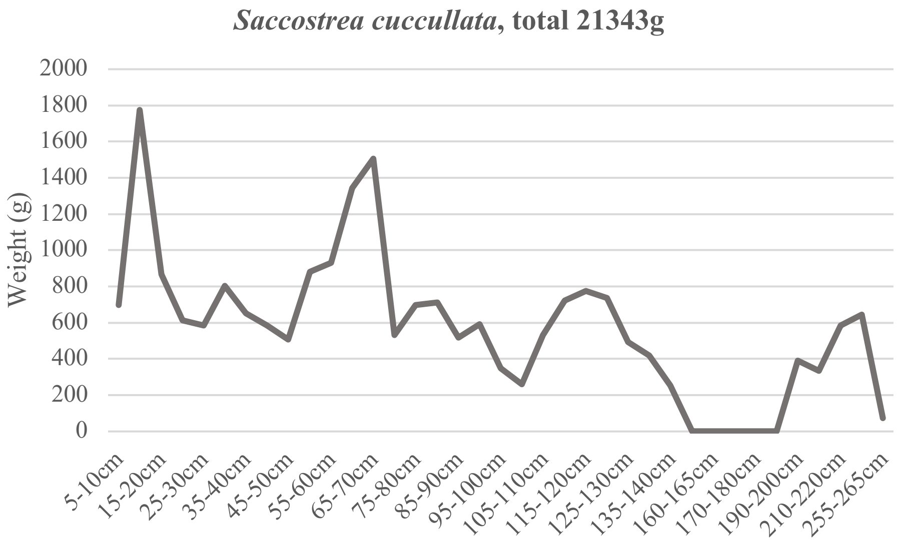
Acanthopleura gemmata minimum number of individuals (MNI) per excavation unit (XU), Square A1 and Square A5, Mazie Bay.



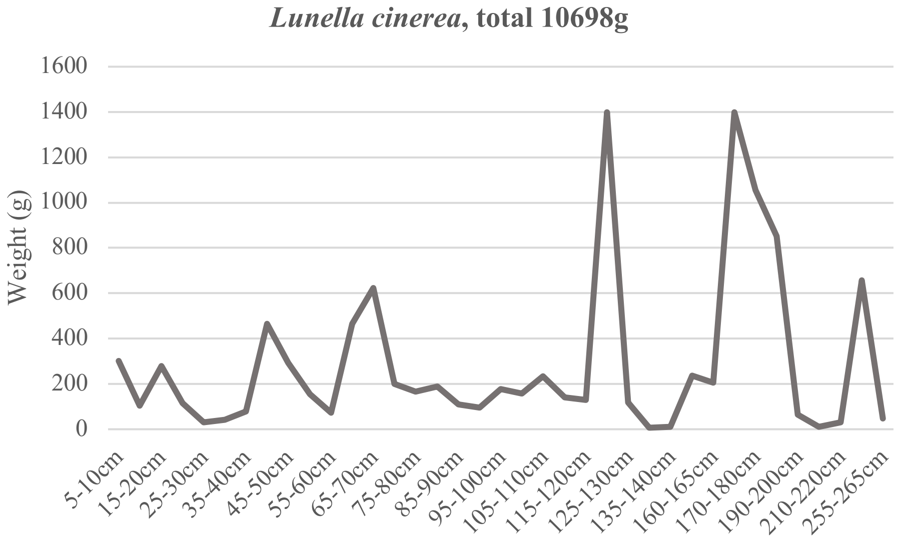
Asaphis violascens weights per excavation unit (XU), Square A1 and Square A5, Mazie Bay.



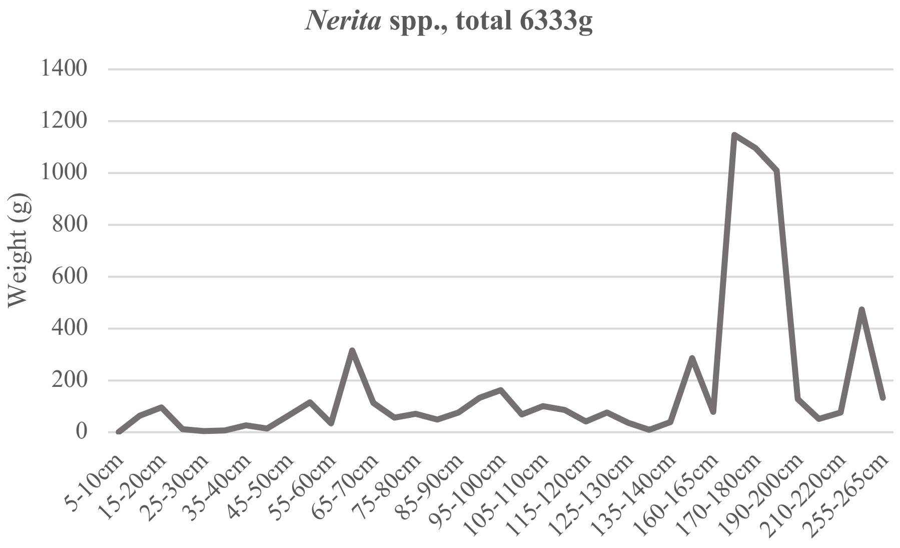
Pinctada spp. weights per excavation unit (XU), Square A1 and Square A5, Mazie Bay.



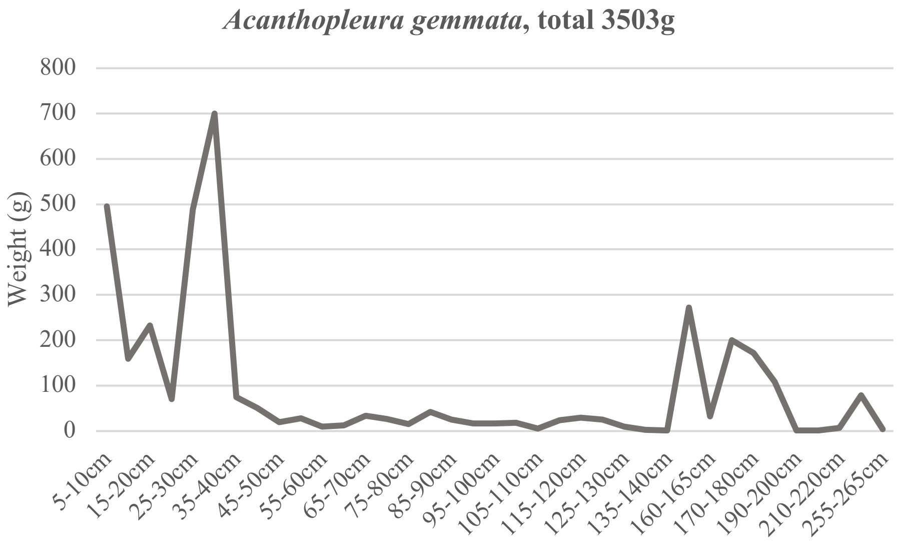
Saccostrea cuccullata weights per excavation unit (XU), Square A1 and Square A5, Mazie Bay.



Lunella cinerea weights per excavation unit (XU), Square A1 and Square A5, Mazie Bay.



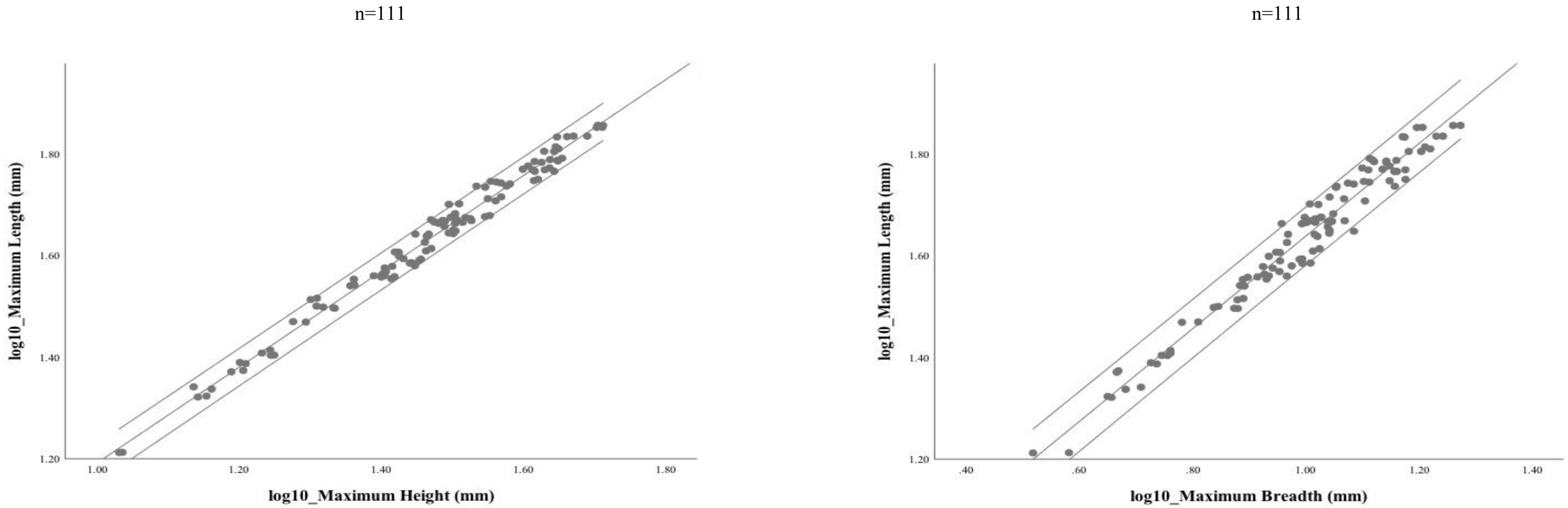
Nerita spp. weights per excavation unit (XU), Square A1 and Square A5, Mazie Bay.



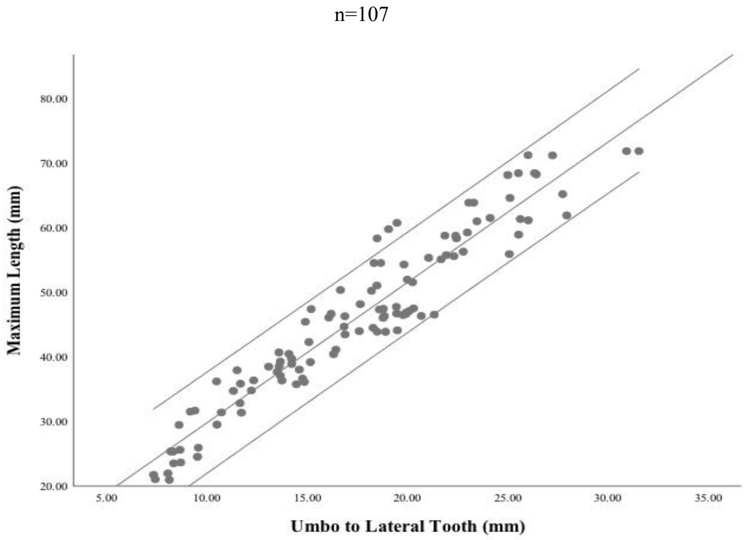
Acanthopleura gemmata weights per excavation unit (XU), Square A1 and Square A5, Mazie Bay.

Appendix D – Linear Regression Scatter Plots for Museum Samples

Asaphis violascens

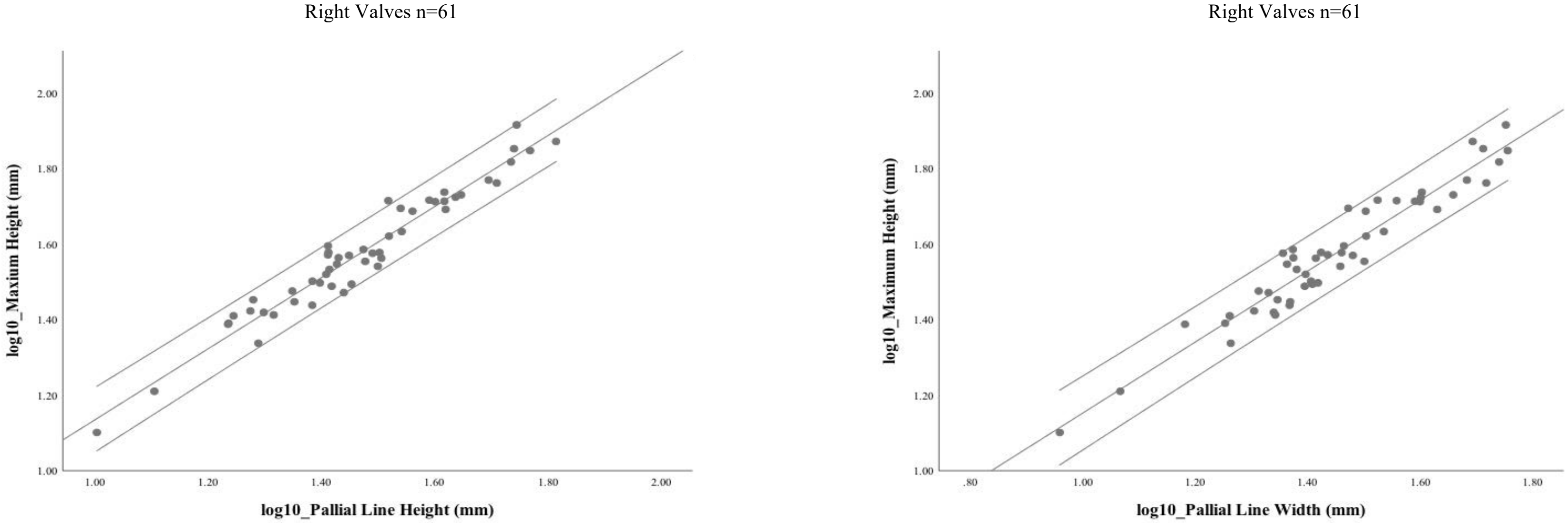


Linear regression scatter plots for independent *Asaphis violascens* samples, showing the 95% confidence intervals.



Linear regression scatter plots for independent *Asaphis violascens* samples, showing the 95% confidence intervals.

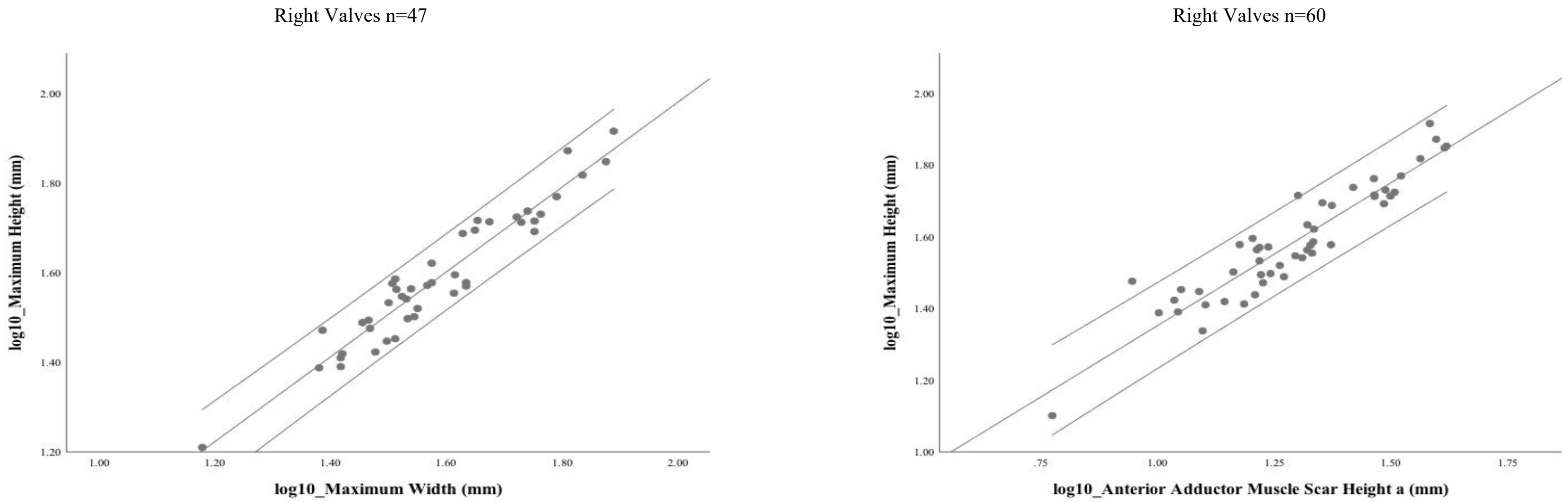
Pinctada sugillata, right valves



Right Valves n=61

Right Valves n=61

Linear regression scatter plots for independent right valve *Pinctada sugillata* samples, showing the 95% confidence intervals.

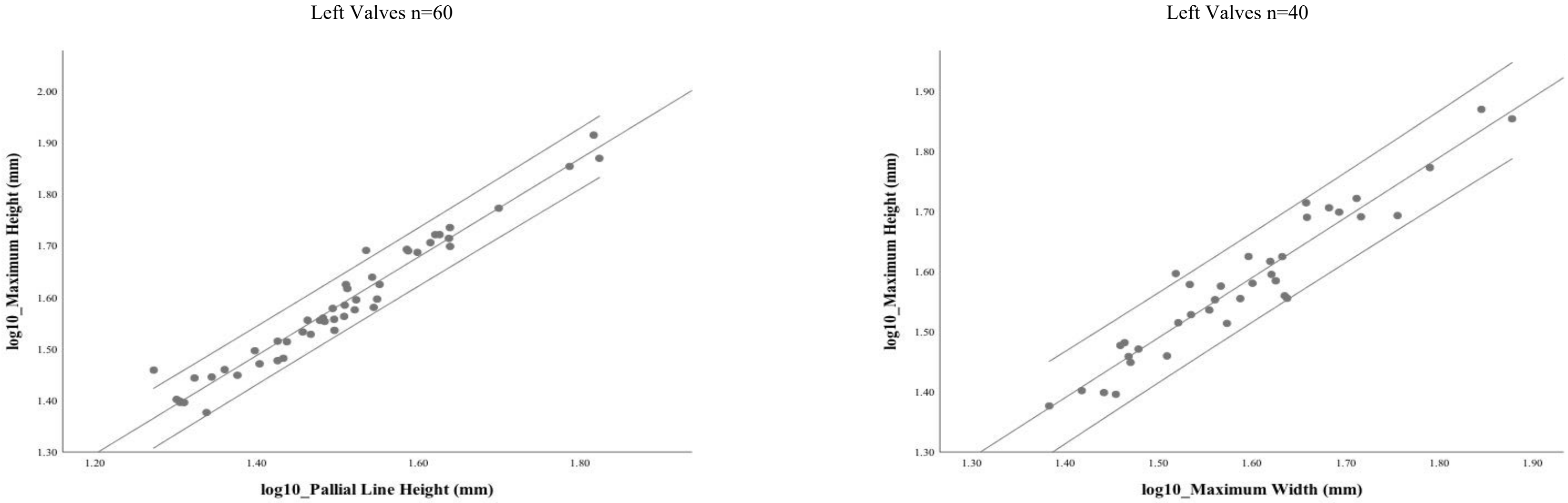


Right Valves n=47

Right Valves n=60

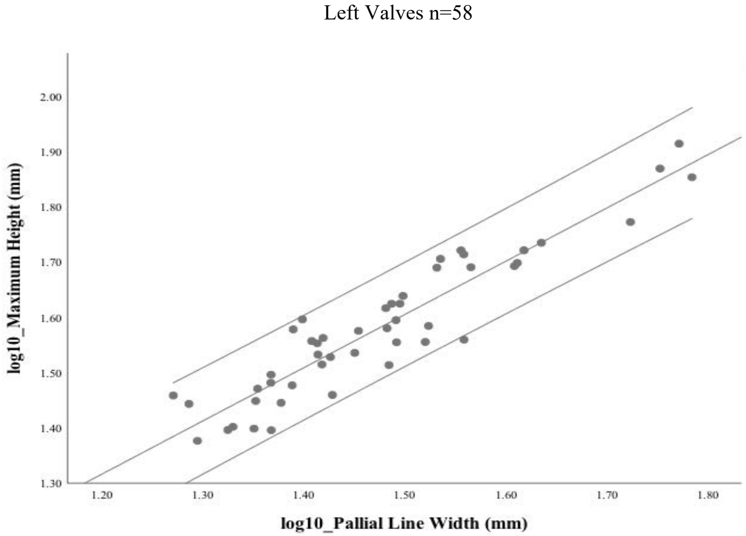
Linear regression scatter plots for independent right valve *Pinctada sugillata* samples, showing the 95% confidence intervals.

Pinctada sugillata, left valves


Left Valves n=60

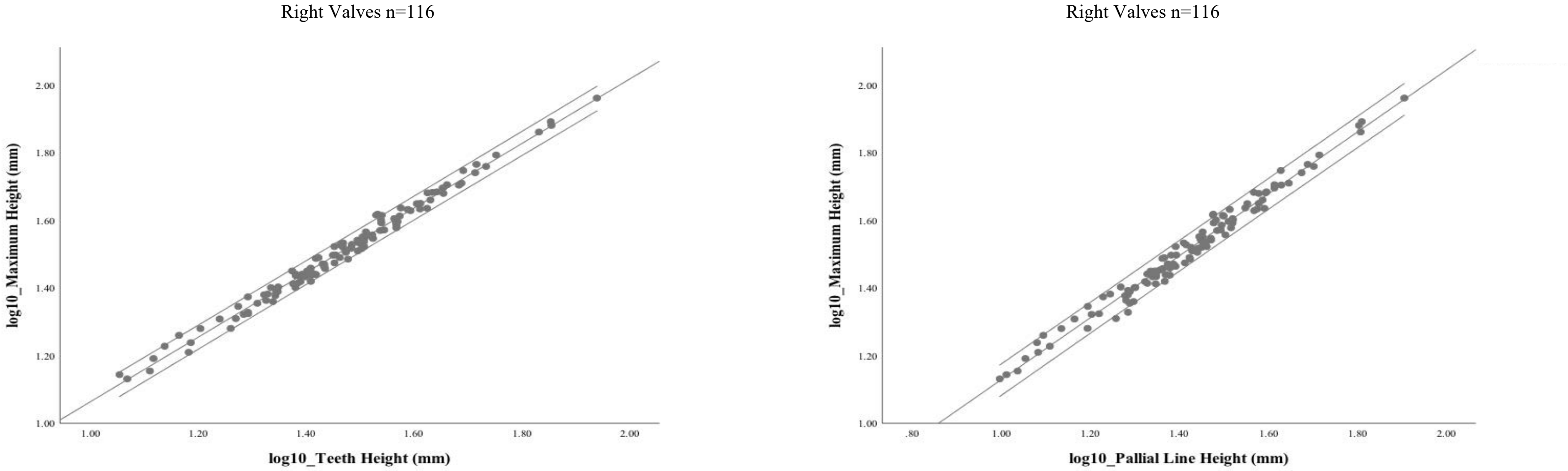
Left Valves n=40

Linear regression scatter plots for independent left valve *Pinctada sugillata* samples, showing the 95% confidence intervals.

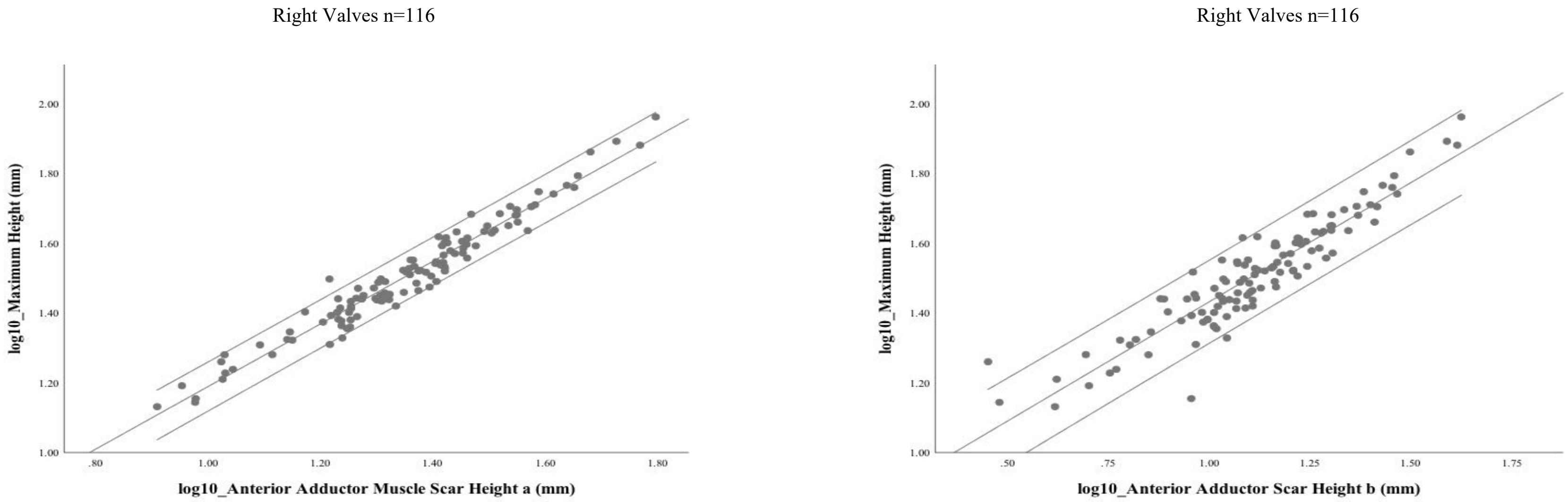

Left Valves n=58

Linear regression scatter plots for independent left valve *Pinctada sugillata* samples, showing the 95% confidence intervals.

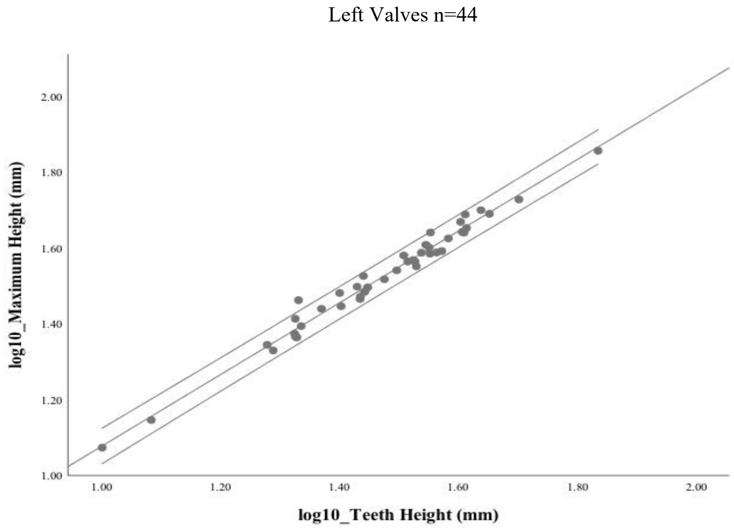
Saccostrea cuccullata, right valves



Linear regression scatter plots for independent right valve *Saccostrea cucullata* samples, showing the 95% confidence intervals.

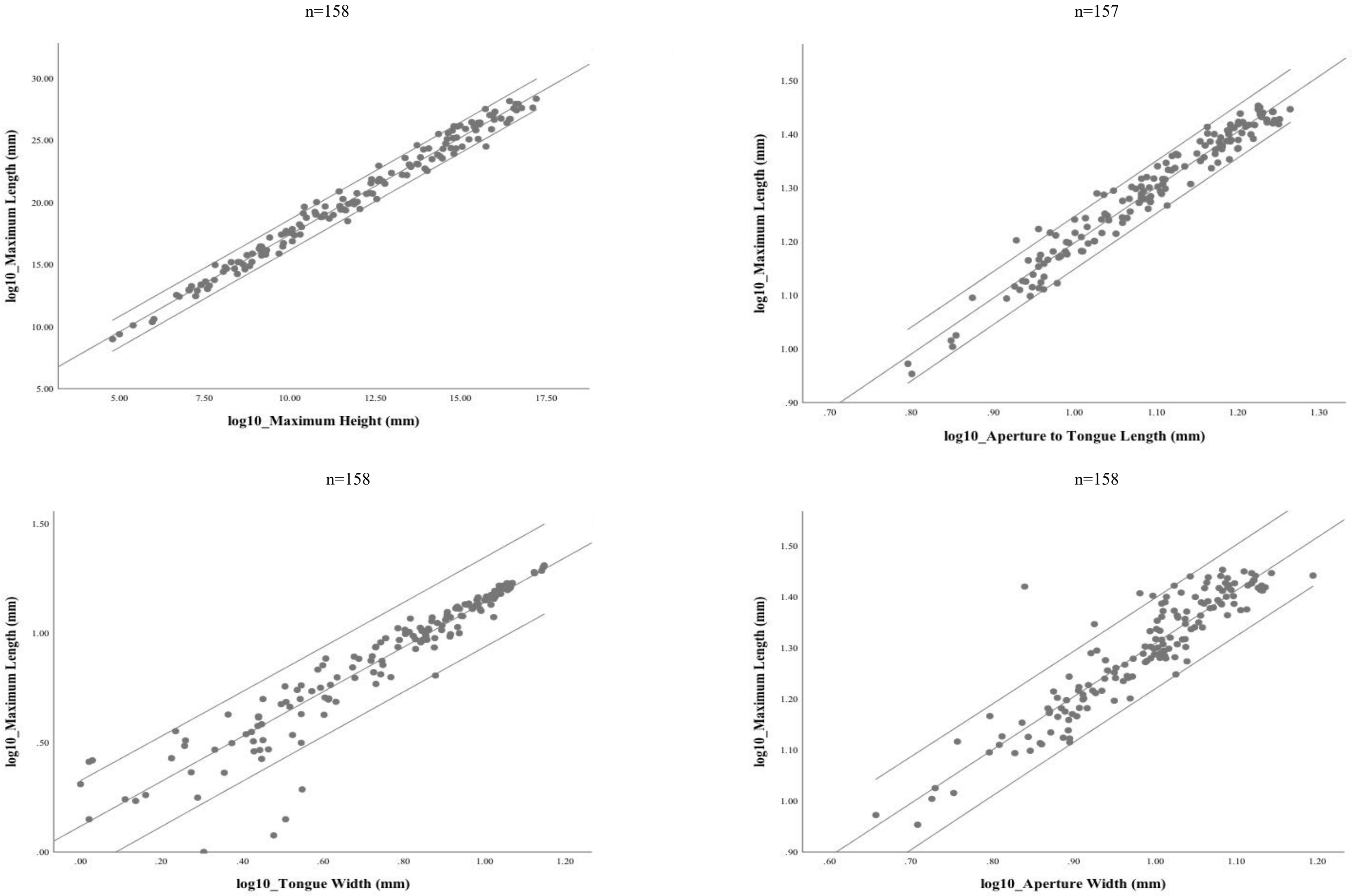


Linear regression scatter plots for independent right valve *Saccostrea cucullata* samples, showing the 95% confidence intervals.

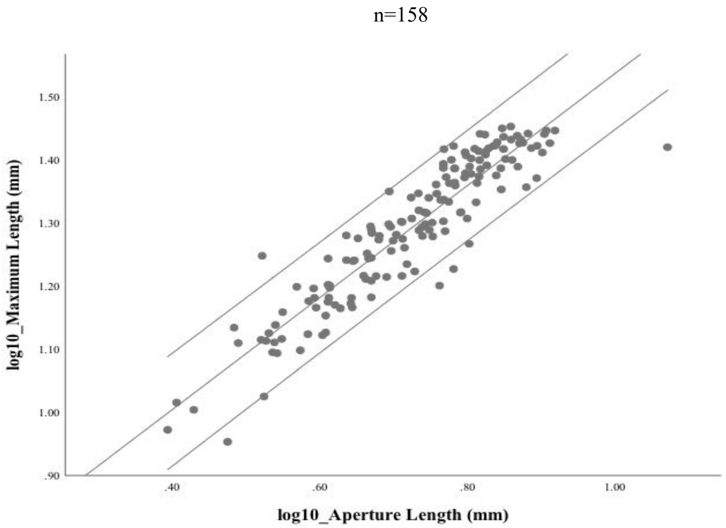


Linear regression scatter plot for the independent left valve *Saccostrea cucullata* sample, showing the 95% confidence intervals.

Nerita chamaeleon

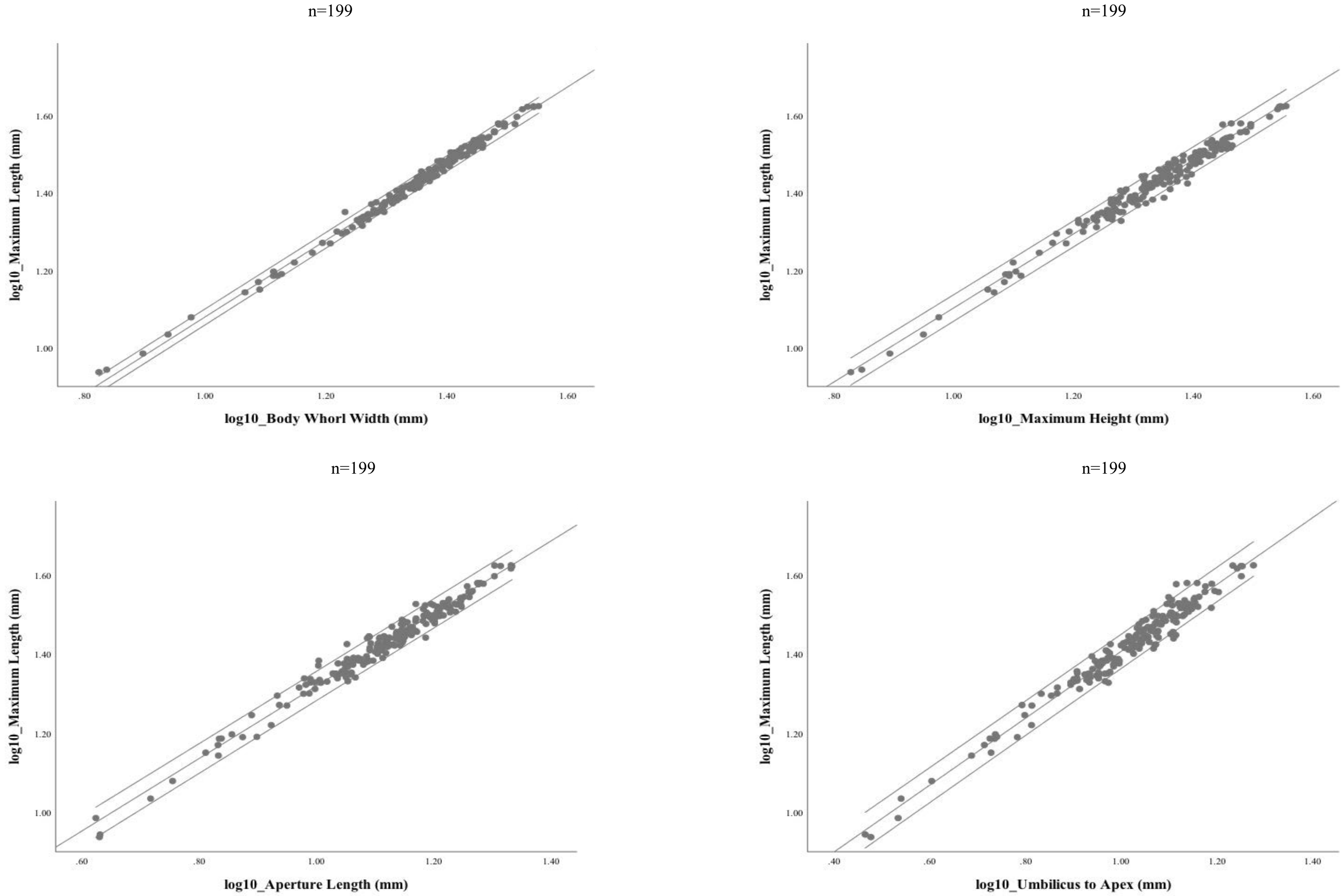


Linear regression scatter plots for independent *Nerita chamaeleon* samples, showing the 95% confidence intervals.



Linear regression scatter plots for independent *Nerita chamaeleon* samples, showing the 95% confidence intervals.

Lunella cinerea

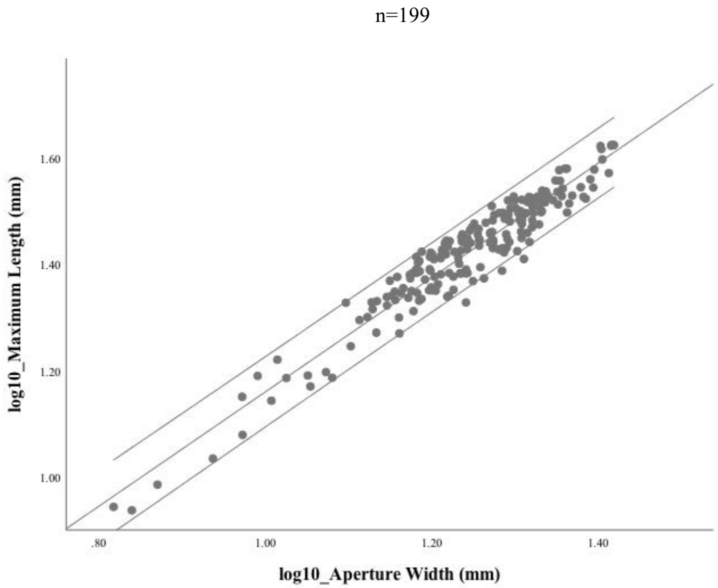

n=199

n=199

n=199

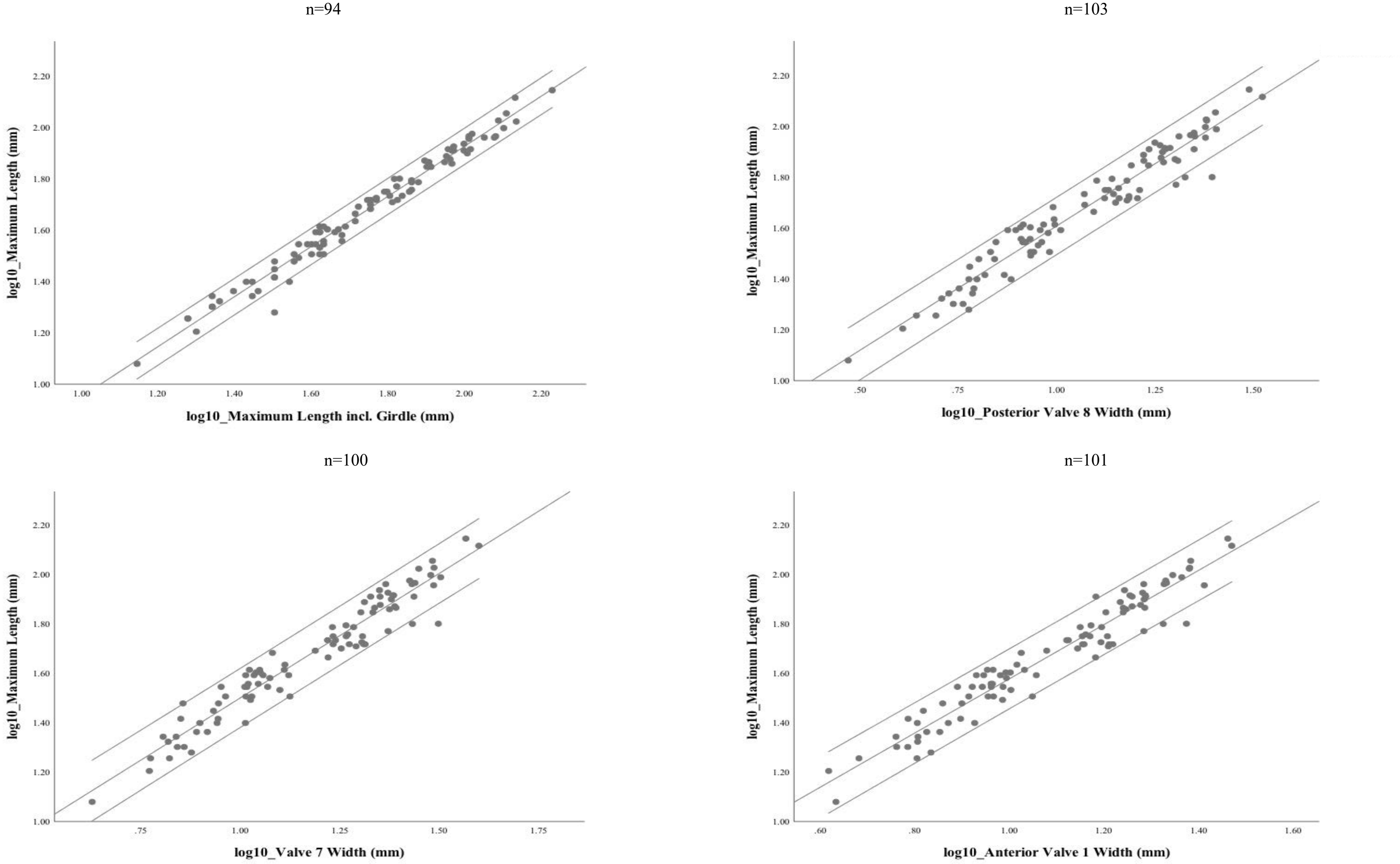
n=199

Linear regression scatter plots for independent *Lunella cinerea* samples, showing the 95% confidence intervals.

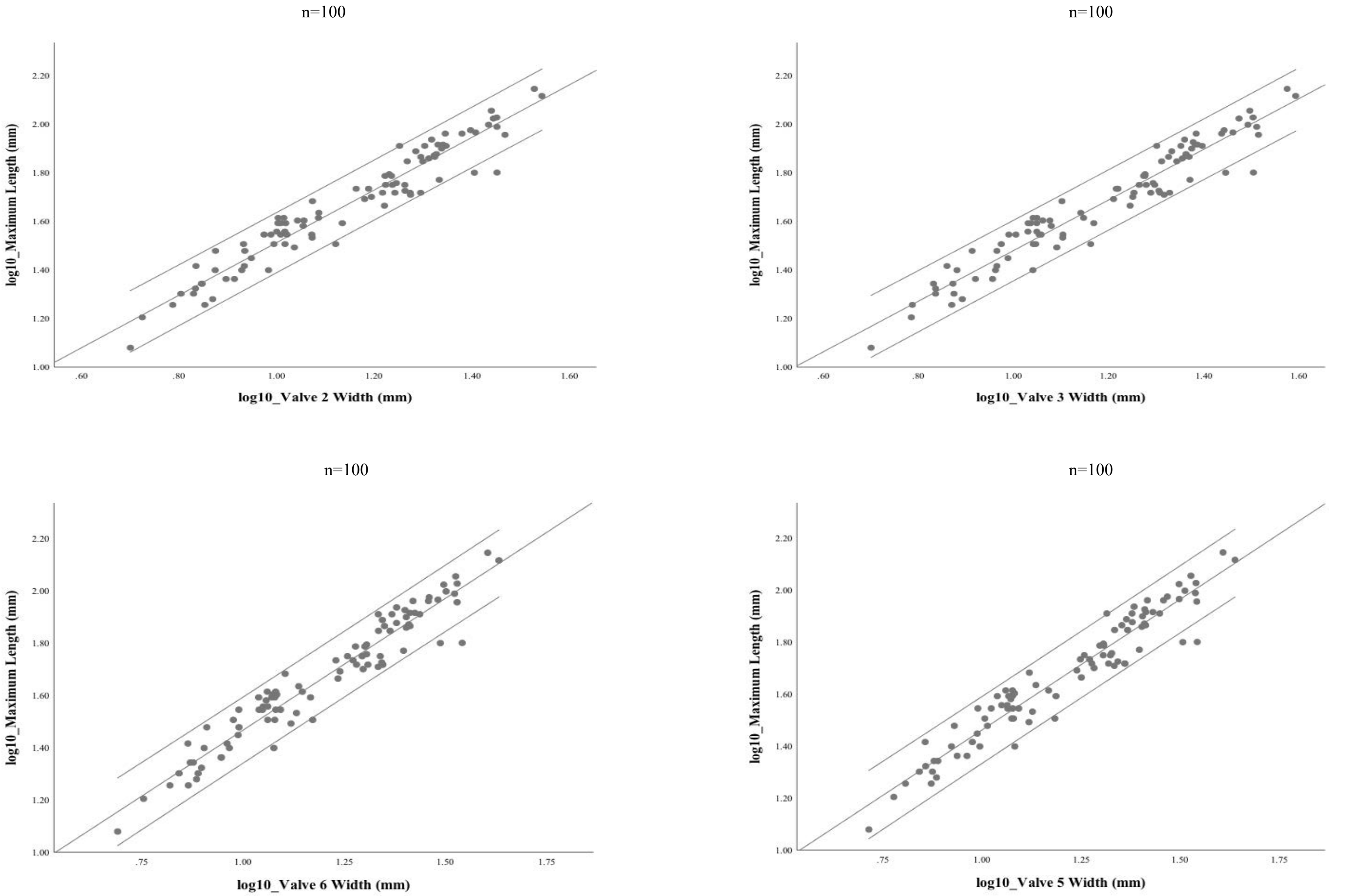


Linear regression scatter plots for independent *Lunella cinerea* samples, showing the 95% confidence intervals.

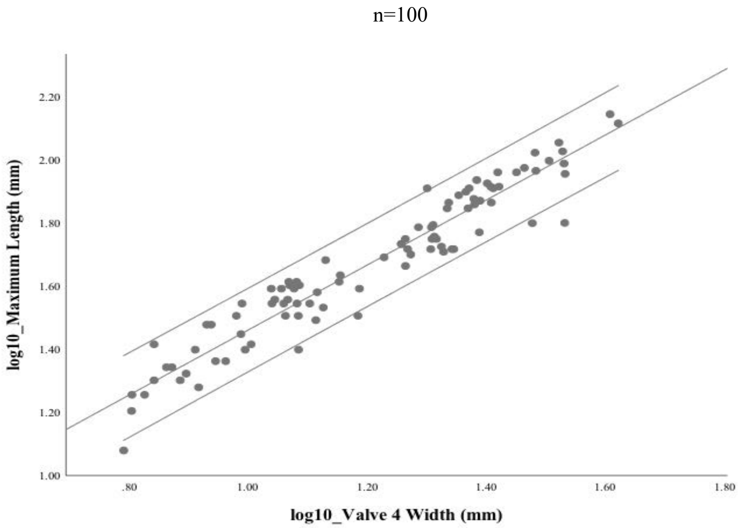
Acanthopleura gemmata



Linear regression scatter plots for independent *Acanthopleura gemmata* samples, showing the 95% confidence intervals.



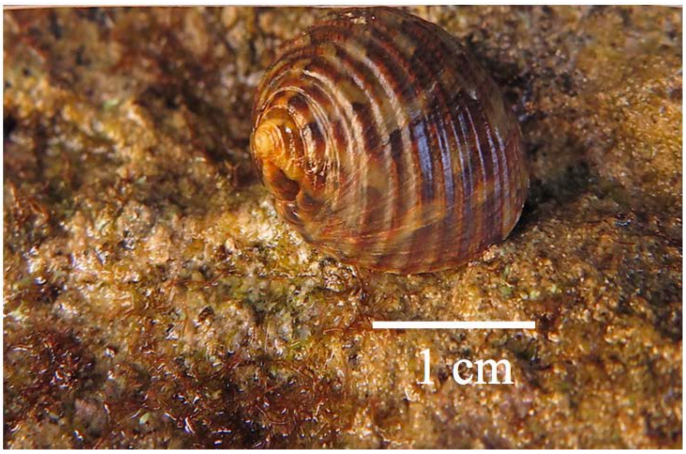
Linear regression scatter plots for independent *Acanthopleura gemmata* samples, showing the 95% confidence intervals.



Linear regression scatter plots for independent *Acanthopleura gemmata* samples, showing the 95% confidence intervals.

Appendix E – *Nerita chamaeleon* Collection Data, Mazie Bay 2018

Nerita chamaeleon were hand collected alive from the upper intertidal zone at Mazie Bay (n=6). The species was easy to identify and extract from the rocks by hand. Shadow movement across the species (i.e. the collectors hand) resulted in foot muscle retraction. The species occupied sunny and shady positions. More individuals were observed at night than during the day in the same areas. Nocturnal and early morning movement of *N. chamaeleon* across sandy patches was observed. A dominant direction towards the water line was not apparent. Other Neritidae species, including fragments of their shells, were observed in the same locations.



Nerita chamaeleon field specimen #2, live-collected from Mazie Bay North Keppel Island, September 2018 (Photograph: Aird 2018).

North Keppel Island (centre) showing live-collection zones in proximity to the Mazie Bay cultural resource use site (Basemap: Google Earth 2016). Top left live-collection zone: *Nerita chamaeleon* samples #4-6, top right live-collection zone: *Nerita chamaeleon* #1-3.

Summary data of live-collected *Nerita chamaeleon* samples from Mazie Bay, North Keppel Island. All samples were collected from large boulders on the rocky shore.

Date	Coordinates	Tide	Collection Time	Field Specimen #	Wet Weight (g)
11/9/18	S 23 05.032 E 150 53.616	Low tide	3.30pm- 4.30pm	1	2
11/9/18	S 23 05.036 E 150 53.614	Low tide	3.30pm- 4.30pm	2	1
11/9/18	S 23 05.034 E 150 53.614	Low tide	3.30pm- 4.30pm	3	1
12/9/18	S 23 04.907 E 150 53.555	Outgoing low tide	2.30pm- 3.30pm	4	1
12/9/18	S 23 04.923 E 150 53.555	Outgoing low tide	2.30pm- 3.30pm	5	1
12/9/18	S 23 04.928 E 150 53.554	Outgoing low tide	2.30pm- 3.30pm	6	2

Appendix F – Mollusc Shell Section Images and Metric Data

Directory

Note: anterior *Acanthopleura gemmata* deep time valve data can be consulted in Appendix G.

F.1 Live-Collected *Saccostrea cuccullata*, Left Valves

F.1.1 Metric Data

Metrical data for *Saccostrea cuccullata* left valve LC#1 growth features.

Year	GI Width (mm)	GI Comments
2006	0.5	Thin dark annual growth lines, thick light annual growth increments. Some precipitation of dark pigmentation in annual growth lines.
2006 – 2007	0.5	
2007 – 2008	1	
2008 – 2009	0.8	
2009 – 2010	0.4	
2010 – 2011	0.3	
2011 – 2012	0.7	
2012 – 2013	0.4	
2013 – 2014	0.4	
2014 – 2015	0.3	
2015 – 2016	0.3	
2016 – 2017	0.3	
2017 – 2018	0.2	
Average (mm)	0.46	
Min (mm)	0.2	
Max (mm)	1	

Metrical data for *Saccostrea cuccullata* left valve LC#2 growth features.

Year	GI Width (mm)	GI Comments
2014	2.1	Thin dark annual growth lines, thick light annual growth increments. Some precipitation of dark pigmentation in annual growth lines.
2014 – 2015	3.3	
2015 – 2016	1.2	
2016 – 2017	1.3	
2017 – 2018	0.6	
Average (mm)	1.7	
Min (mm)	0.6	
Max (mm)	2.1	

Metrical data for *Saccostrea cuccullata* left valve LC#3 growth features.

Year	GI Width (mm)	GI Comments
2013	1	Thin dark annual growth lines, thick light annual growth increments. Some precipitation of dark pigmentation in annual growth lines.
2013 – 2014	0.7	
2014 – 2015	0.4	
2015 – 2016	0.5	
2016 – 2017	0.2	
2017 – 2018	0.4	
Average (mm)	0.53	
Min (mm)	0.2	
Max (mm)	1	

Metrical data for *Saccostrea cuccullata* left valve LC#4 growth features.

Year	GI Width (mm)	GI Comments
2004	0.6	Thin light growth lines, thick dark growth increments.
2004 – 2005	0.2	
2005 – 2006	0.2	
2006 – 2007	0.2	
2007 – 2008	0.3	
2008 – 2009	0.5	
2009 – 2010	0.5	
2010 – 2011	0.3	
2011 – 2012	0.6	
2012 – 2013	0.3	
2013 – 2014	0.3	
2014 – 2015	0.3	
2015 -2016	0.3	
2016 – 2017	0.3	
2017 – 2018	0.3	
Average (mm)	0.34	
Min (mm)	0.2	
Max (mm)	0.6	

Metrical data for *Saccostrea cuccullata* left valve #5 growth features.

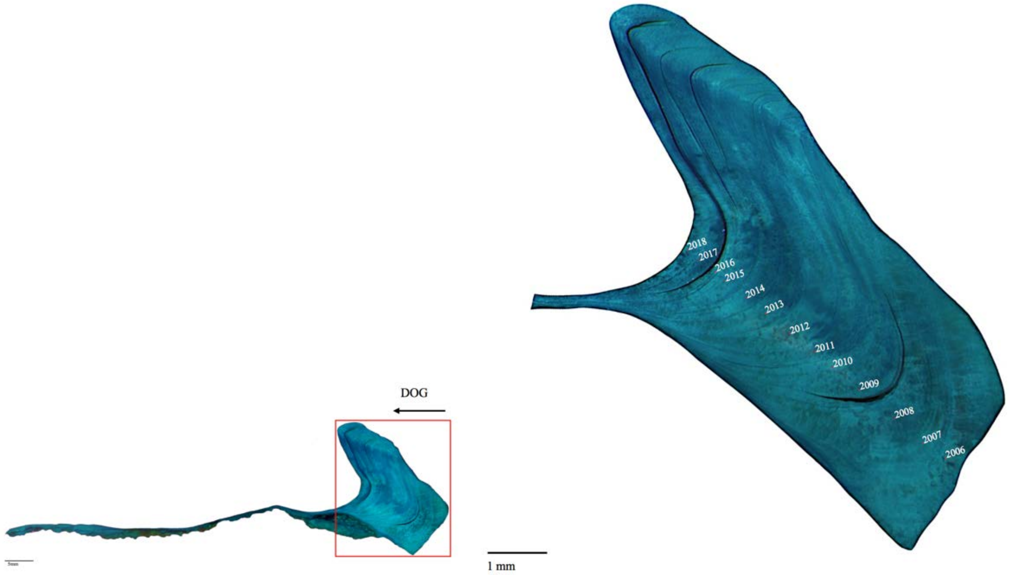
Year	GI Width (mm)	GI Comments
2010	0.1	Thin dark annual growth lines, thick light annual growth increments. Some precipitation of dark pigmentation in annual growth lines.
2010 – 2011	0.3	
2011 – 2012	0.3	
2012 – 2013	0.5	
2013 – 2014	0.4	
2014 – 2015	0.5	
2015 – 2016	0.3	
2016 – 2017	1.2	
2017 – 2018	1	
Average (mm)	0.51	
Min (mm)	0.1	
Max (mm)	1.2	

Metrical data for *Saccostrea cuccullata* left valve LC#6 growth features.

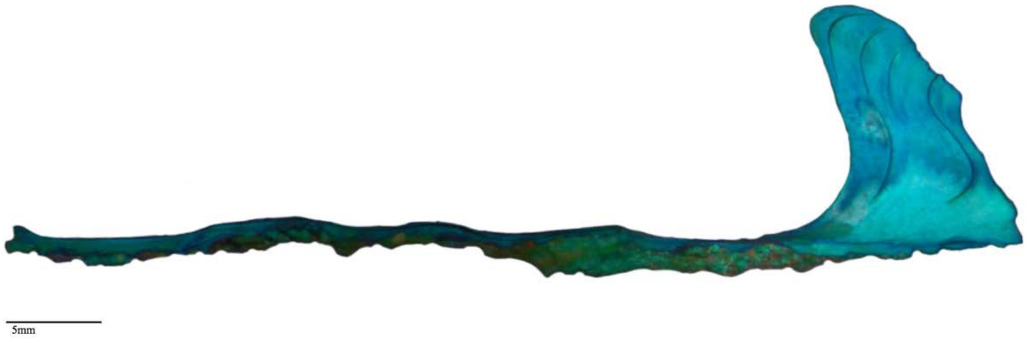
Year	GI Width (mm)	GI Comments
2010	0.5	Thin dark annual growth lines, thick light annual growth increments.
2010 – 2011	0.3	
2011 – 2012	0.5	
2012 – 2013	0.2	
2013 – 2014	0.5	
2014 – 2015	1.1	
2015 – 2016	0.4	
2016 – 2017	0.6	
2017 – 2018	1.2	
Average (mm)	0.58	
Min (mm)	0.2	
Max (mm)	1.2	

F.1.2 Section Images

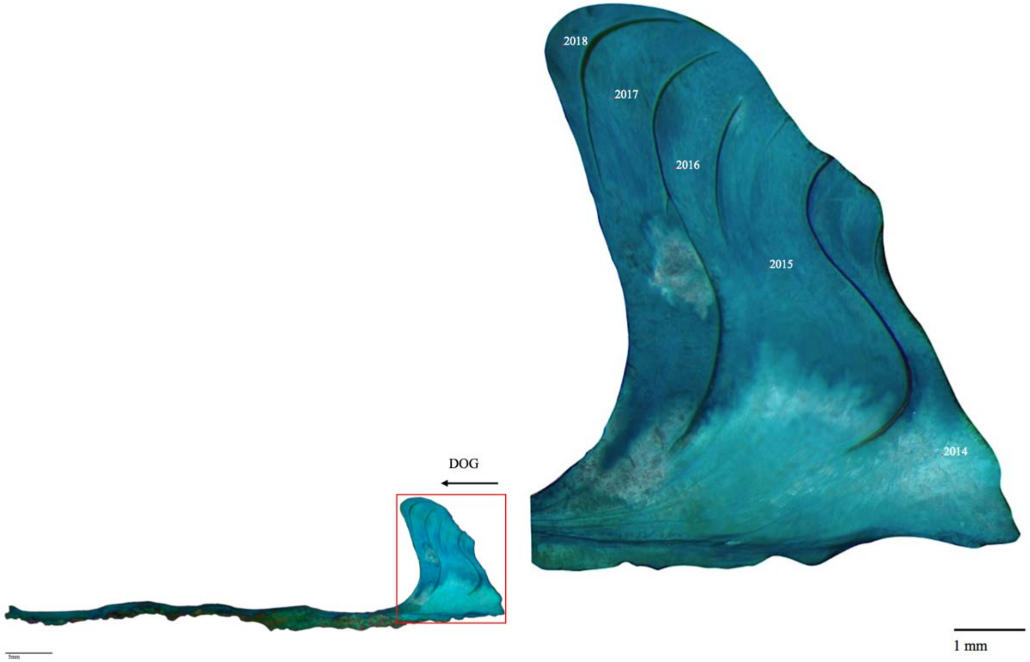
Complete section of *Saccostrea cuccullata* left valve LC#1.



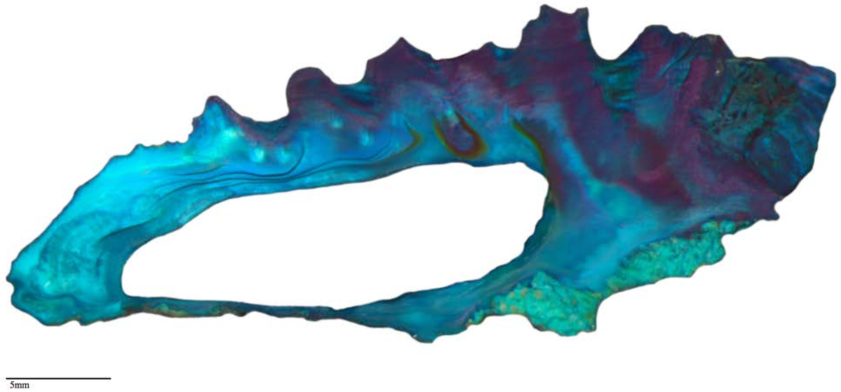
Portioned section of *Saccostrea cuccullata* left valve LC#1 and determined growth features.



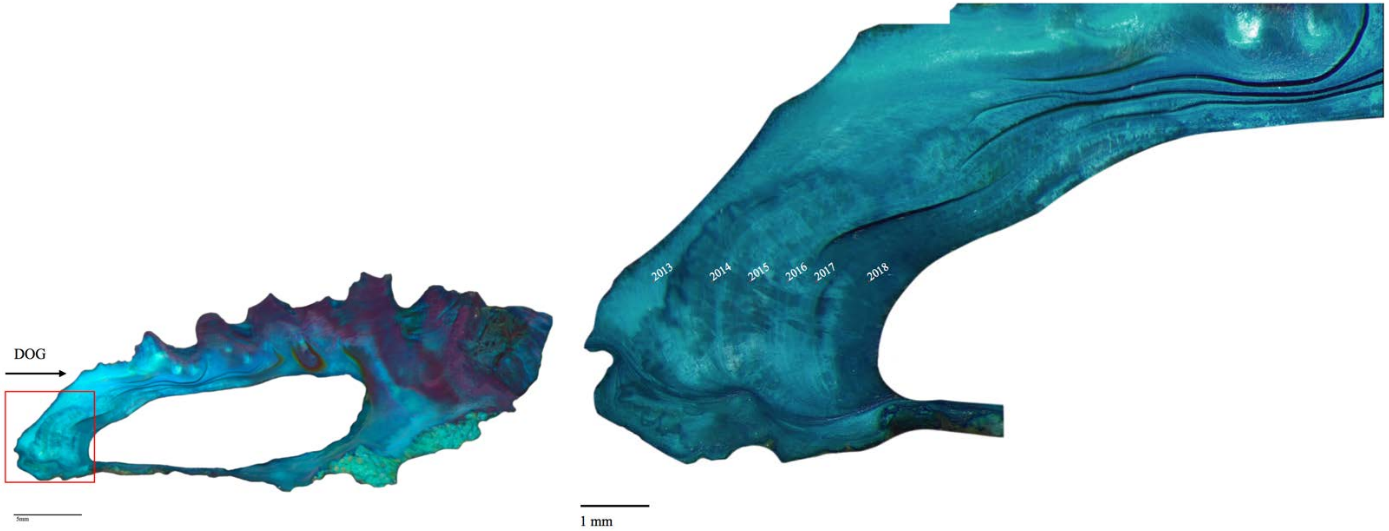
Complete section of *Saccostrea cuccullata* left valve LC#2.



Portioned section of *Saccostrea cuccullata* left valve LC#2 and determined growth features.

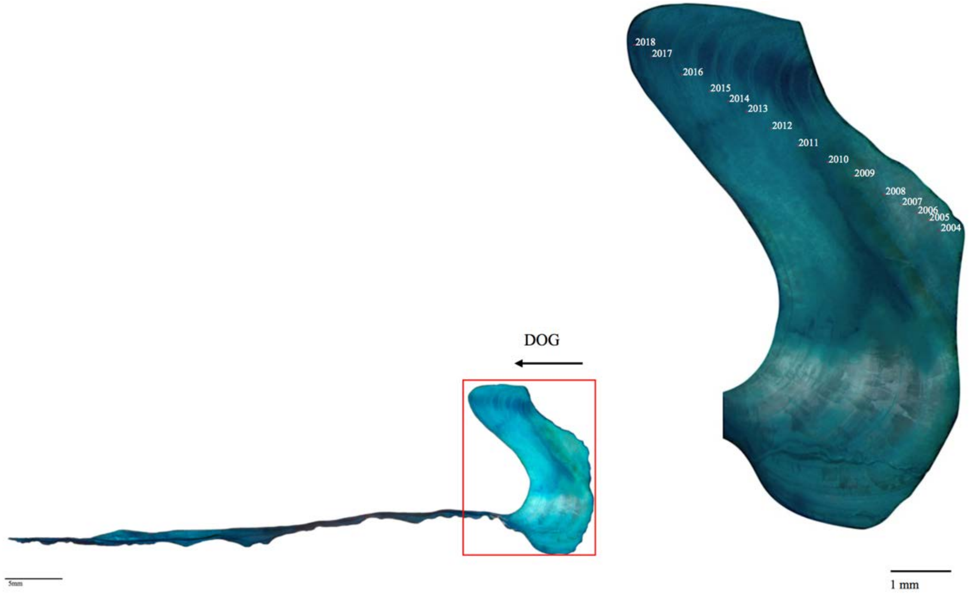


Complete section of *Saccostrea cuccullata* left valve LC#3.



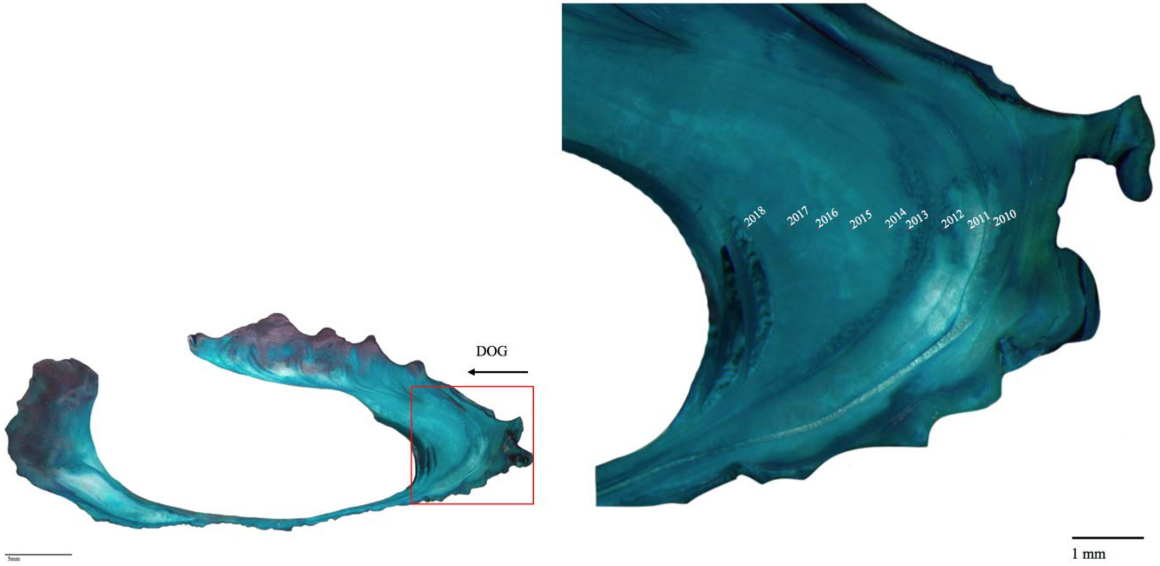
Portioned section of *Saccostrea cuccullata* left valve LC#3 and determined growth features.

Complete section of *Saccostrea cuccullata* left valve LC#4.



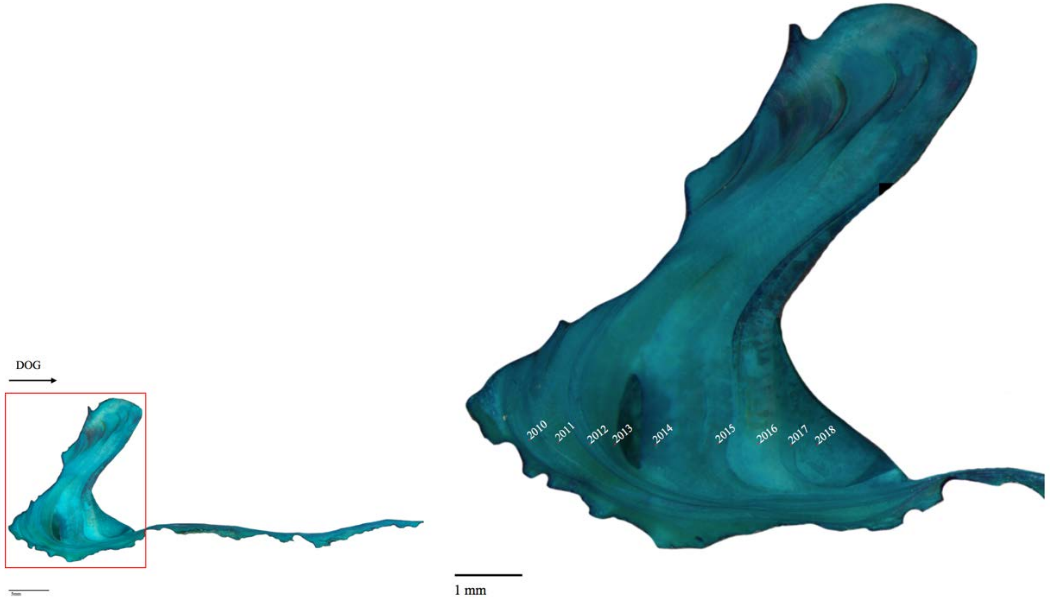
Portioned section of *Saccostrea cuccullata* left valve LC#4 and determined growth features. Annual growth increments are represented as dark bands between growth lines.

Complete section of *Saccostrea cuccullata* left valve LC#5.



Portioned section of *Saccostrea cuccullata* left valve LC#5 and determined growth features. Annual growth increments are represented as light bands between growth lines.

Complete section of *Saccostrea cuccullata* left valve LC#6.



Portioned section of *Saccostrea cuccullata* left valve LC#6 and determined growth features.

F.2 Live-Collected *Saccostrea cuccullata*, Left Valves

F.2.1 Metric Data

Metrical data for *Saccostrea cuccullata* right valve LC#1 growth features.

Year	GI Width (mm)	GI Comments
2018 - 2017	0.2	Thin dark annual growth lines, thick light annual growth increments.
2017 - 2016	0.7	
2016 - 2015	0.5	
2015 - 2014	0.7	
2014 - 2013	0.8	
2013 - 2012	0.3	
2012 - 2011	0.6	
2011 - 2010	0.4	
2010 - 2009	0.5	
2009 - 2008	0.2	
2008 - 2007	0.3	
2007 - 2006	0.2	
2006	0.1	
Average (mm)	0.42	
Min (mm)	0.1	
Max (mm)	0.8	

Metrical data for *Saccostrea cuccullata* right valve LC#2 growth features.

Year	GI Width (mm)	GI Comments
2018 - 2017	0.7	Thin dark annual growth lines, thick light annual growth increments.
2017 - 2016	1.1	
2016 - 2015	0.8	
2015 - 2014	0.5	
2014 - 2013	0.9	
2013	0.9	
Average (mm)	0.81	
Min (mm)	0.5	
Max (mm)	1.1	

Metrical data for *Saccostrea cuccullata* right valve LC#3 growth features.

Year	GI Width (mm)	GI Comments
2018 - 2017	0.9	Thin dark annual growth lines, thick light annual growth increments.
2017 - 2016	1.1	
2016 - 2015	0.9	
2015 - 2014	0.8	
2014 - 2013	1.3	
2013	1.4	
Average (mm)	1.06	
Min (mm)	0.8	
Max (mm)	1.4	

Metrical data for *Saccostrea cuccullata* right valve LC#4 growth features.

Year	GI Width (mm)	GI Comments
2018 - 2017	0.3	Thin light growth lines, thick light growth increments.
2017 - 2016	0.6	
2016 - 2015	0.8	
2015 - 2014	0.5	
2014 - 2013	0.3	
2013 - 2012	0.3	
2012 - 2011	0.3	
2011 - 2010	0.2	
2010 - 2009	0.3	
2009 - 2008	0.3	
2008 - 2007	0.2	
2007 - 2006	0.3	
2006 - 2005	0.3	
2005 - 2004	0.2	
2004	1.1	
Average (mm)	0.4	
Min (mm)	0.2	
Max (mm)	1.1	

Metrical data for *Saccostrea cuccullata* right valve LC#5 growth features.

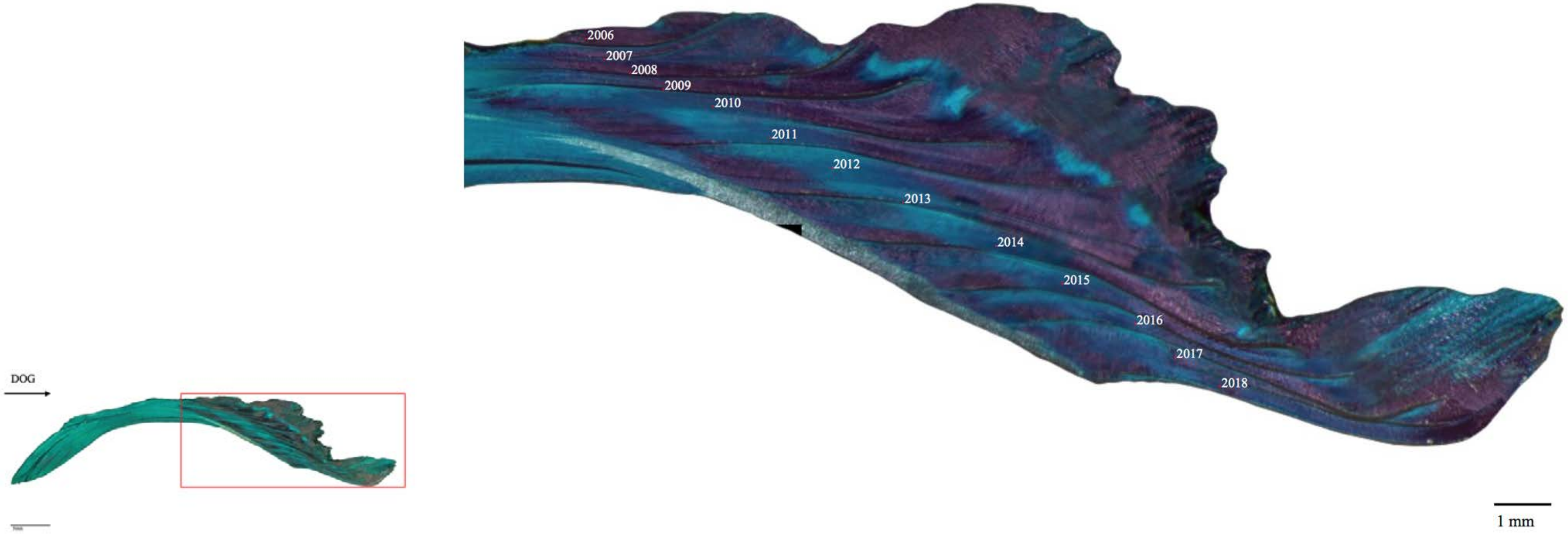
Year	GI Width (mm)	GI Comments
2018 - 2017	0.2	Thin dark annual growth lines, thick light annual growth increments. Some precipitation of dark pigmentation in annual growth lines.
2017 - 2016	1.7	
2016 - 2015	0.3	
2015 - 2014	0.4	
2014 - 2013	0.4	
2013 - 2012	0.3	
2012 - 2011	1.8	
2011 - 2010	0.8	
2010	2.5	
Average (mm)	0.93	
Min (mm)	0.2	
Max (mm)	2.5	

Metrical data for *Saccostrea cuccullata* right valve LC#6 growth features.

Year	GI Width (mm)	GI Comments
2018 - 2017	0.8	Thin dark annual growth lines, thick light annual growth increments. Some precipitation of dark pigmentation in annual growth lines.
2017 - 2016	0.8	
2016 - 2015	0.7	
2015 - 2014	0.5	
2014 - 2013	0.4	
2013 - 2012	0.7	
2012 - 2011	0.7	
2011 - 2010	0.2	
2010	0.1	
Average (mm)	0.54	
Min (mm)	0.1	
Max (mm)	0.8	

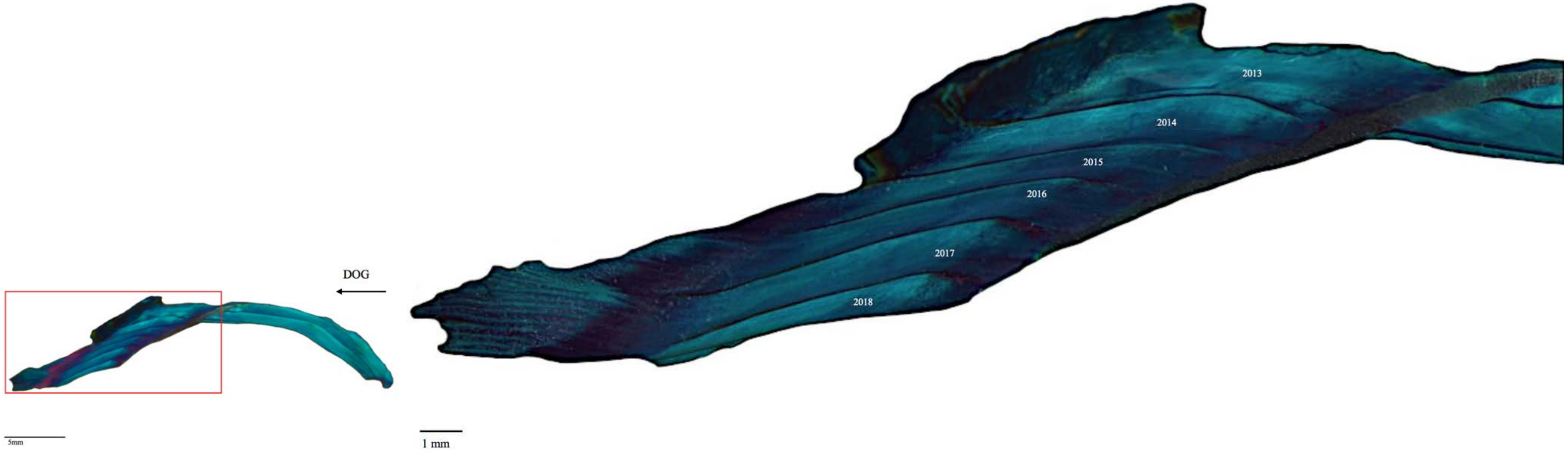
F.2.2 Section Images

Complete section of *Saccostrea cuccullata* right valve LC#1.



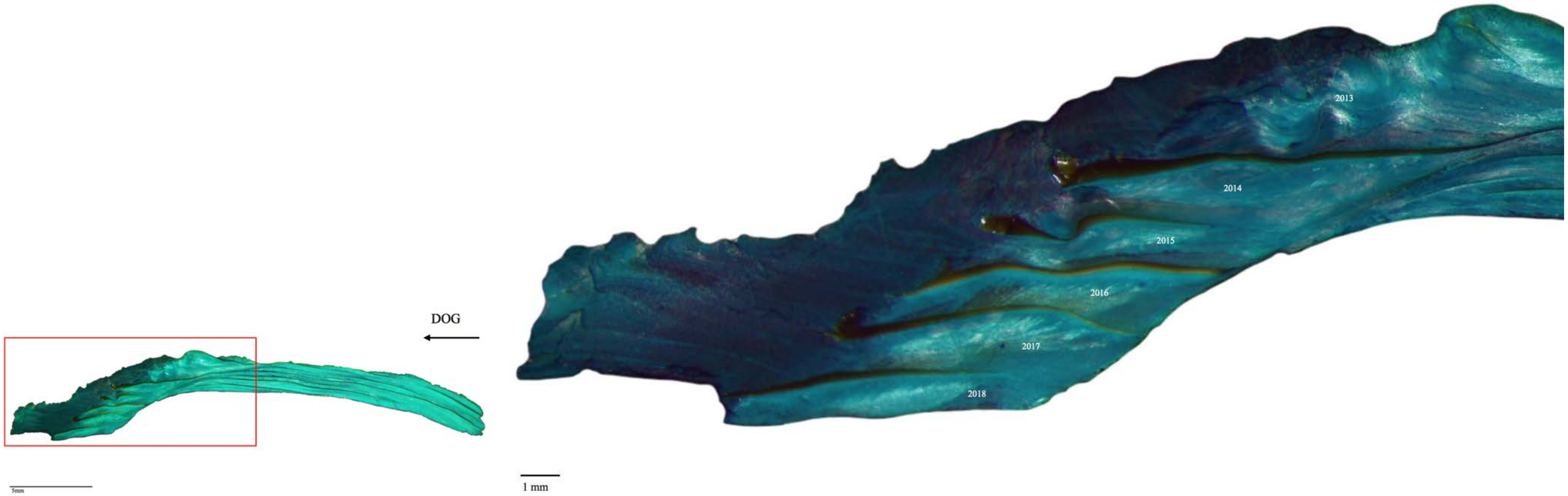
Portioned section of *Saccostrea cuccullata* right valve #LC1 and determined growth features.

Complete section of *Saccostrea cuccullata* right valve LC#2.

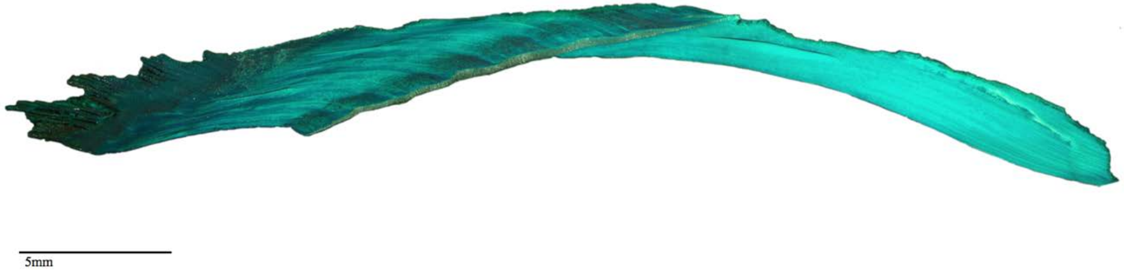


Portioned section of *Saccostrea cuccullata* right valve LC#2 and determined growth features.

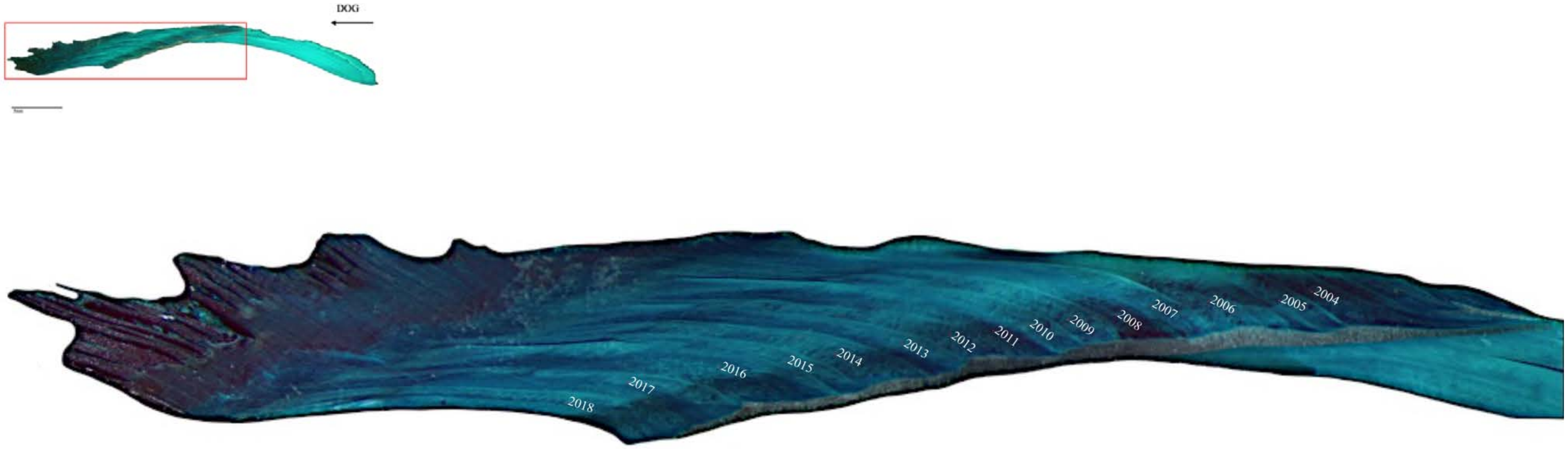
Complete section of *Saccostrea cuccullata* right valve LC#3.



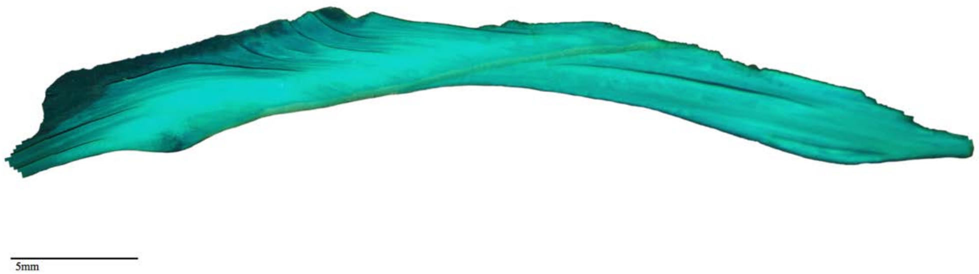
Portioned section of *Saccostrea cuccullata* right valve LC#3 and determined growth features.



Complete section of *Saccostrea cuccullata* right valve LC#4.

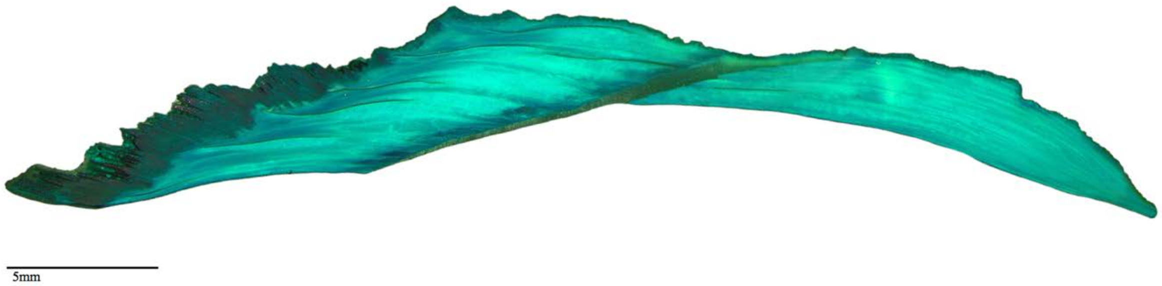


Portioned section of *Saccostrea cuccullata* right valve LC#4 and determined growth features.



Complete section of *Saccostrea cuccullata* right valve LC#5.

Portioned section of *Saccostrea cuccullata* right valve LC#5 and determined growth features.



Complete section of *Saccostrea cuccullata* right valve LC#6.

Portioned section of *Saccostrea cuccullata* right valve LC#6 and determined growth features.

F.3 Deep Time *Saccostrea cuccullata*, Right Valves

F.3.1 Metric Data

Metrical data for *Saccostrea cuccullata* right valve 5-10cm#1 growth features.

Year	GI Width (mm)	GI Comments
13	0.8	Thin dark annual growth lines, thick light annual growth increments. Dark pigmentation in annual growth lines are mostly precipitated.
12	0.3	
11	0.2	
10	0.3	
9	0.3	
8	0.2	
7	0.2	
6	0.3	
5	0.2	
4	0.4	
3	0.2	
2	0.3	
1	0.5	
0-1	0.3	
Average (mm)	0.32	
Min (mm)	0.2	
Max (mm)	0.8	

Metrical data for *Saccostrea cuccullata* right valve 5-10cm#2 growth features.

Year	GI Width (mm)	GI Comments
16	0.3	Thin light annual growth lines, thick dark annual growth increments.
15	0.1	
14	0.1	
13	0.5	
12	0.3	
11	0.3	
10	0.3	
9	0.4	
8	0.2	
7	0.3	
6	0.3	
5	0.5	
4	0.3	
3	0.4	
2	0.2	
1	0.4	
0-1	0.1	
Average (mm)	0.29	
Min (mm)	0.1	
Max (mm)	0.5	

Metrical data for *Saccostrea cuccullata* right valve 60-65cm#1 growth features.

Year	GI Width (mm)	GI Comments
10	0.3	Thin light annual growth lines, thick dark annual growth increments.
9	0.1	
8	0.3	
7	0.5	
6	0.2	
5	0.2	
4	0.7	
3	0.4	
2	0.5	
1	0.7	
0-1	0.2	
Average (mm)	0.37	
Min (mm)	0.1	
Max (mm)	0.7	

Metrical data for *Saccostrea cuccullata* right valve 60-65cm#2 growth features.

Year	GI Width (mm)	GI Comments
8	0.1	Thin light annual growth lines, thick dark annual growth increments.
7	0.3	
6	0.8	
5	0.7	
4	0.4	
3	0.9	
2	1	
1	0.9	
0-1	1.1	
Average (mm)	0.68	
Min (mm)	0.1	
Max (mm)	0.9	

Metrical data for *Saccostrea cuccullata* right valve 130-135cm#1 growth features.

Year	GI Width (mm)	GI Comments
13	0.6	Thin light annual growth lines, thick dark annual growth increments. Dark pigmentation in annual growth lines are mostly precipitated.
12	0.1	
11	0.1	
10	0.1	
9	0.2	
8	0.3	
7	0.5	
6	0.3	
5	0.3	
4	0.4	
3	0.2	
2	0.5	
1	0.3	
0-1	0.9	
Average (mm)	0.34	
Min (mm)	0.1	
Max (mm)	0.9	

Metrical data for *Saccostrea cuccullata* right valve 190-200cm#1 growth features.

Year	GI Width (mm)	GI Comments
6	0.9	Thin light annual growth lines, thick dark annual growth increments.
5	0.4	
4	0.4	
3	0.7	
2	0.6	
1	0.6	
0-1	0.1	
Average (mm)	0.52	
Min (mm)	0.1	
Max (mm)	0.9	

Metrical data for *Saccostrea cuccullata* right valve 190-200cm#2 growth features.

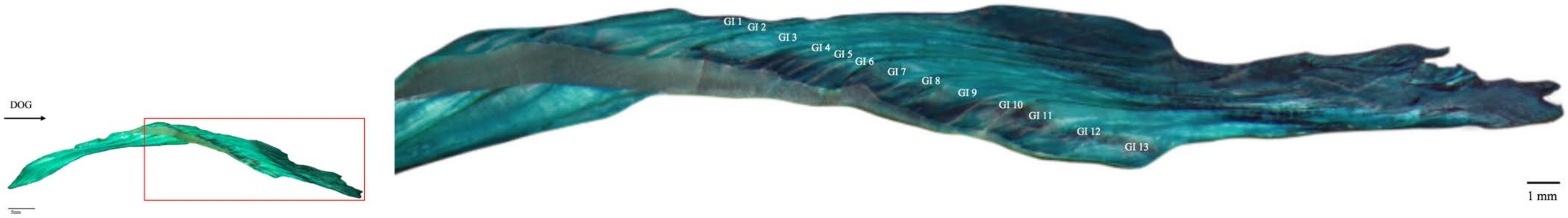
Year	GI Width (mm)	GI Comments
8	0.7	Thin light annual growth lines, thick dark annual growth increments.
7	0.7	
6	0.4	
5	0.5	
4	0.6	
4	0.7	
3	0.3	
2	0.3	
0-1	1	
Average (mm)	0.57	
Min (mm)	0.3	
Max (mm)	0.7	

Metrical data for *Saccostrea cuccullata* right valve 220-230cm#1 growth features.

Year	GI Width (mm)	GI Comments
8	0.6	Thin dark annual growth lines, thick dark annual growth increments. Dark pigmentation in annual growth lines are mostly precipitated.
7	0.5	
6	0.6	
5	0.9	
4	0.3	
3	0.8	
2	0.3	
1	1	
0-1	0.2	
Average (mm)	0.57	
Min (mm)	0.2	
Max (mm)	1	

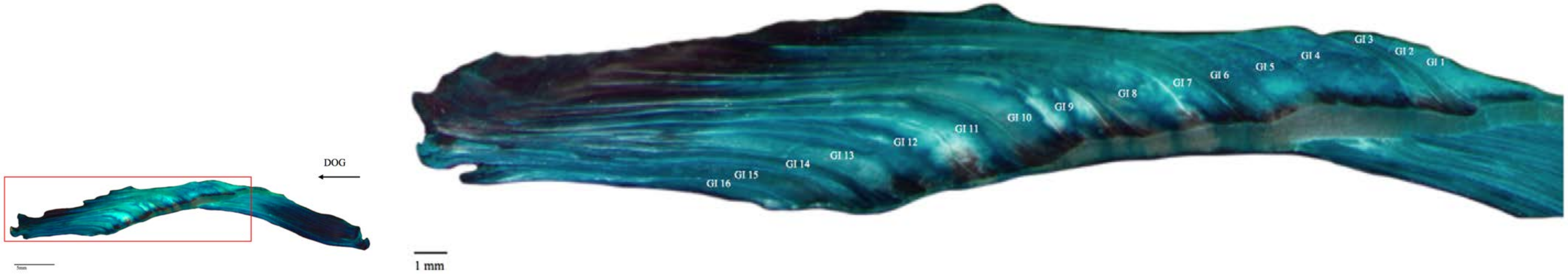
F.3.2 Section Images

Complete section of *Saccostrea cuccullata* right valve 5-10cm#1.



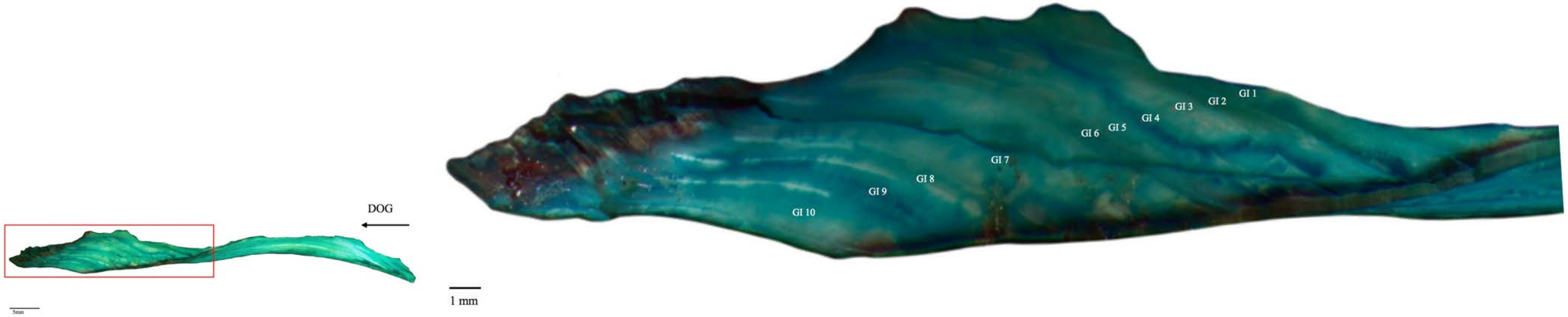
Portioned section of *Saccostrea cuccullata* right valve 5-10cm#1 and determined growth features.

Complete section of *Saccostrea cuccullata* right valve 5-10cm#2.

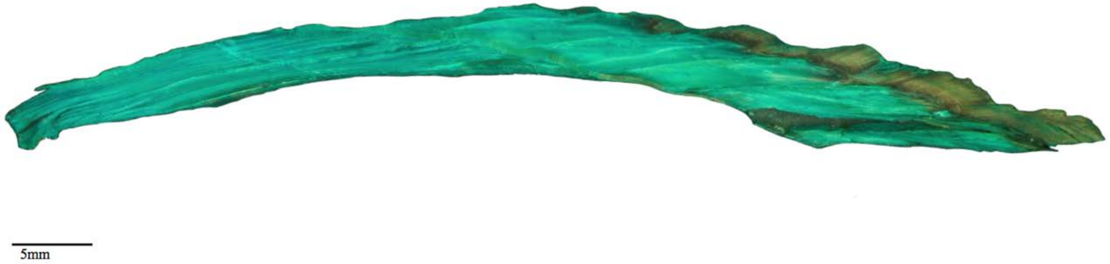


Portioned section of *Saccostrea cuccullata* right valve 5-10cm#2 and determined growth features.

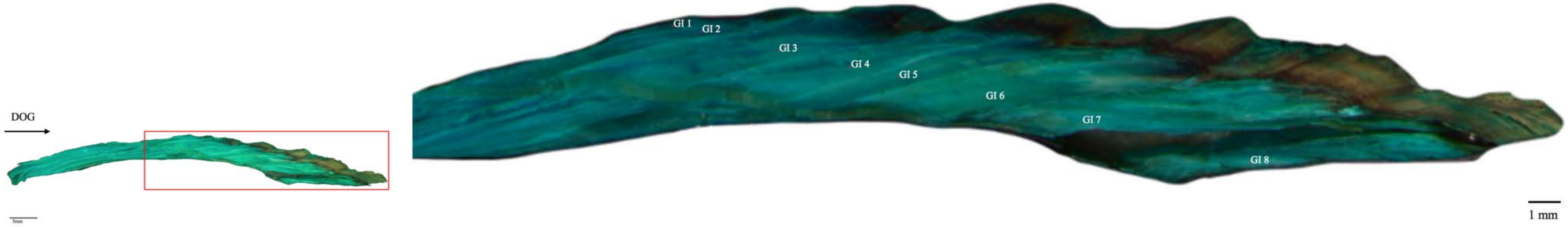
Complete section of *Saccostrea cuccullata* right valve 60-65cm#1.



Portioned section of *Saccostrea cuccullata* right valve 60-65cm#1 and determined growth features.

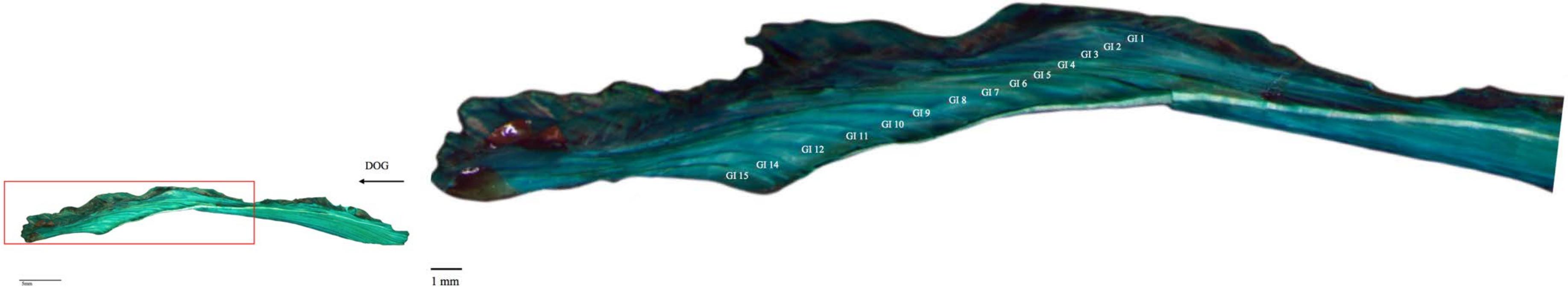


Complete section of *Saccostrea cuccullata* right valve 60-65cm#2.

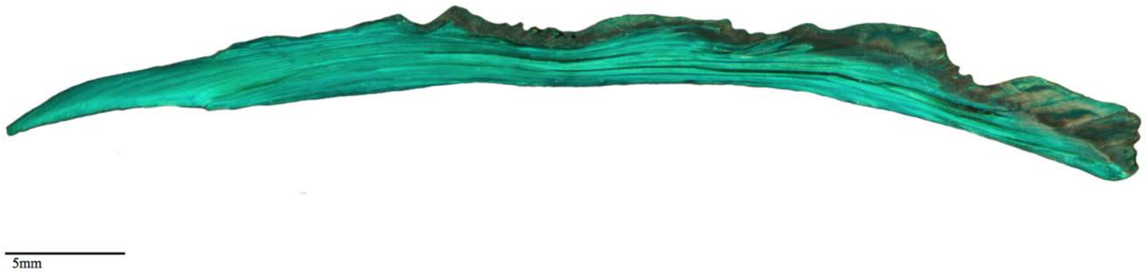


Portioned section of *Saccostrea cuccullata* right valve 60-65cm#2 and determined growth features.

Complete section of *Saccostrea cuccullata* right valve 130-135cm#1.

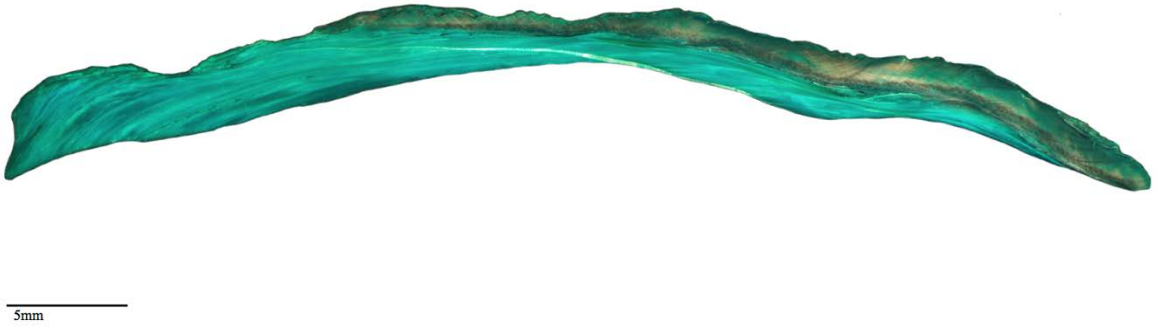


Portioned section of *Saccostrea cuccullata* right valve 130-135cm#1 and determined growth features.

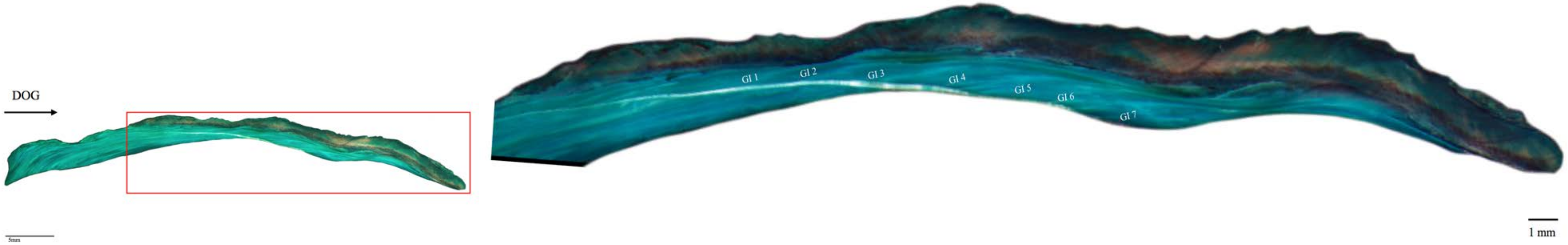


Complete section of *Saccostrea cuccullata* right valve 130-135cm#2.

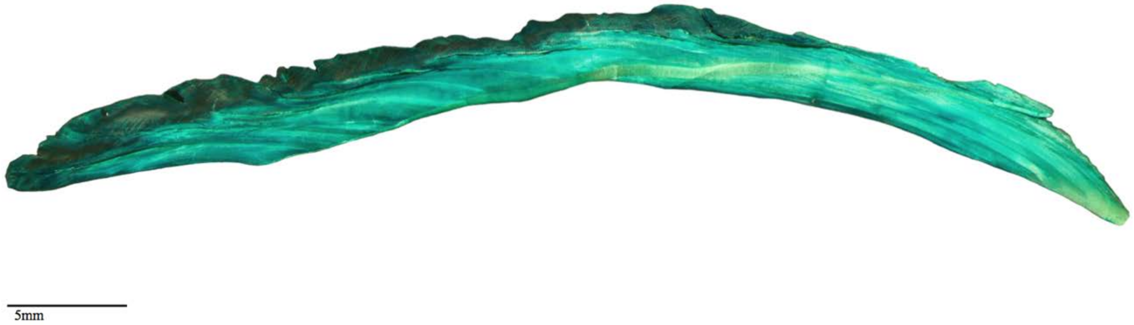
Portioned section of *Saccostrea cuccullata* right valve 130-135cm#2 for growth increment analysis. Metric data for growth increments was not collected due to the inability to define growth features in the sample.



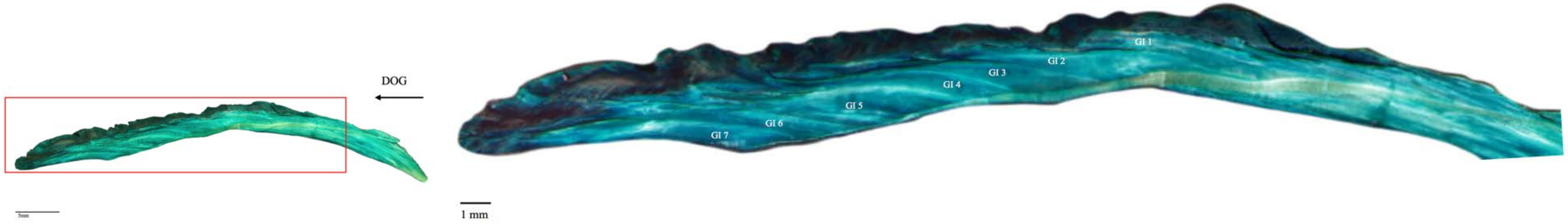
Complete section of *Saccostrea cuccullata* right valve 190-200cm#1.



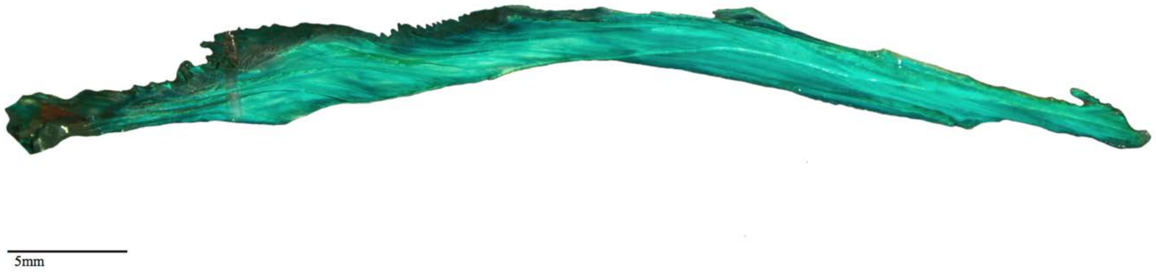
Portioned section of *Saccostrea cuccullata* right valve 190-200cm#1 and determined growth features.



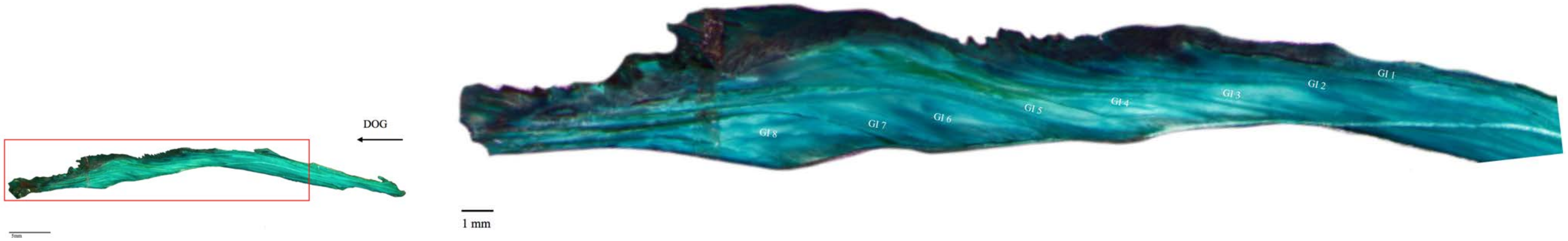
Complete section of *Saccostrea cuccullata* right valve 190-200#2.



Portioned section of *Saccostrea cuccullata* right valve 190-200cm#2 and determined growth features.



Complete section of *Saccostrea cuccullata* right valve 220-230cm#1.



Portioned section of *Saccostrea cuccullata* right valve 220-230cm#1 and determined growth features.

Complete section of *Saccostrea cuccullata* right valve 255-265cm#1.

Portioned section of *Saccostrea cuccullata* right valve 255-265cm#1 for growth increment analysis. Metric data for growth increments was not collected due to the inability to define growth features in the sample.

F.4 Live-Collected *Lunella cinerea*

F.4.1 Metric Data

Metrical data for *Lunella cinerea* LC#1 growth features.

Growth Feature	Comments	Other
DL 1	Notch in prismatic shell layer.	Sub-annual growth lines represented in the prismatic shell layer.

Metrical data for *Lunella cinerea* LC#3 growth features.

Growth Feature	Comments	Other
DL 1	Notch in prismatic shell layer.	Sub-annual growth lines represented in the prismatic shell layer.
GL 1, GL 2, GL 3	Dark pigmentation, situated in the prismatic shell layer.	
DL 2	Notch in prismatic shell layer. Thick light pigmented line protruding from the prismatic shell layer into the nacreous shell layer in the opposite direction of growth.	

Metrical data for *Lunella cinerea* LC#4 growth features.

Growth Feature	Comments	Other
GL 1 – GL 6	Dark pigmentation, situated in the prismatic shell layer.	Sub-annual growth lines represented in the prismatic shell layer.

Metrical data for *Lunella cinerea* LC#6 growth features.

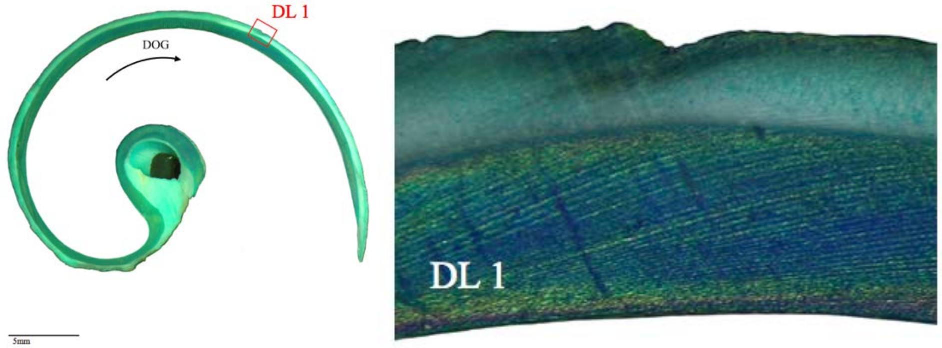
Growth Feature	Comments	Other
GL 1	Situated in the prismatic shell layer and protruding into the nacreous shell layer.	Sub-annual growth lines represented in the prismatic shell layer.
GL 2 – GL 5	Dark pigmentation, situated in the prismatic shell layer.	

Metrical data for *Lunella cinerea* LC#7 growth features.

Growth Feature	Comments	Other
DL 1	Notch in prismatic shell layer. Thick light pigmented line protruding from the prismatic shell layer into the nacreous shell layer in the opposite direction of growth.	Sub-annual growth lines represented in the prismatic shell layer.
GL 1 – GL 6	Dark pigmentation, situated in the prismatic shell layer.	
GL 7	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Beginning lightly pigmented but then transitions into a dark pigment.	
GL 8	Situated in the prismatic shell layer.	
GL 9, GL 10	Dark pigmentation, situated in the prismatic shell layer.	

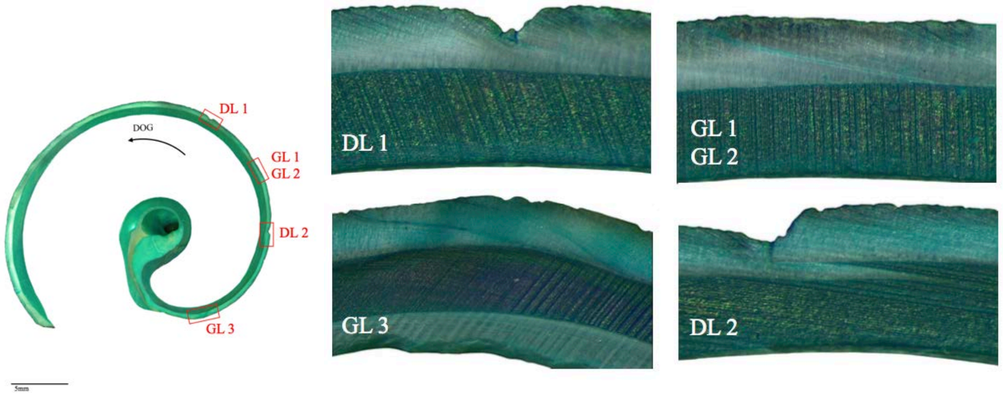
F.4.2 Section Images

Complete section of *Lunella cinerea* sample LC#1.



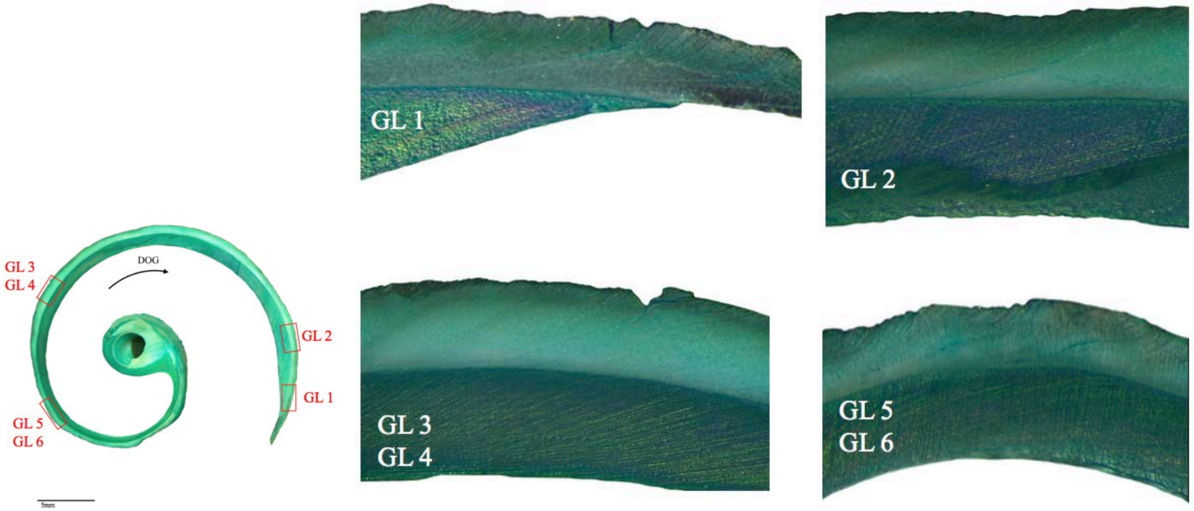
Portioned section of *Lunella cinerea* LC#1 and determined growth features.

Complete section of *Lunella cinerea* sample LC#3.



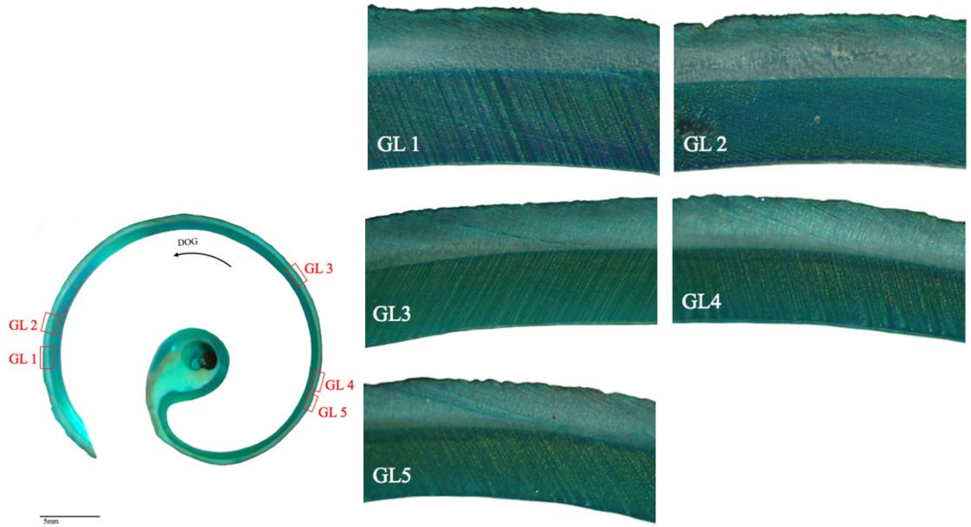
Portioned section of *Lunella cinerea* LC#3 and determined growth features.

Complete section of *Lunella cinerea* sample LC#4.



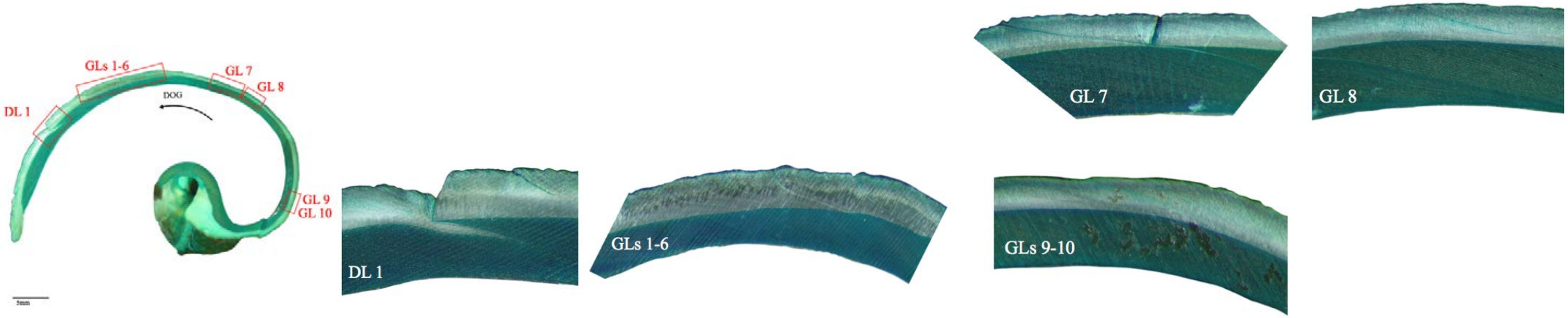
Portioned section of *Lunella cinerea* LC#4 and determined growth features.

Complete section of *Lunella cinerea* sample LC#6.



Portioned section of *Lunella cinerea* LC#6 and determined growth features.

Complete section of *Lunella cinerea* sample LC#7.



Portioned section of *Lunella cinerea* LC#7 and determined growth features.

F.5 Deep-Time *Lunella cinerea*

F.5.1 Metric Data

Metrical data for *Lunella cinerea* 5-10cm#1 growth features.

Growth Feature	Comments	Other
GL 1 – GL 7	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	Sample appears to have been subjected to pre-mortem environmental impacts at the GLs 1-7 and DL 1 site. Sub-annual growth lines represented in the prismatic shell layer.
DL 1	Notch in prismatic shell layer. Thick light pigmented line protruding from the prismatic shell layer into the nacreous shell layer in the opposite direction of growth.	
GL 8	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	

Metrical data for *Lunella cinerea* 5-10cm#2 growth features.

Growth Feature	Comments	Other
GL 1	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	Sub-annual growth lines represented in the prismatic shell layer.
GL 2	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	
GL 3, GL 4	Dark pigmentation, situated in the prismatic shell layer. Notch in prismatic shell layer.	
DL 1, DL 2	Thick light pigmented line protruding from the prismatic shell layer into the nacreous shell layer in the opposite direction of growth.	

Metrical data for *Lunella cinerea* 55-60cm#1 growth features.

Growth Feature	Comments	Other
GL 1	Dark pigmentation, situated in the prismatic shell layer.	Sub-annual growth lines represented in the prismatic shell layer.
GL 2	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	
GL 3	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	

Metrical data for *Lunella cinerea* 60-65cm#1 growth features.

Growth Feature	Comments	Other
GL 1, GL 2	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	Sub-annual growth lines represented in the prismatic shell layer.

Metrical data for *Lunella cinerea* 105-110cm#1 growth features.

Growth Feature	Comments	Other
GL 1	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	Sub-annual growth lines represented in the prismatic shell layer.
	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	
GL 2	Sediment observable in prismatic shell layer along length of growth line.	

Metric data for *Lunella cinerea* 110-115cm#1 growth features.

Growth Feature	Comments	Other
GL 1, GL 2	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	Sub-annual growth lines represented in the prismatic shell layer.
DL 1	Notch in prismatic shell layer. Thick light pigmented line protruding from the prismatic shell layer into the nacreous shell layer in the opposite direction of growth.	
GL 3	Dark pigmentation, situated in the prismatic shell layer.	
GL 4 – GL 6	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	

Metric data for *Lunella cinerea* 170-180cm#1 growth features.

Growth Feature	Comments	Other
GL 1 – GL 11	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	Sub-annual growth lines represented in the prismatic shell layer.

Metric data for *Lunella cinerea* 170-180cm#2 growth features.

Growth Feature	Comments	Other
GL 1 – GL 11	Situated in the prismatic shell layer and protruding into the nacreous shell layer. Light pigmentation.	Sub-annual growth lines represented in the prismatic shell layer.

Metrical data for *Lunella cinerea* 255-265cm#1 growth features.

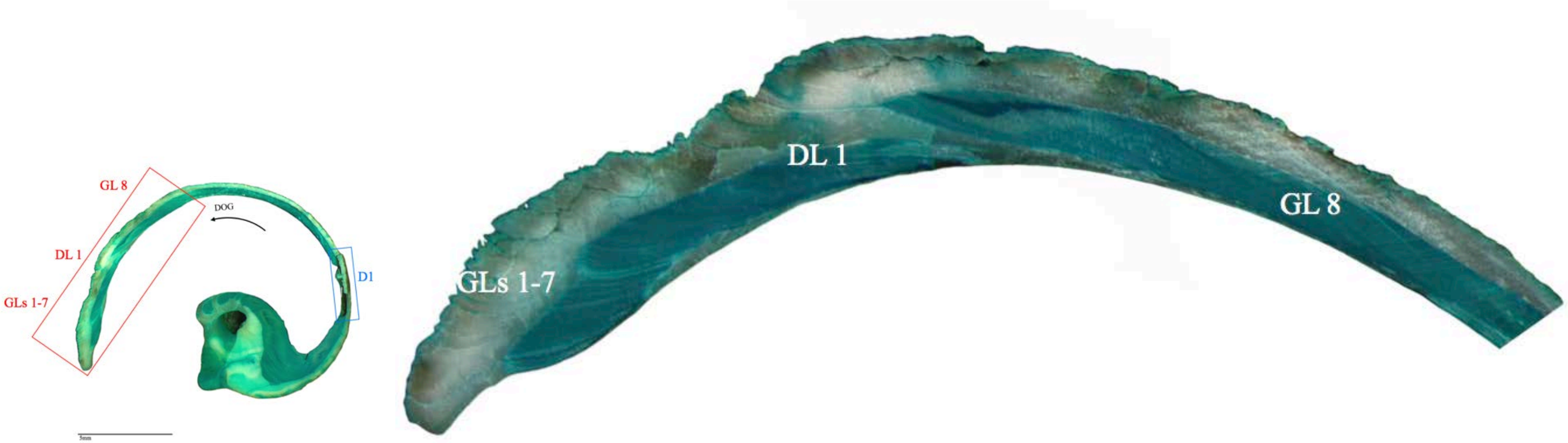
Growth Feature	Comments	Other
GL 1	Light pigmentation, situated in the nacreous shell layer.	Sub-annual growth lines represented in the prismatic shell layer.

Metrical data for *Lunella cinerea* 255-265cm#2 growth features.

Growth Feature	Comments	Other
GL 1, GL 2	Dark pigmentation, situated in the nacreous shell layer.	Sub-annual growth lines represented in the prismatic shell layer.

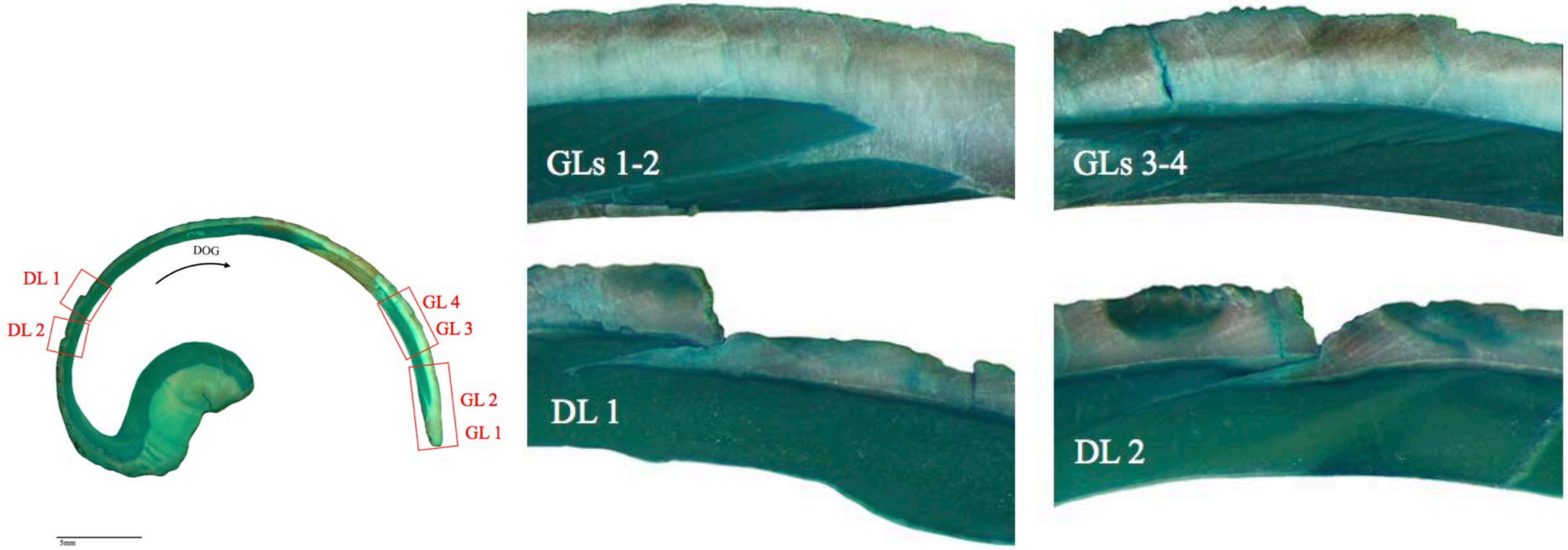
F.5.2 Section Images

Complete section of *Lunella cinerea* sample 5-10cm#1.



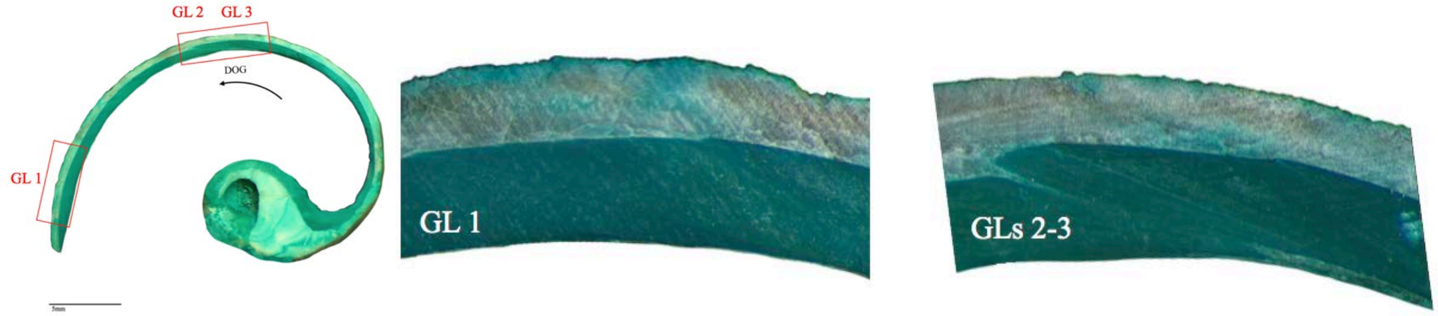
Portioned section of *Lunella cinerea* 5-10cm#1 and determined growth features. D1 (Damage 1), post-mortem damage to the sample during the preparation of sectioning.

Complete section of *Lunella cinerea* sample 5-10cm#2.



Portioned section of *Lunella cinerea* 5-10cm#2 and determined growth features.

Complete section of *Lunella cinerea* sample 55-60cm#1.

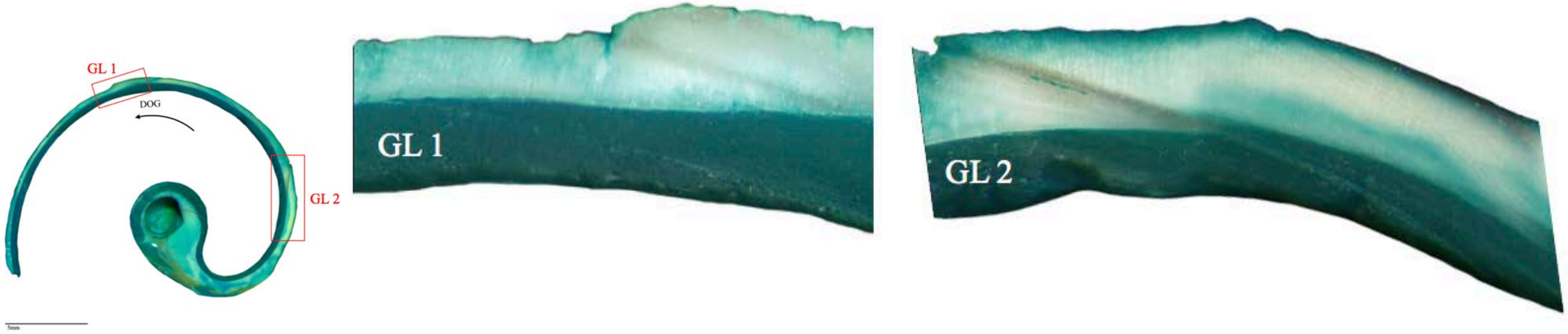


Portioned section of *Lunella cinerea* 55-60cm#1 and determined growth features.

Complete section of *Lunella cinerea* sample 60-65cm#1.

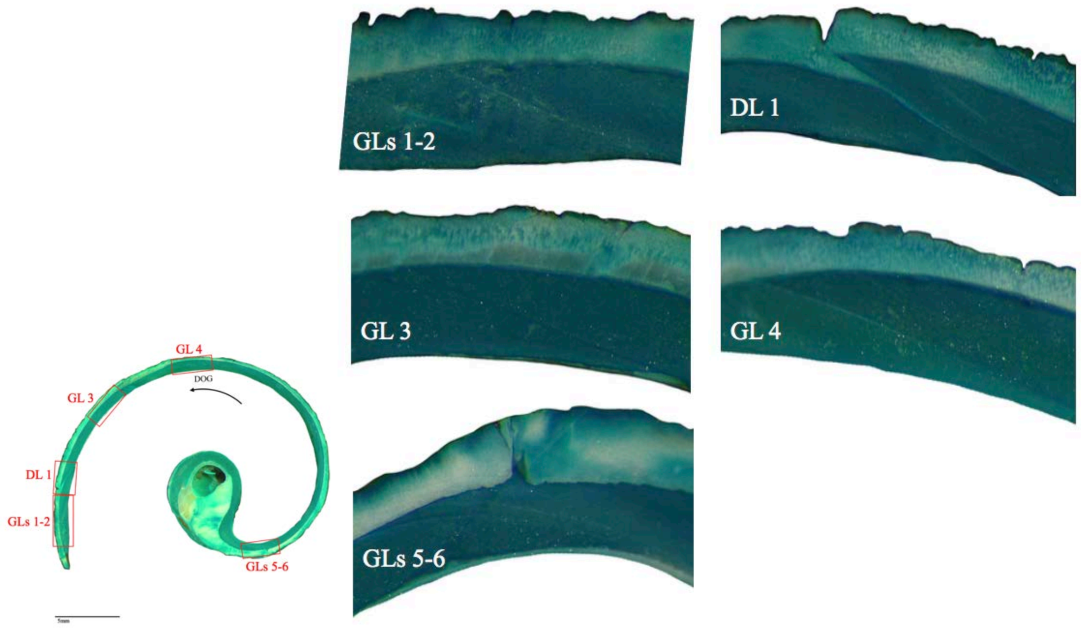
Portioned section of *Lunella cinerea* 60-65cm#1 and determined growth features.

Complete section of *Lunella cinerea* sample 105-110cm#1.



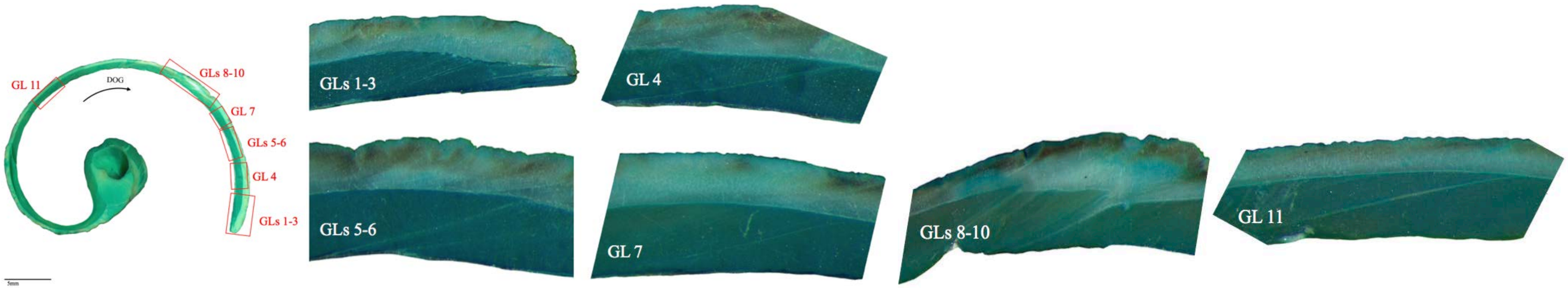
Portioned section of *Lunella cinerea* 105-110cm#1 and determined growth features.

Complete section of *Lunella cinerea* sample 110-115cm#1.



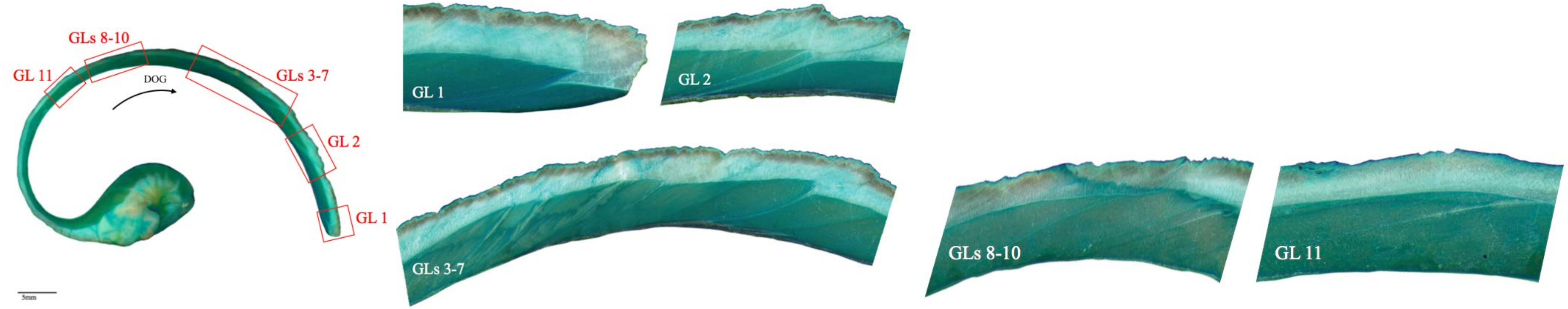
Portioned section of *Lunella cinerea* 110-115cm#1 and determined growth features.

Complete section of *Lunella cinerea* sample 170-180cm#1.



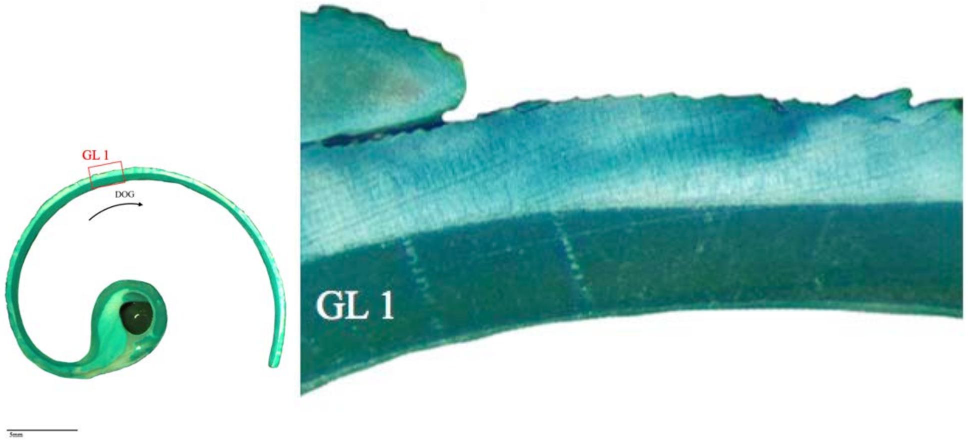
Portioned section of *Lunella cinerea* 170-180cm#1 and determined growth features.

Complete section of *Lunella cinerea* sample 170-180cm#2.



Portioned section of *Lunella cinerea* 170-180cm#2 and determined growth features.

Complete section of *Lunella cinerea* sample 255-265cm#1.



Portioned section of *Lunella cinerea* 255-265cm#1 and determined growth features.

Complete section of *Lunella cinerea* sample 255-265cm#2.

Portioned section of *Lunella cinerea* 255-265cm#2 and determined growth features.

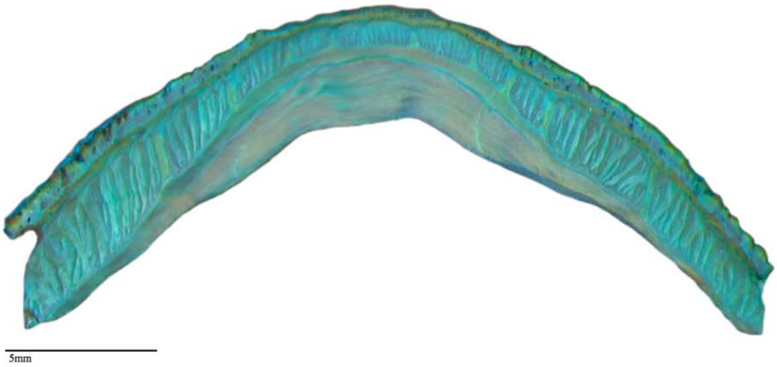
F.6 Live-Collected *Acanthopleura gemmata*, Anterior Valve

F.6.1 Metric Data

Metrical data for *Acanthopleura gemmata* anterior LC#5, LC#7, LC#8 growth features.

FEATURE	Average
GL no.	0
GL Width (mm)	0
GL Comments	Not observed
GI no.	0
GI Width (mm)	0
GI Comments	Not observed
DL no.	0
DL Width (mm)	0
DL Comments	Not observed

F.6.2 Section Images



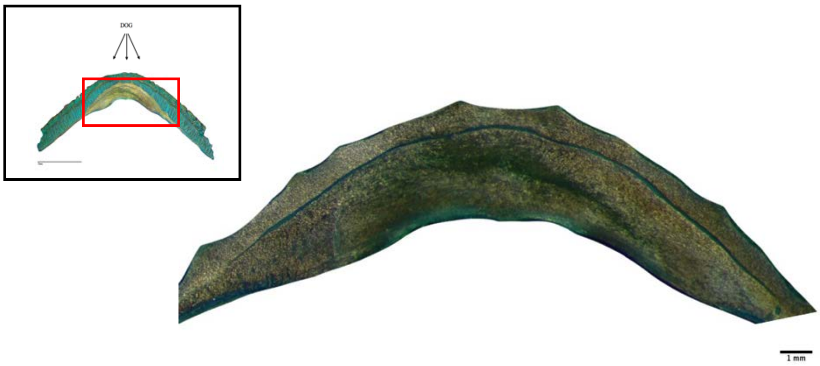
Complete section of *Acanthopleura gemmata* anterior valve LC#5.

Portioned section of *Acanthopleura gemmata* sample anterior valve LC#5 analysed for growth features.

Complete section of *Acanthopleura gemmata* anterior valve LC#7.

Portioned section of *Acanthopleura* sample anterior valve LC#7 analysed for growth features.

Complete section of *Acanthopleura gemmata* anterior valve LC#8.



Portioned section of *Acanthopleura gemmata* anterior valve LC#8 analysed for growth features.

F.7 Live-Collected *Acanthopleura gemmata*, Posterior Valve

F.7.1 Metric Data

Metrical data for *Acanthopleura gemmata* posterior LC#5 growth features.

LEFT 1	**GI Width (mm)**	**RIGHT 1**	**GI Width (mm)**	**Comments**
2018 - 2017	0.2	2018 - 2017	0.6	Thin dark annual growth lines, thick light annual growth increments. Thin dark sub-annual growth lines observable.
2017 - 2016	0.4	2017 - 2016	0.5	
2016 - 2015	0.5	2016 - 2015	0.5	
2015 - 2014	0.5	2015 - 2014	0.5	
2014 - 2013	0.5	2014 - 2013	0.5	
2013 - 2012	0.5	2013 - 2012	0.4	
2012 - 2011	0.3	2012 - 2011	0.4	
2011 - 2010	0.3	2011 - 2010	0.3	
2010 - 2009	0.4	2010 - 2009	0.7	
2009 - 2008	0.5	2009 - 2008	0.6	
2008	1.1	2008	0.8	
Average (mm)	0.47	**Average (mm)**	0.52	
Min (mm)	0.2	**Min (mm)**	0.3	
Max (mm)	1.1	**Max (mm)**	0.8	

LEFT 2	**GI Width (mm)**	**RIGHT 2**	**GI Width (mm)**
2018 - 2017	0.5	2018 - 2017	0.4
2017 - 2016	0.5	2017 - 2016	0.5
2016 - 2015	0.8	2016 - 2015	0.7
2015 - 2014	0.3	2015 - 2014	0.5
2014 - 2013	0.4	2014 - 2013	0.5
2013 - 2012	0.3	2013 - 2012	0.5
2012 - 2011	0.5	2012 - 2011	0.7
2011 - 2010	1.7	2011 - 2010	0.7
2010 - 2009	1.2	2010 - 2009	1.1
2009 - 2008	0.9	2009 - 2008	1.4
2008	2.3	2008	2.9
Average (mm)	0.85	**Average (mm)**	0.9
Min (mm)	0.3	**Min (mm)**	0.4
Max (mm)	2.3	**Max (mm)**	2.9

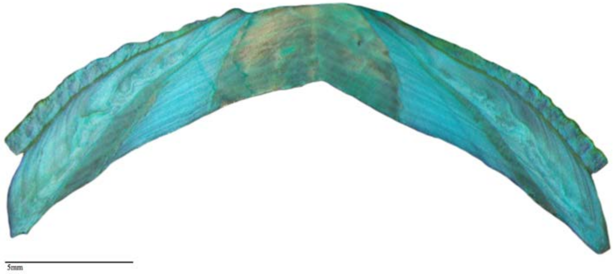
Metrical data for *Acanthopleura gemmata* posterior LC#7 growth features.

LEFT 1	GI Width (mm)	RIGHT 1	GI Width (mm)	Comments
2018 - 2017	1	2018 - 2017	2	Thin dark annual growth lines, thick light annual growth increments. Thin dark sub-annual growth lines observable.
2017 - 2016	0.3	2017 - 2016	0.3	
2016 - 2015	0.2	2016 - 2015	0.2	
2015 - 2014	0.4	2015 - 2014	0.2	
2014 - 2013	0.7	2014 - 2013	0.3	
2013 - 2012	0.9	2013 - 2012	0.6	
2012 - 2011	0.7	2012 - 2011	0.2	
2011 - 2010	0.2	2011 - 2010	0.4	
2010	0.1	2010	0.5	
Average (mm)	0.5	**Average (mm)**	0.52	
Min (mm)	0.1	**Min (mm)**	0.2	
Max (mm)	1	**Max (mm)**	2	
LEFT 2	**GI Width (mm)**	**RIGHT 2**	**GI Width (mm)**	
-	0.6	-	0.2	
-	0.4	-	0.9	
-	0.8	-	0.3	
-	1.2	-	0.5	
-	2.3	-	0.5	
		-	0.4	
		-	1	
		-	3.5	

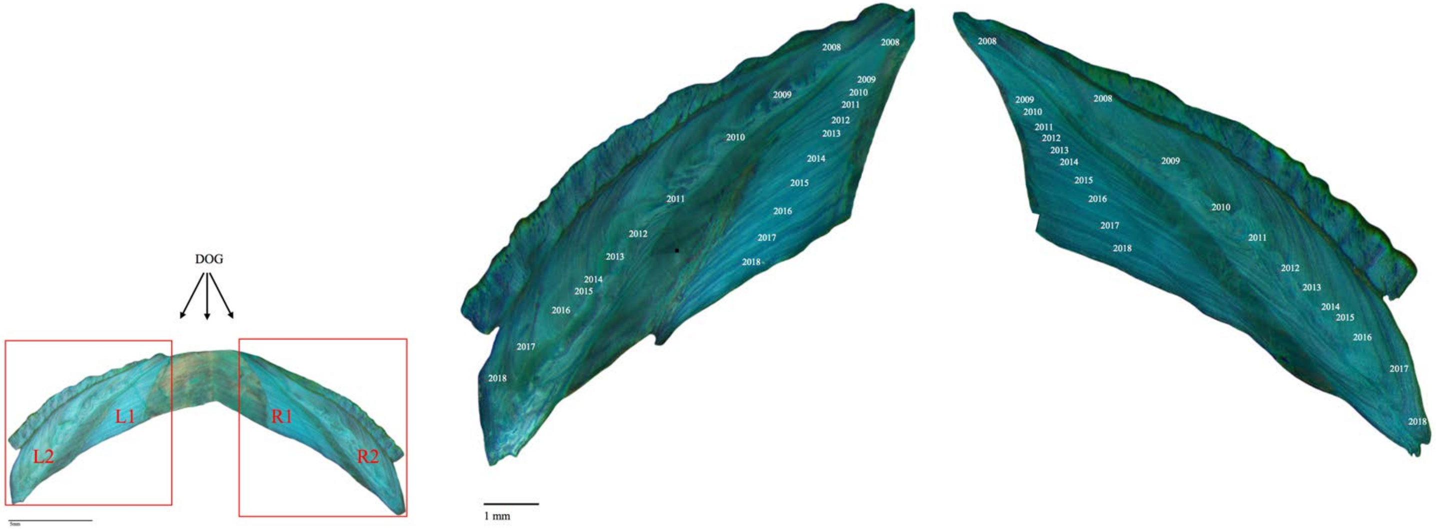
Metrical data for *Acanthopleura gemmata* posterior LC#8 growth features.

LEFT 1	**GI Width (mm)**	**RIGHT 1**	**GI Width (mm)**	**GI Comments**
2018 - 2017	0.2	2018 - 2017	0.2	Thin dark annual growth lines, thick light annual growth increments. Thin dark sub-annual growth lines observable.
2017 - 2016	0.2	2017 - 2016	0.2	
2016 - 2015	0.3	2016 - 2015	0.2	
2015 - 2014	0.2	2015 - 2014	0.4	
2014 - 2013	0.7	2014 - 2013	0.6	
2013 - 2012	0.4	2013 - 2012	0.4	
2012 - 2011	0.1	2012 - 2011	0.3	
2011 - 2010	0.3	2011 - 2010	0.4	
2010 - 2009	0.5	2010 - 2009	0.6	
2009	1.8	2009	0.3	
Average (mm)	0.47	**Average (mm)**	0.36	
Min (mm)	0.1	**Min (mm)**	0.2	
Max (mm)	1.8	**Max (mm)**	0.6	
LEFT 2	**GI Width (mm)**	**RIGHT 2**	**GI Width (mm)**	
-	0.2	-	0.2	
-	0.6	-	1.3	
-	0.6	-	1.9	
-	1.3	-	1.2	
-	2.8	-	3.1	
-	3			

F.7.2 Section Images

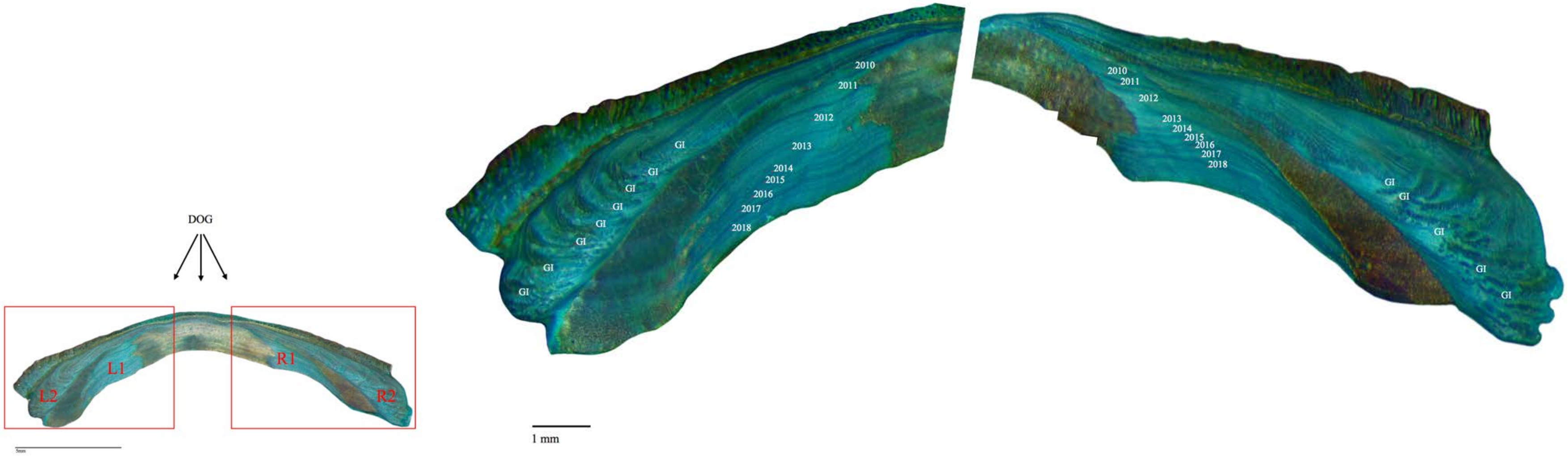


Complete section of *Acanthopleura gemmata* sample posterior valve LC#5.

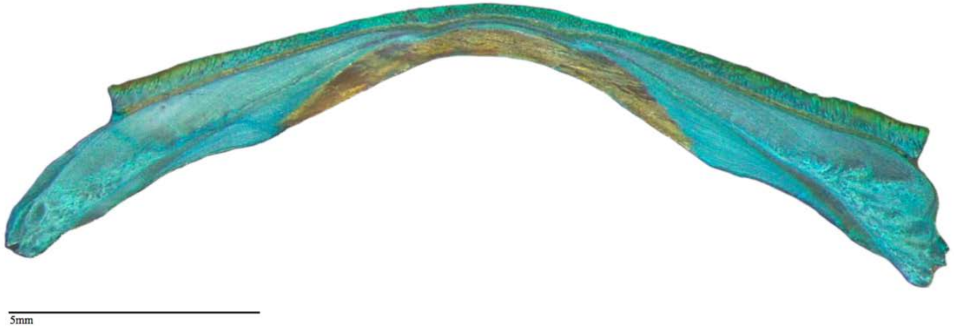


Portioned section of *Acanthopleura gemmata* posterior valve LC#5 and determined growth features. LC#5 is 11 years old.

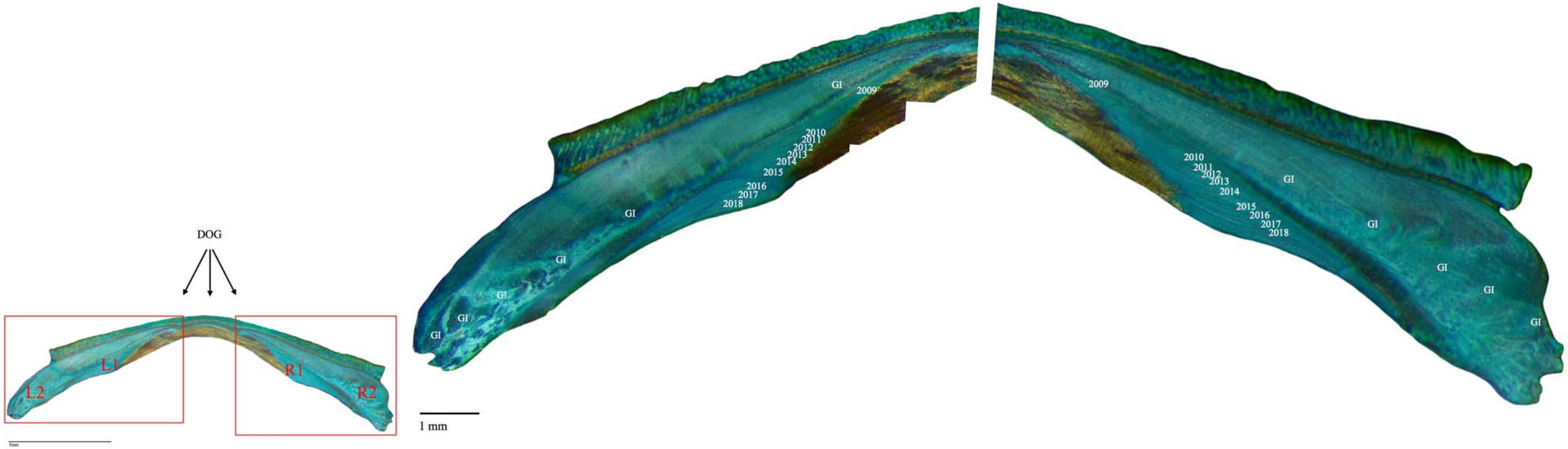
Complete section of *Acanthopleura gemmata* posterior valve LC#7.



Portioned section of *Acanthopleura gemmata* posterior valve LC#7 and determined growth features. Annual growth increments are represented as light bands between growth lines. LC#7 is 9 years old.



Complete section of *Acanthopleura gemmata* posterior valve LC#8.



Portioned section of *Acanthopleura gemmata* posterior valve LC#8 and determined growth features. LC#8 is 10 years old.

F.8 Deep Time *Acanthopleura gemmata*, Posterior Valve

F.8.1 Metric Data

Metrical data for *Acanthopleura gemmata* posterior valve 5-10cm#2, L1, growth features.

Year	GI Width (mm)	GI Comments
12	0.1	Thin dark annual growth lines, thick light annual growth increments. Thin dark sub-annual growth lines observable. Some growth lines appear faded in sections.
11	0.2	
19	0.3	
9	0.5	
8	0.3	
7	0.3	
6	0.6	
5	0.3	
4	0.5	
3	0.5	
2	0.6	
1	0.9	
0-1	0	
Average (mm)	0.42	
Min (mm)	0.1	
Max (mm)	0.9	

Metrical data for *Acanthopleura gemmata* posterior valve 60-65cm#2, L1, growth features.

Year	GI Width (mm)	GI Comments
10	0.1	Thin dark annual growth lines, thick light annual growth increments. Thin dark sub-annual growth lines observable.
9	0.2	
8	0.2	
7	0.2	
6	0.4	
5	0.4	
4	0.2	
3	0.3	
2	0.6	
1	1	
0-1	0	
Average (mm)	0.36	
Min (mm)	0.1	
Max (mm)	0.6	

Metrical data for *Acanthopleura gemmata* posterior valve 125-130cm#2, L1, growth features.

Year	GI Width (mm)	GI Comments
9	0.2	Thin dark annual growth lines, thick light annual growth increments. Thin dark sub-annual growth lines observable. Some growth lines appear faded in sections.
8	0.3	
7	0.4	
6	0.2	
5	0.2	
4	0.3	
3	0.1	
2	0.1	
1	0.2	
0-1	0	
Average (mm)	0.22	
Min (mm)	0.1	
Max (mm)	0.4	

Metrical data for *Acanthopleura gemmata* posterior valve 180-190cm#2, L1, growth features.

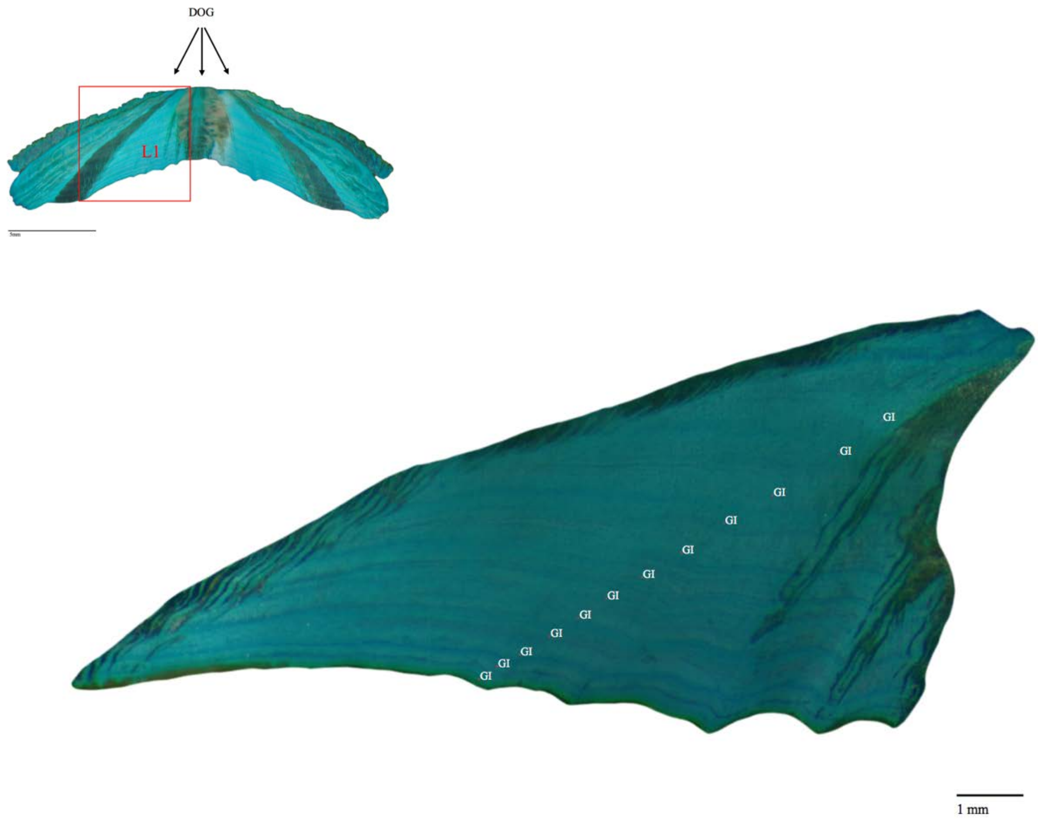
Year	GI Width (mm)	GI Comments
13	0.4	Thin dark annual growth lines, thick light annual growth increments. Thin dark sub-annual growth lines observable.
12	0.5	
11	0.8	
10	0.5	
9	0.6	
8	0.3	
7	0.3	
6	0.2	
5	0.4	
4	0.3	
3	0.5	
2	0.2	
1	0.2	
0-1	0	
Average (mm)	0.4	
Min (mm)	0.2	
Max (mm)	0.8	

Metrical data for *Acanthopleura gemmata* posterior valve 220-230cm#2, L1, growth features.

Year	GI Width (mm)	GI Comments
12	0.3	Thin dark annual growth lines, thick light annual growth increments. Thin dark sub-annual growth lines observable. Some growth lines appear faded in sections.
11	0.4	
10	0.3	
9	0.3	
8	0.3	
7	0.3	
6	0.3	
5	0.8	
4	1	
3	1.2	
2	0.5	
1	1.4	
0-1	0	
Average (mm)	0.59	
Min (mm)	0.3	
Max (mm)	1.4	

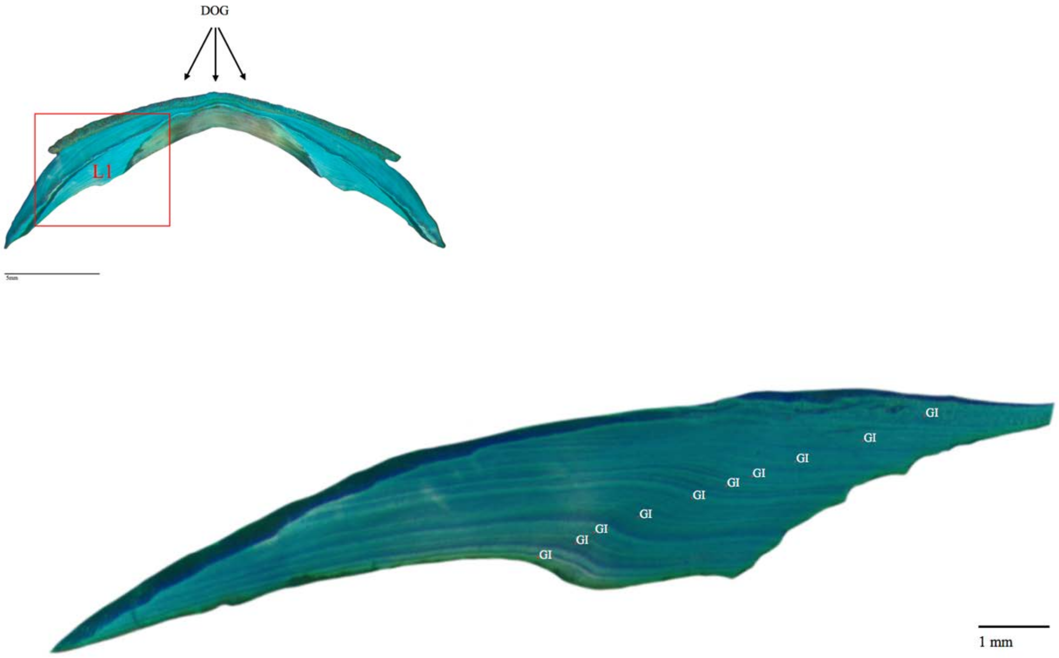
F.8.2 Section Images

Complete section of *Acanthopleura gemmata* posterior valve 5-10cm#2.



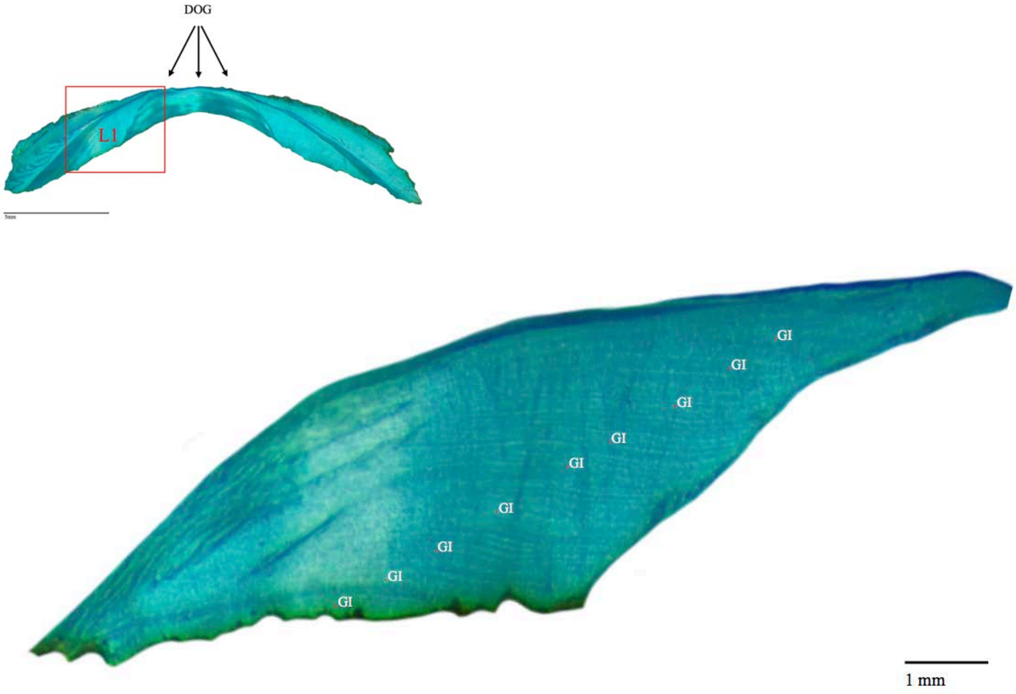
Portioned section of *Acanthopleura* gemmata posterior valve 5-10cm#2 and location of L1 growth features.

Complete section of *Acanthopleura gemmata* posterior valve 60-65cm#2.

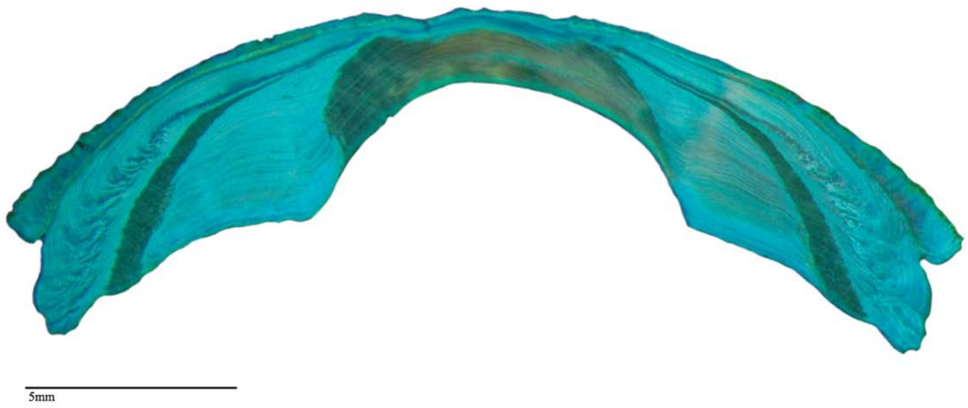


Portioned section of *Acanthopleura gemmata* posterior valve 60-65cm#2 location of L1 growth features.

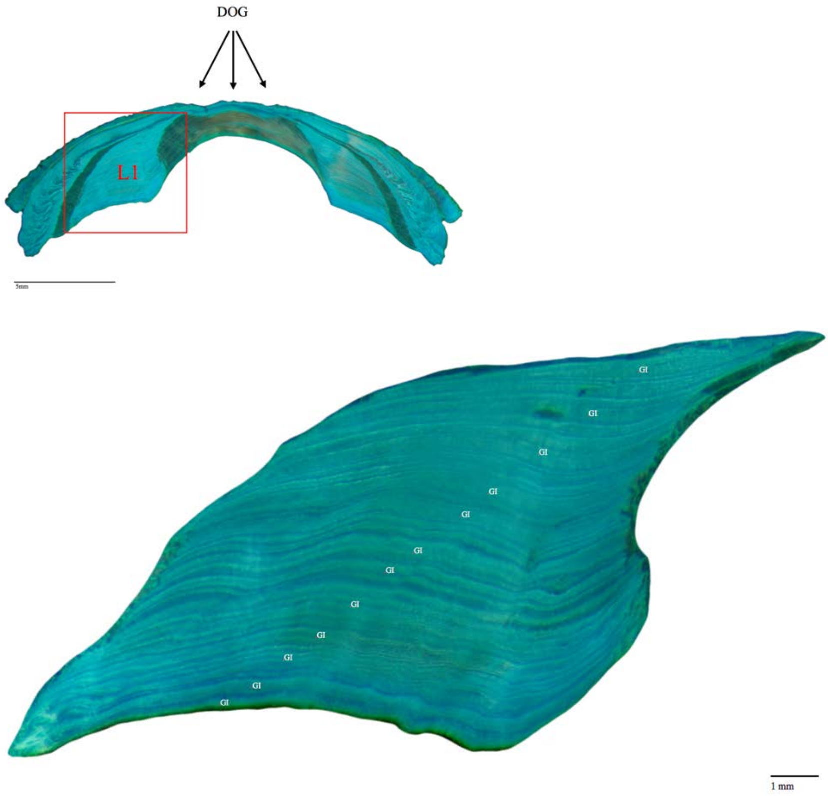
Complete sectioned *Acanthopleura gemmata* posterior valve 125-130cm#2.



Portioned section of *Acanthopleura gemmata* posterior valve 125-130cm#2 and location of LI growth features.

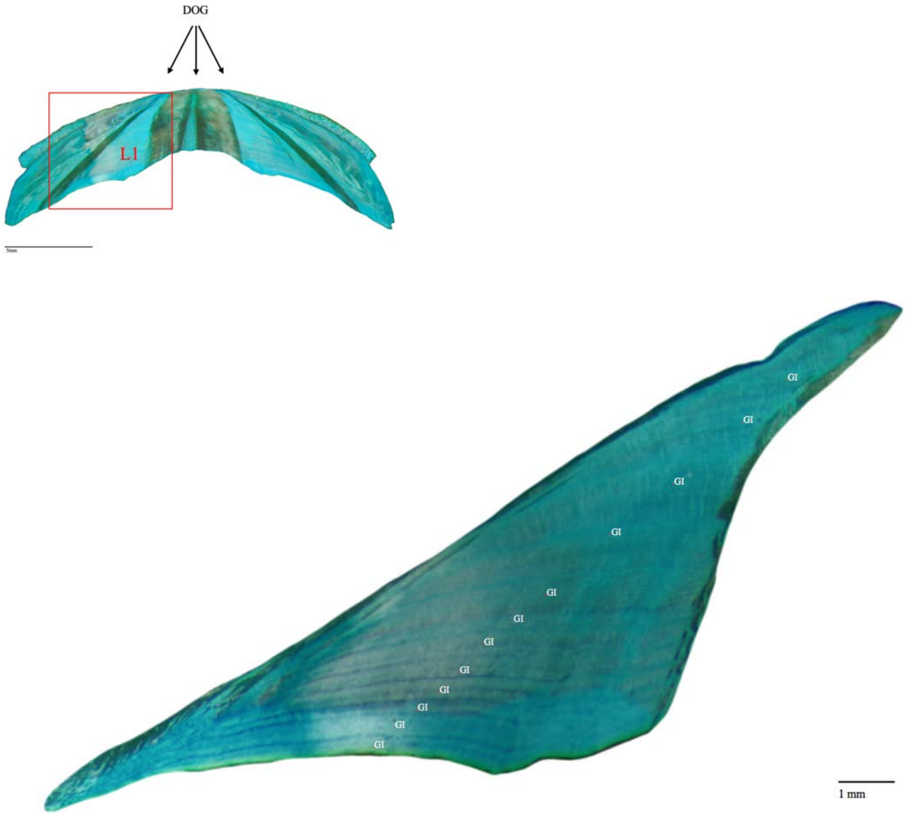


Complete section of *Acanthopleura gemmata* posterior valve 180-190cm#2.



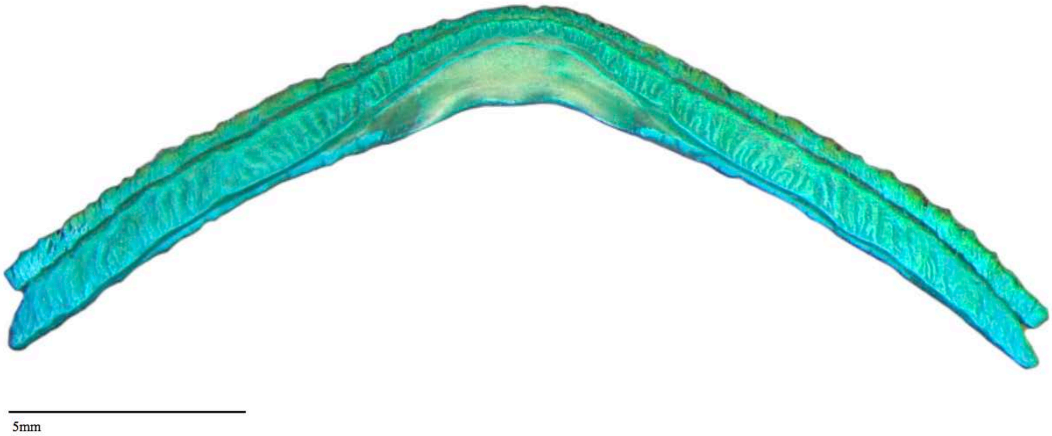
Portioned section of *Acanthopleura gemmata* posterior valve 180-190cm#2 and location of LI growth features.

Complete sectioned *Acanthopleura gemmata* posterior valve 220-230cm#2.

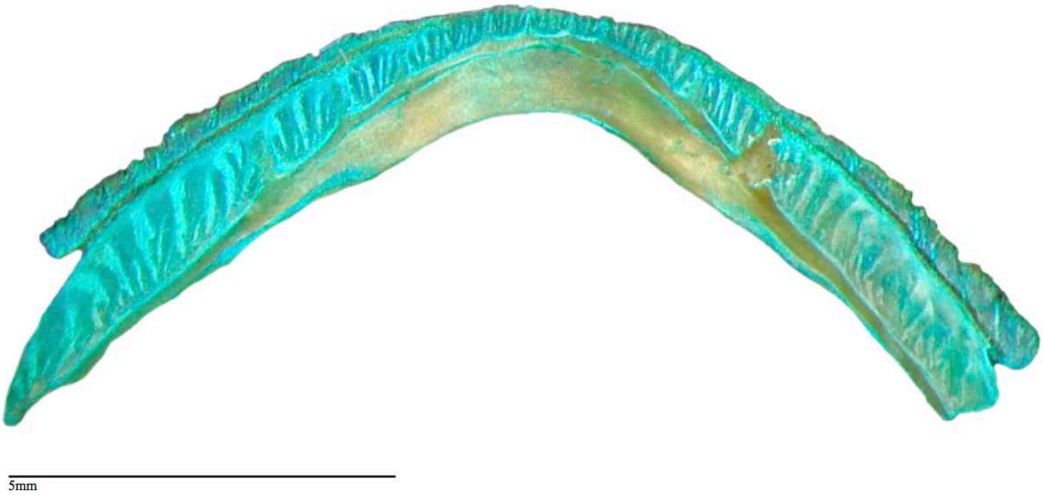


Portioned section of *Acanthopleura* gemmata posterior valve 220-230cm#2 and location of LI growth features.

Appendix G - Deep Time *Acanthopleura gemmata* Anterior Valve Sections



Complete section of *Acanthopleura gemmata* anterior valve 5-10cm#1.



Complete section of *Acanthopleura gemmata* anterior valve 60-65cm#1.

Complete section of *Acanthopleura gemmata* anterior valve 125-135cm#1.

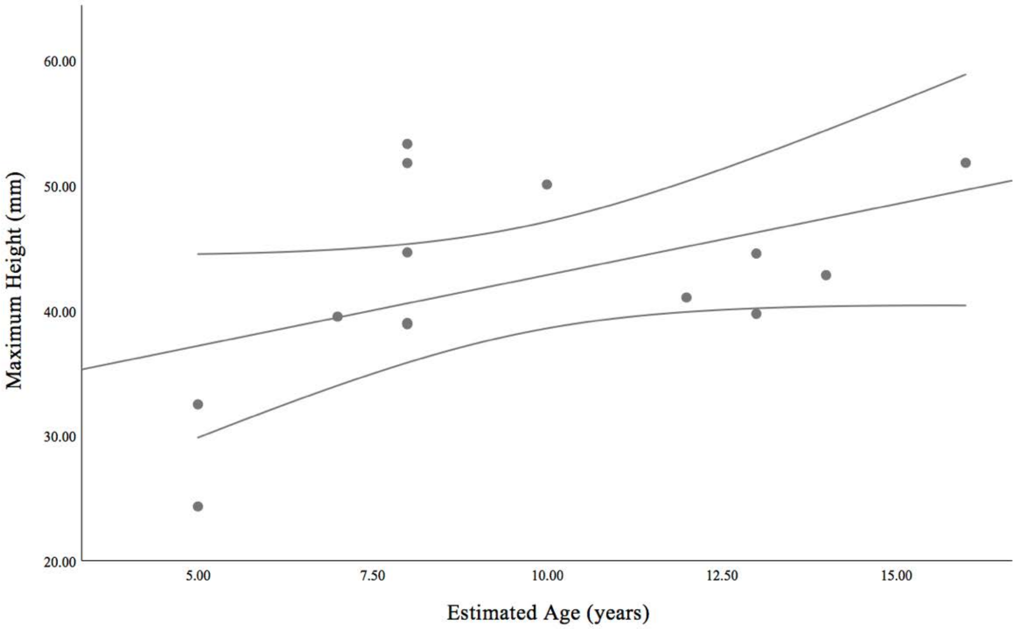
Complete section of *Acanthopleura gemmata* anterior valve 180-190cm#1.

Complete section of *Acanthopleura gemmata* anterior valve 220-230cm#1.

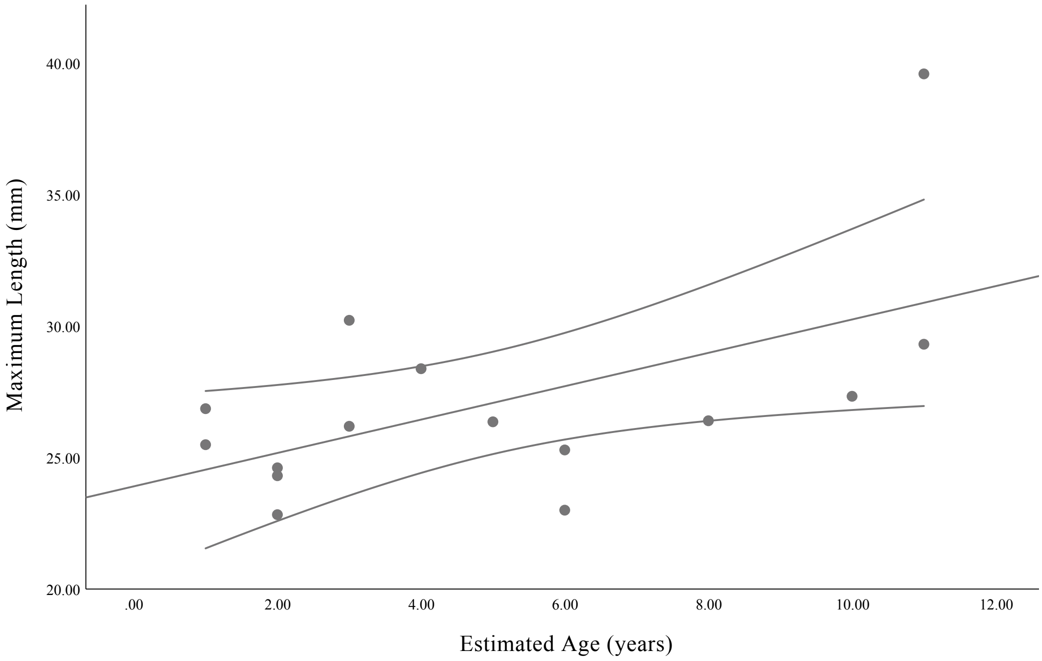
Appendix H – Summary Data for Maximum Shell Sizes and Ontogenetic Ages

Summary of descriptive statistics for maximum shell sizes and estimated ontogenetic age. Unit of measure = mm.

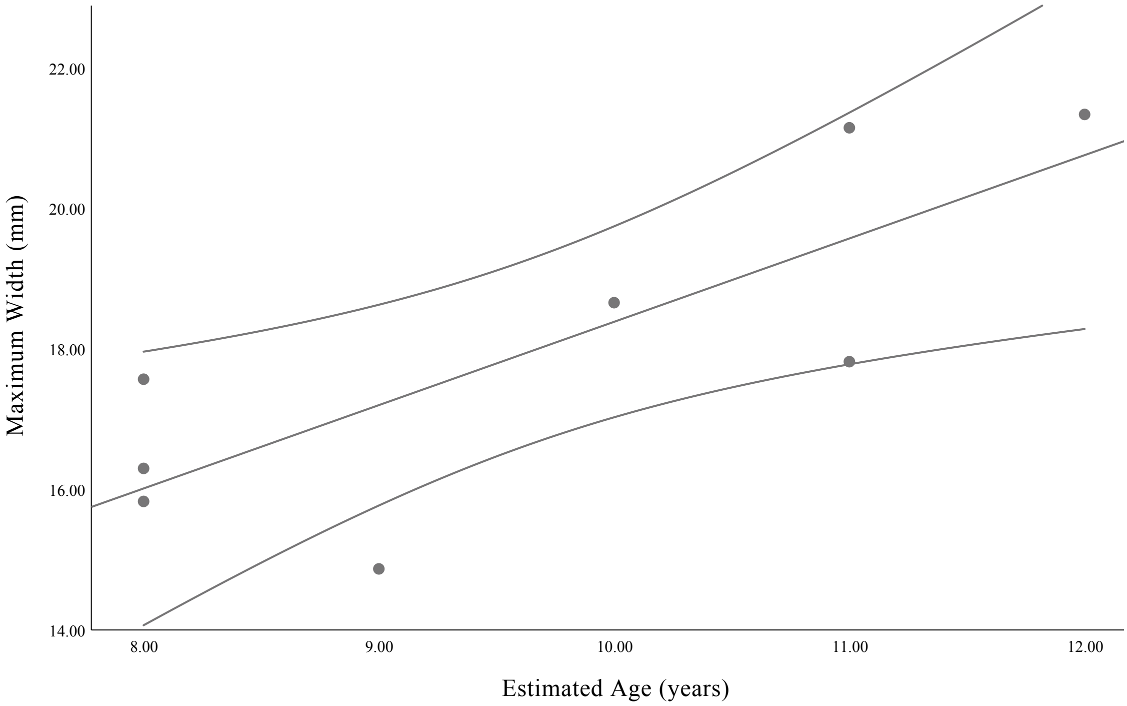
Species	n=	Mean	SD	Min	Max	Skew	Kurtosis
Saccostrea cuccullata (right valves)							
Maximum Height	14	42.44	7.99	24.33	53.34	-0.64	0.67
Estimated Age	14	9.64	3.41	5.00	16.00	0.42	-0.86
Lunella cinerea							
Maximum Length	15	27.07	4.04	22.83	39.59	2.25	6.63
Estimated Age	15	5.00	3.54	1.00	11.00	0.66	-0.92
Acanthopleura gemmata (posterior valve/L1)							
Posterior Width	8	17.94	2.36	14.87	21.34	0.42	-0.99
Estimated Age	8	9.62	1.59	8.00	12.00	0.25	-1.74



Linear regression scatter plot for *Saccostrea cuccullata* samples (n=14), showing the 95% confidence interval.



Linear regression scatter plot for *Lunella cinerea* samples (n=15), showing the 95% confidence interval.

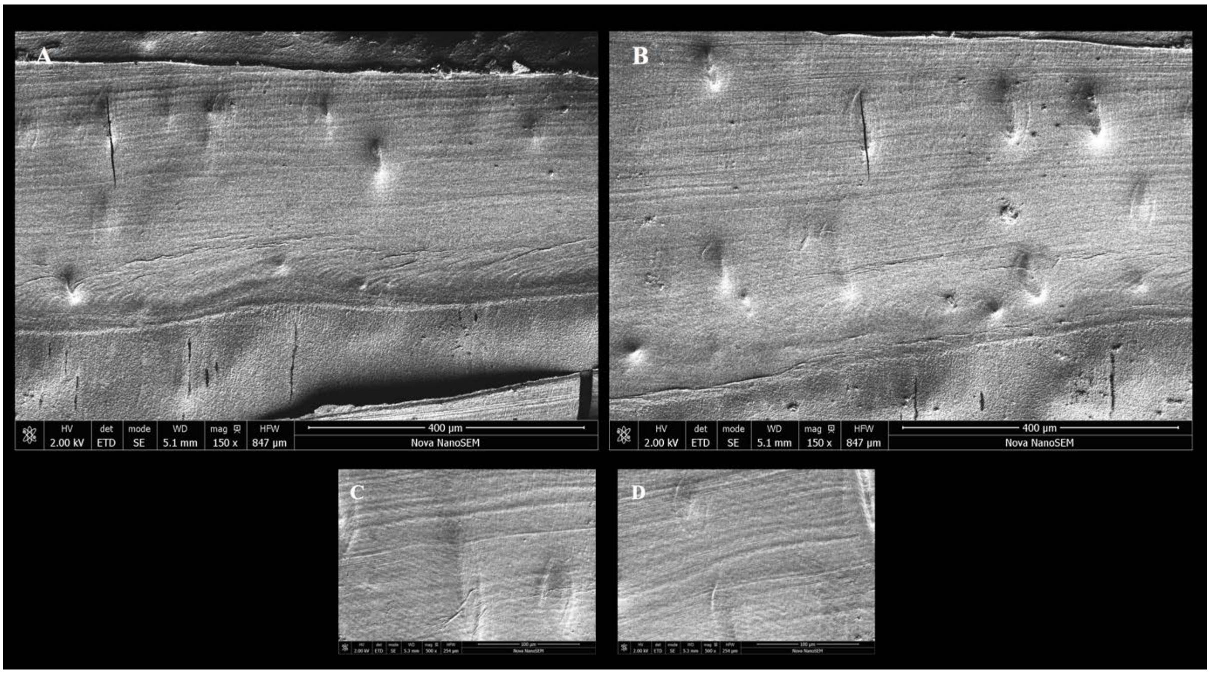


Linear regression scatter plot for *Acanthopleura gemmata* samples (n=8), showing the 95% confidence interval.

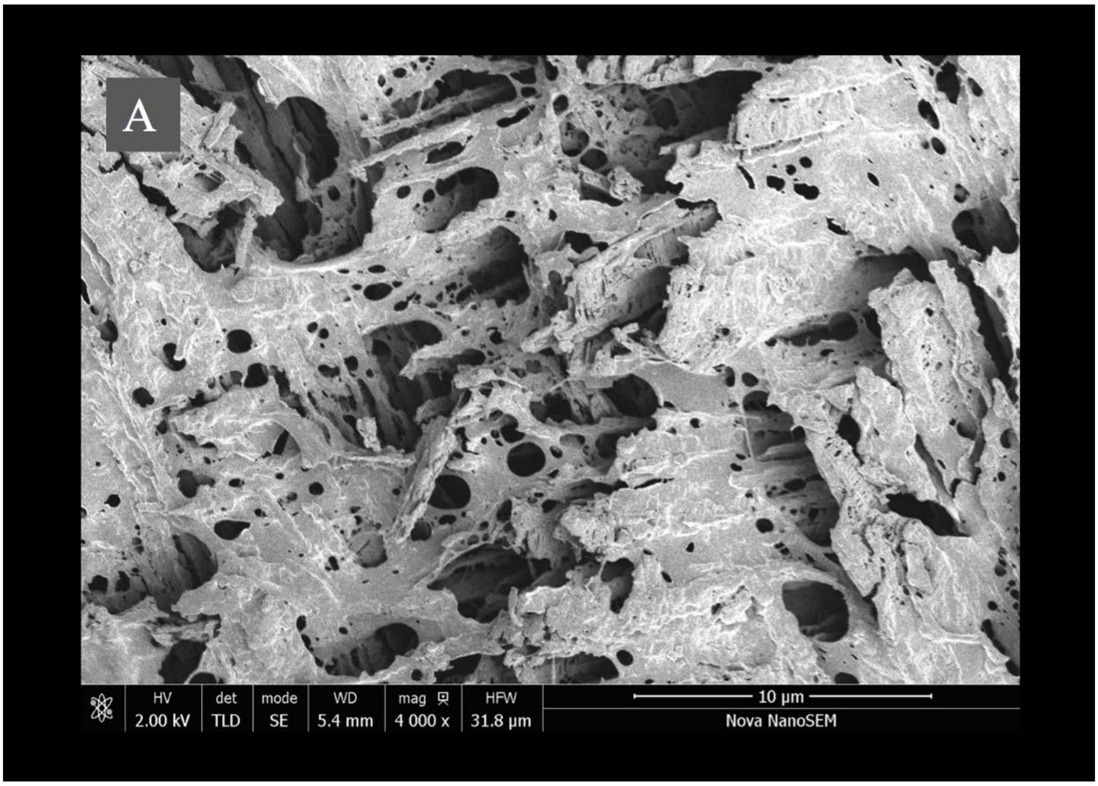
Appendix I – SEM Micrographs, *Acanthopleura gemmata*

Acanthopleura gemmata – samples #E1, #E2, #E3 are fragments of an intermediate *A. gemmata* valve that was live-collected from Mazie Bay in 2018. A mallet was used to fracture the valve in order to observe the internal microstructures. Each sample was mounted onto a slide and painted with carbon resin. Three distinct shell layers were observed under the SEM but crystal structures could not be detected and therefore micrographs are not shown (but see sample #E5 below).

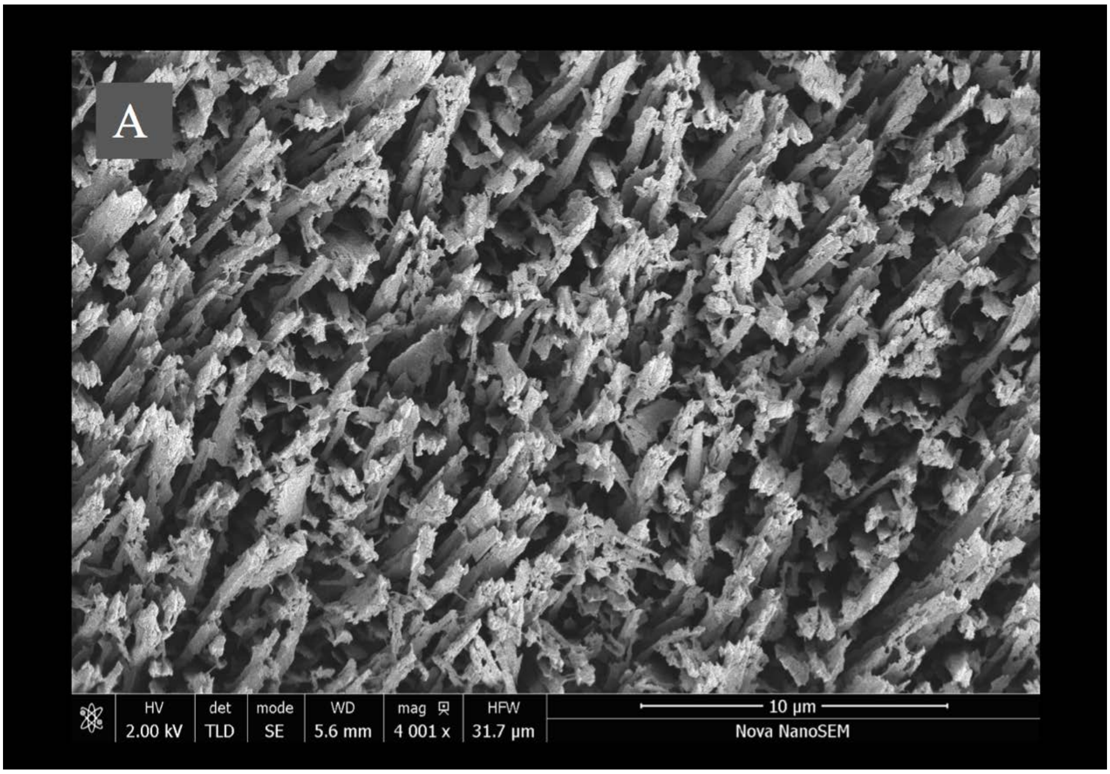
Acanthopleura gemmata – sample #E5 is a posterior valve, selected from a modern articulated *A. gemmata*, live-collected from Mazie Bay in 2018. A hand saw was used to section the shell valve in order to observe the internal microstructure. The sample was then etched in hydrochloric acid (HCI) for 10 minutes before being rinsed in freshwater and dried in an 80ºC oven for 5 minutes. After the pre-treatment process was completed, the sample was mounted onto a slide and painted with carbon resin. Three major layers were observable under the SEM. Etching in HCI made the shell surface smooth which made observation of crystal structures impossible.



Scanning Electron Microscope (SEM) micrographs for *Acanthopleura gemmata* sample #E5. A) section of shell showing the tegmentum layer, the middle articulamentum layer, and the bottom sublayer, crystal structure not detected, magnification x 150 scale = 400 µm; B) section of shell showing the articulamentum and bottom sublayer, crystal structure not detected, magnification x 150 scale = 400 µm; C) the articulamentum layer, crystal structure not detected, magnification x 500 scale = 100 µm; D) the articulamentum layer, crystal structure not detected, magnification x 500 scale = 100 µm.



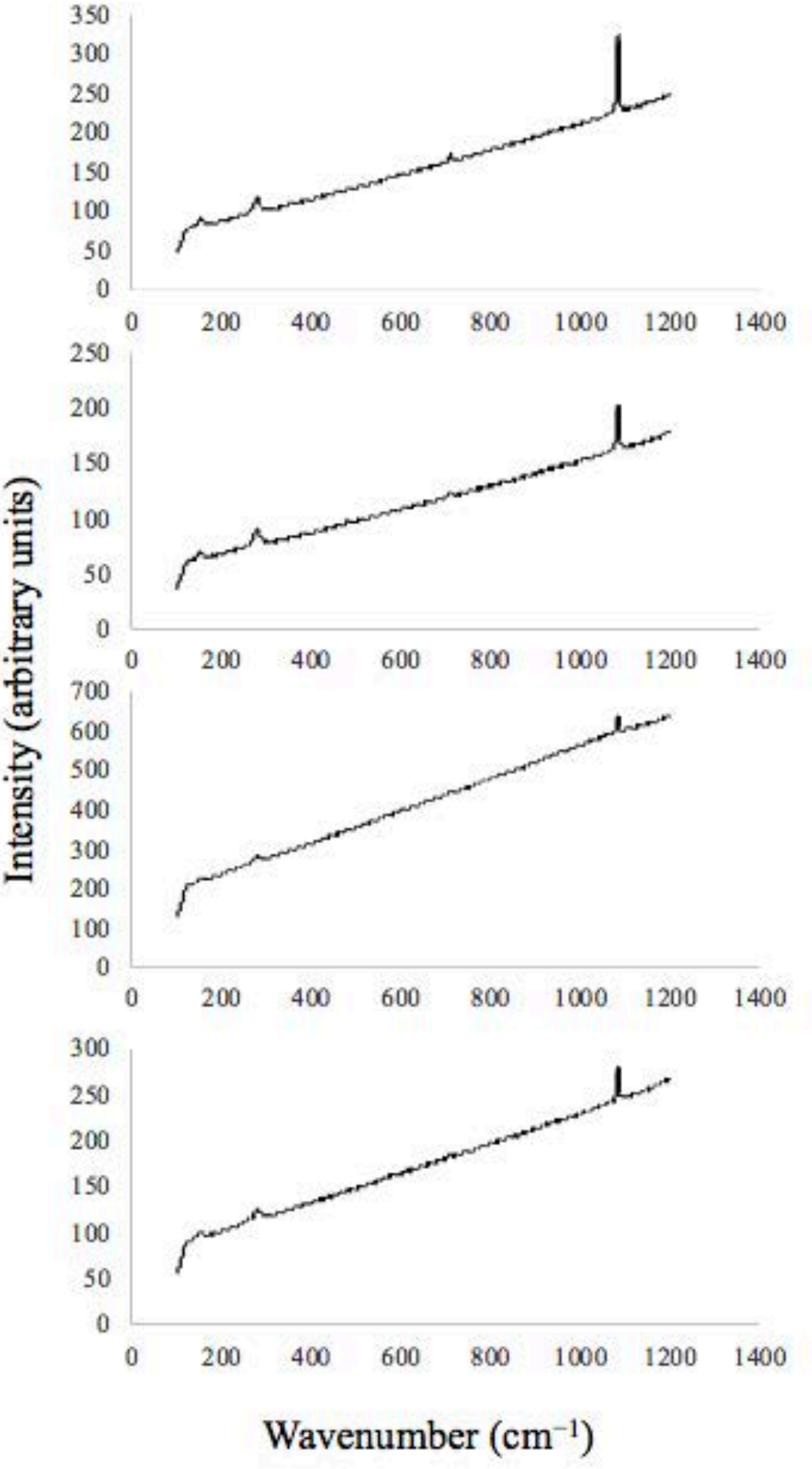
Supplementary micrograph – *Acanthopleura gemmata* sample 5-10cm#2, posterior valve. Magnification x 4000 scale = 10 µm.



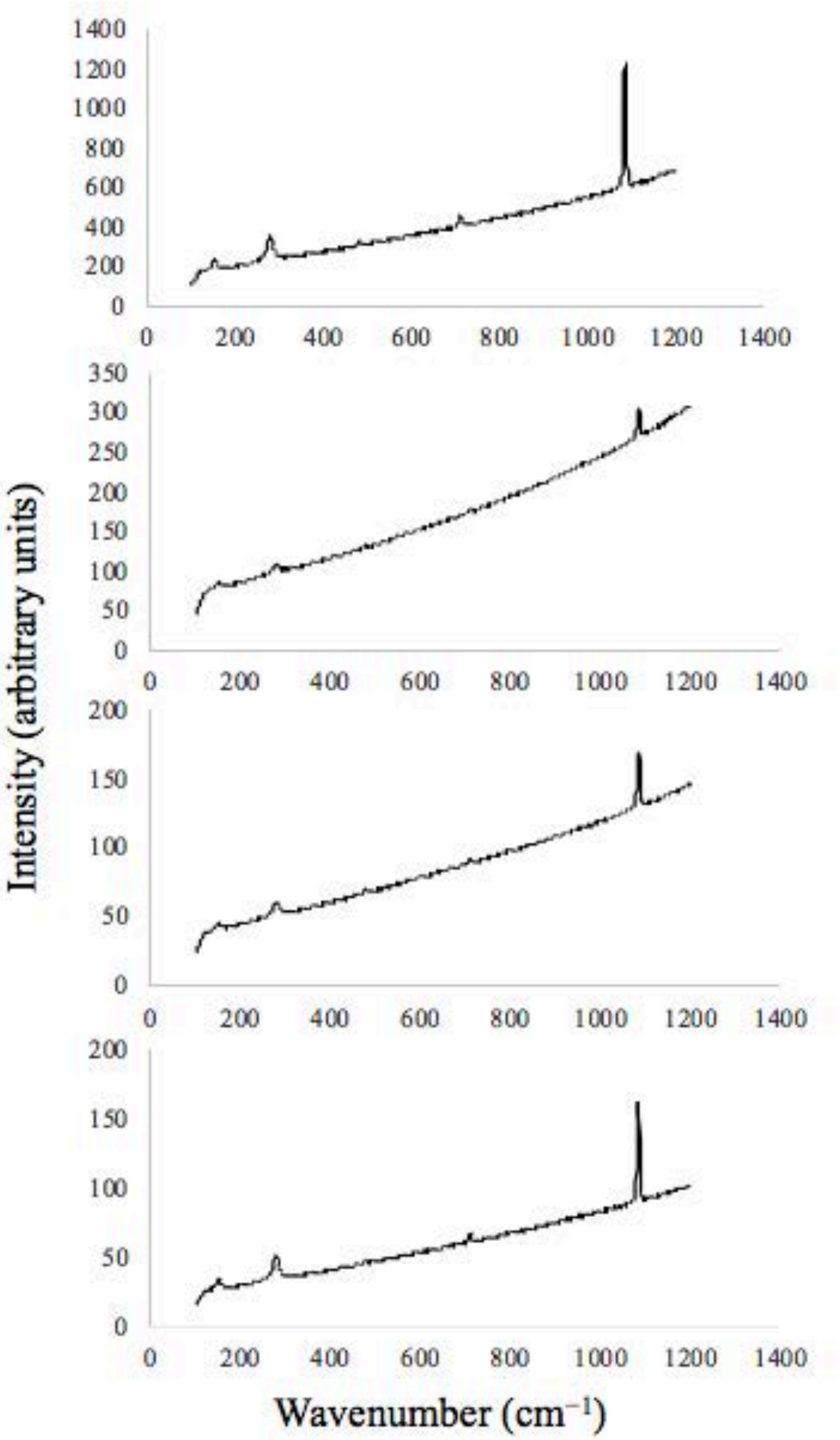
Supplementary micrograph – *Acanthopleura gemmata* sample 220-230cm#2, posterior valve. Magnification x 4001 scale = 10 µm.

Appendix J – Raman Spectroscopy Graphs

Live-Collected *Saccostrea cuccullata*

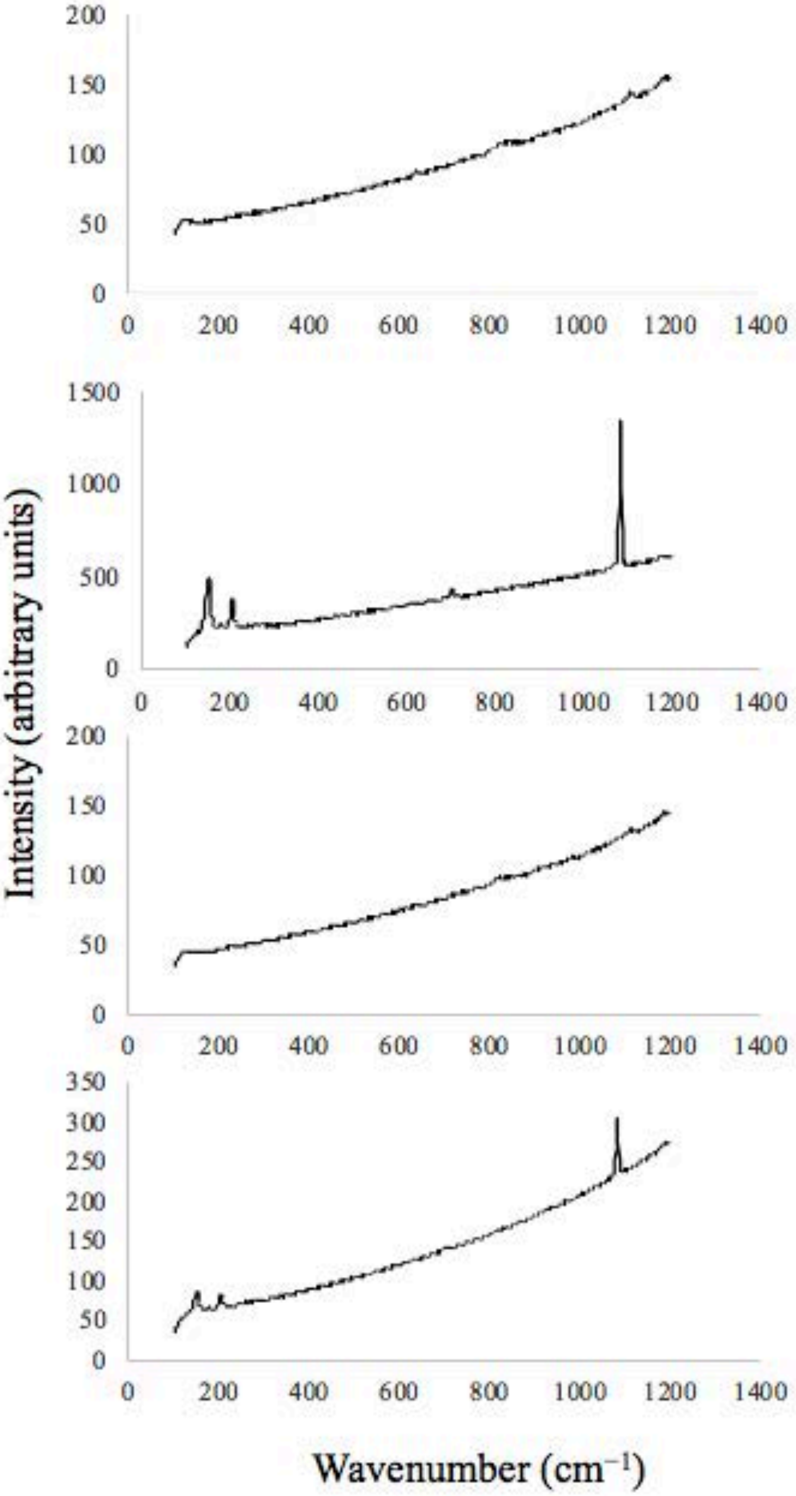


Raman spectra of the right valve in live-collected *Saccostrea cuccullata* sample LC#2.

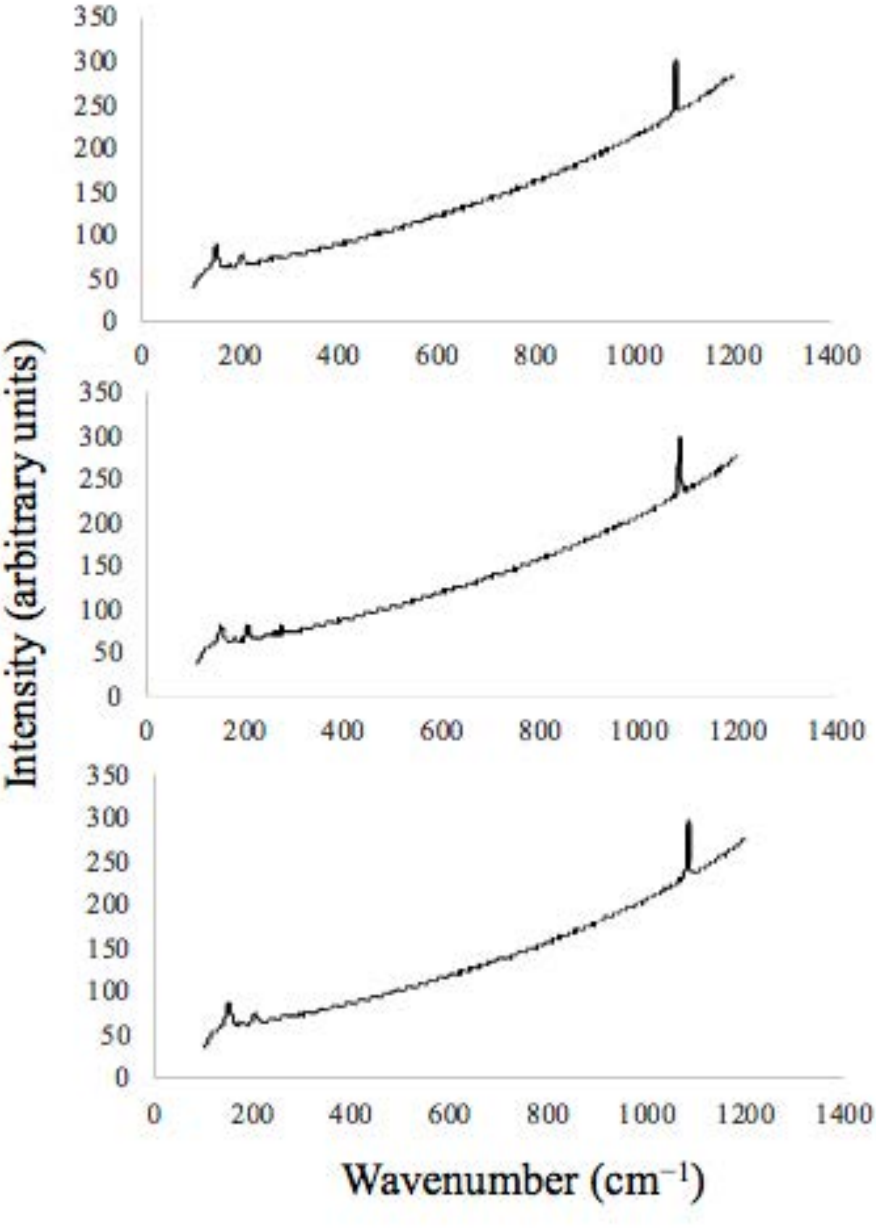


Raman spectra of the right valve in live-collected *Saccostrea cucculata* sample LC#4.

Live-Collected *Lunella cinerea*

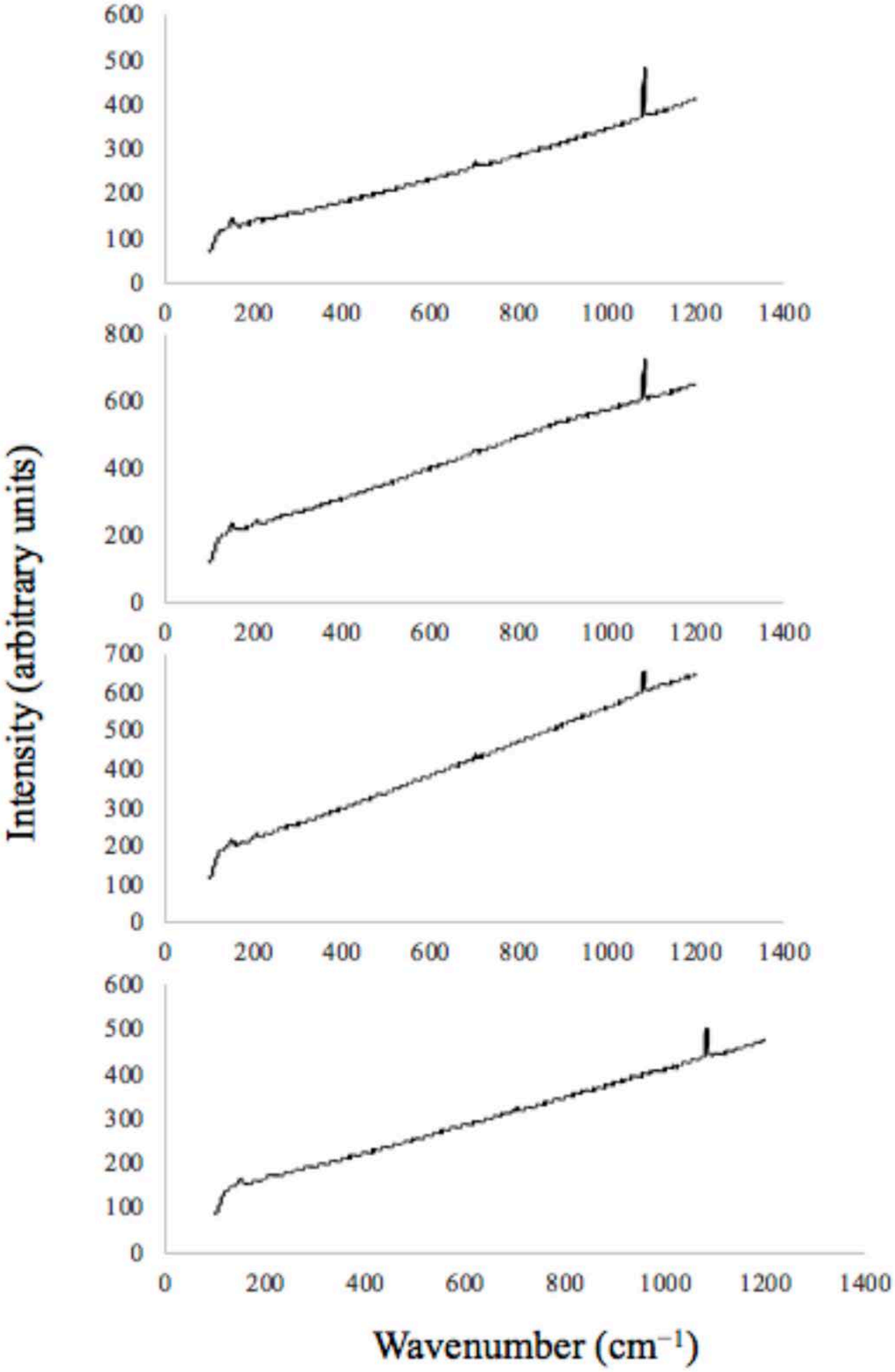


Raman spectra of the outer shell layer in a live-collected *Lunella cinerea* sample LC#5.



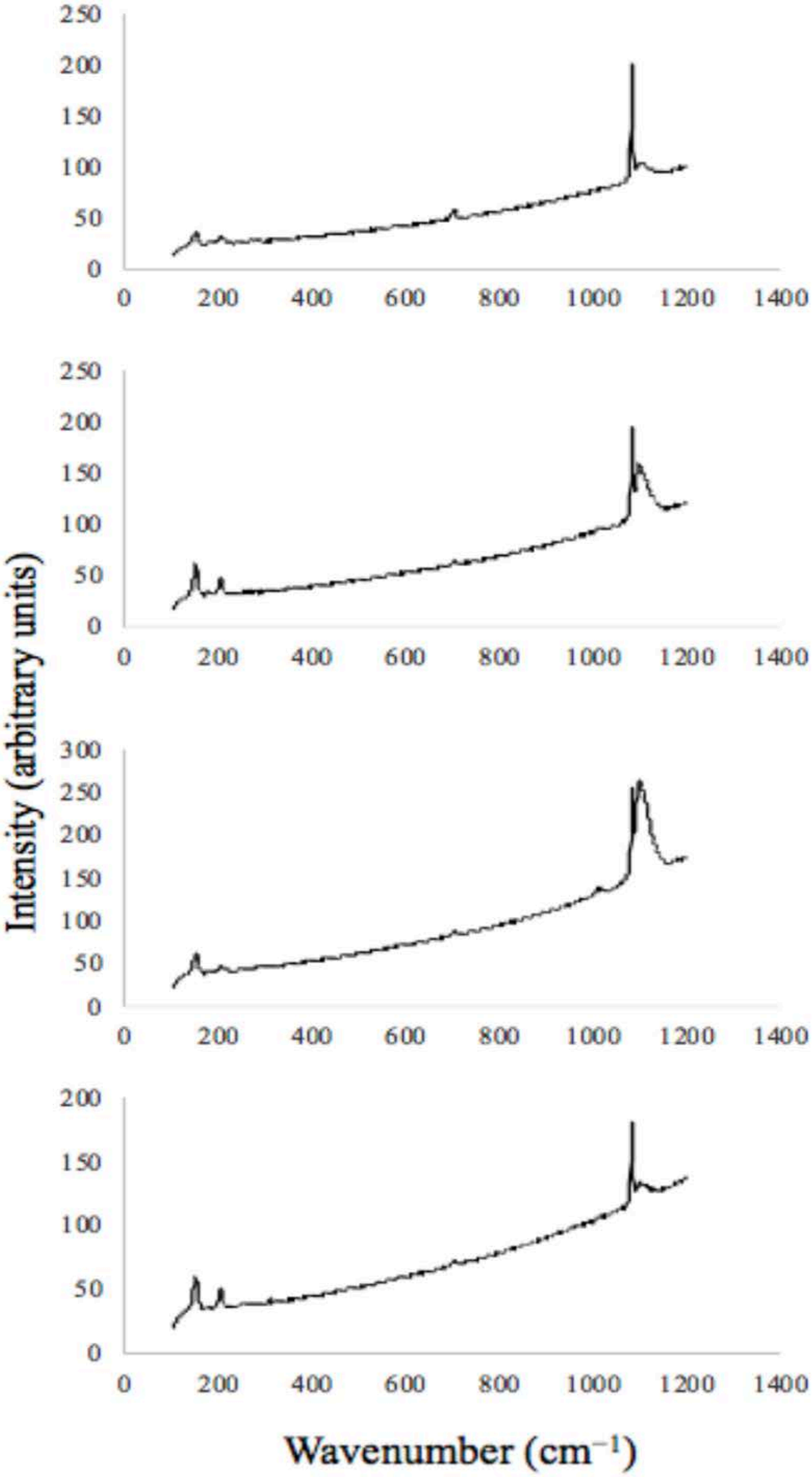
Raman spectra of the inner shell layer in a live-collected *Lunella cinerea* sample LC#5.

Deep Time *Lunella cinerea*

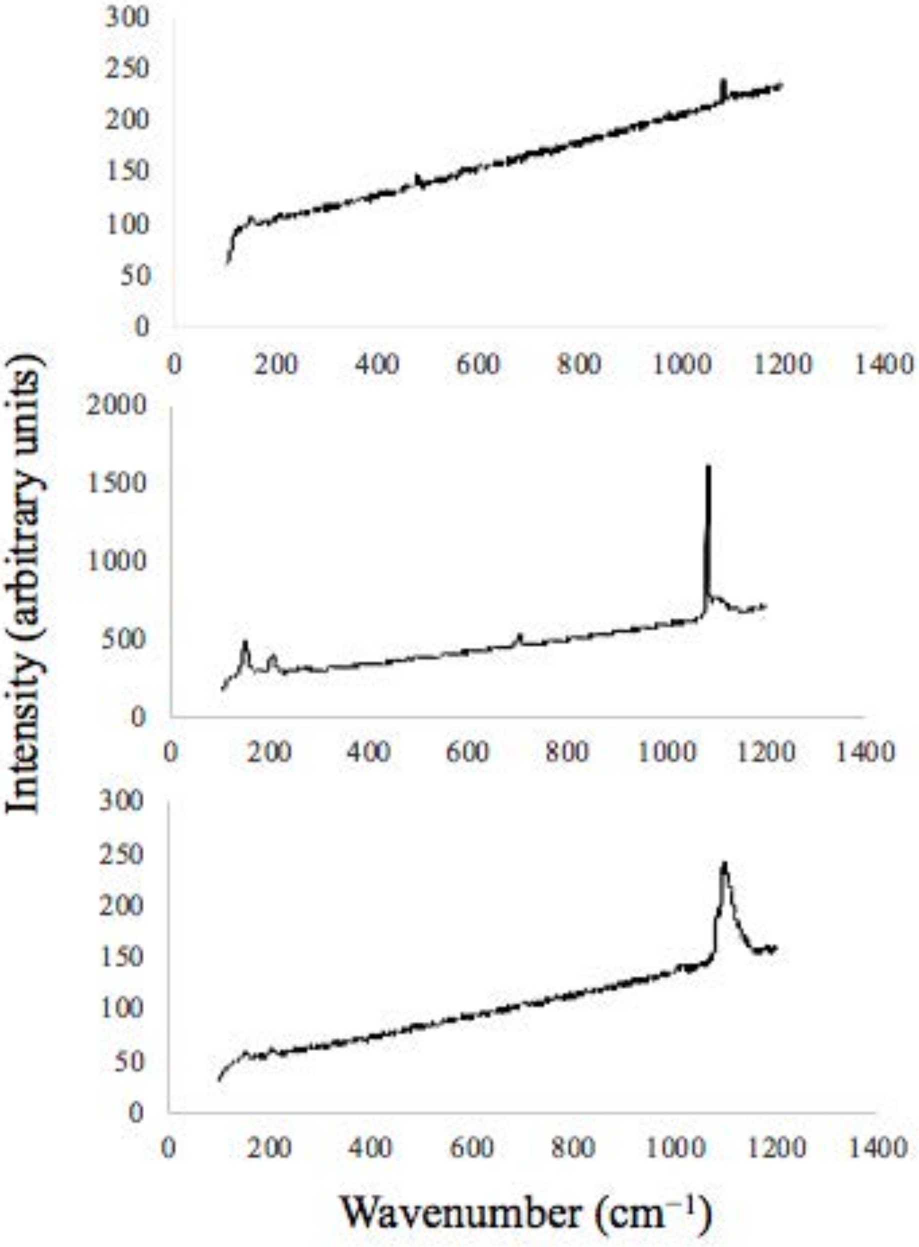


Raman spectra of the outer shell layer in deep time *Lunella cinerea* sample 60-65cm#1. Note issues with the run on the inner shell layer were encountered and therefore these spectra are not shown.

Live-Collected *Acanthopleura gemmata*

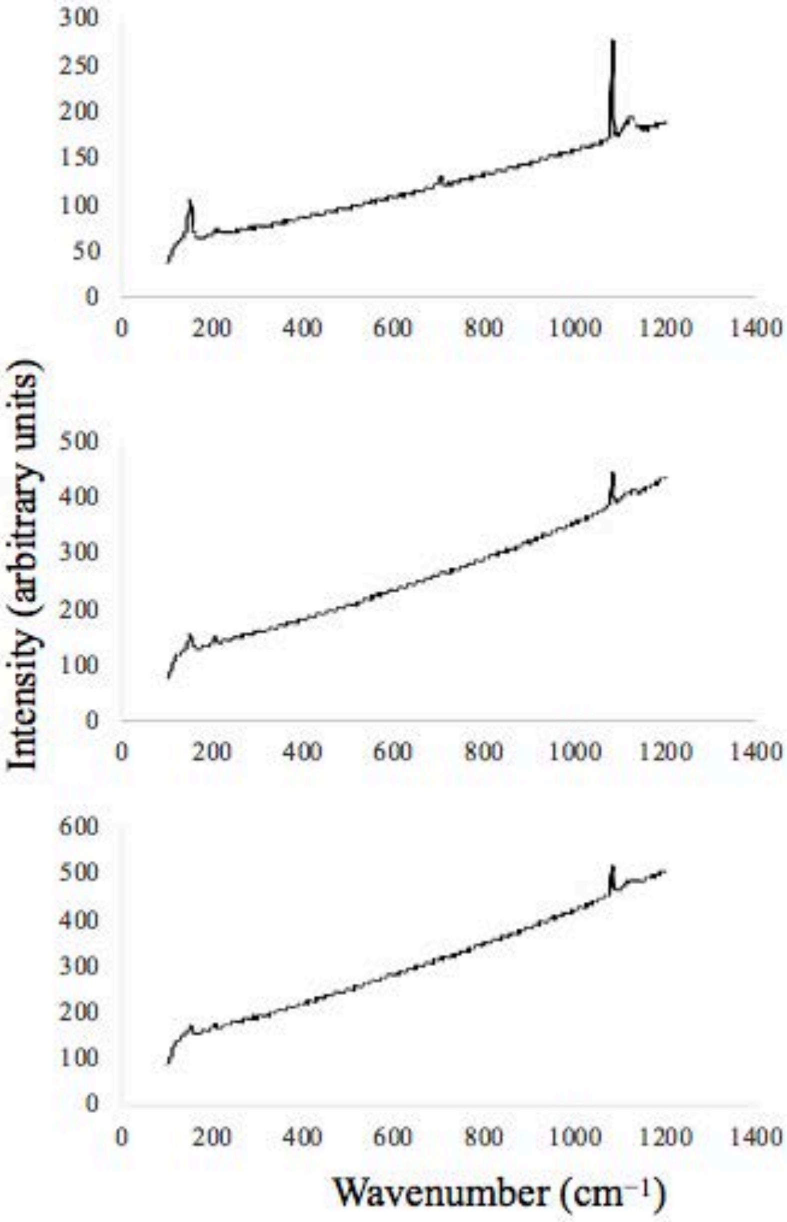


Raman spectra of the anterior shell valve in live-collected *Acanthopleura gemmata* sample LC#5.

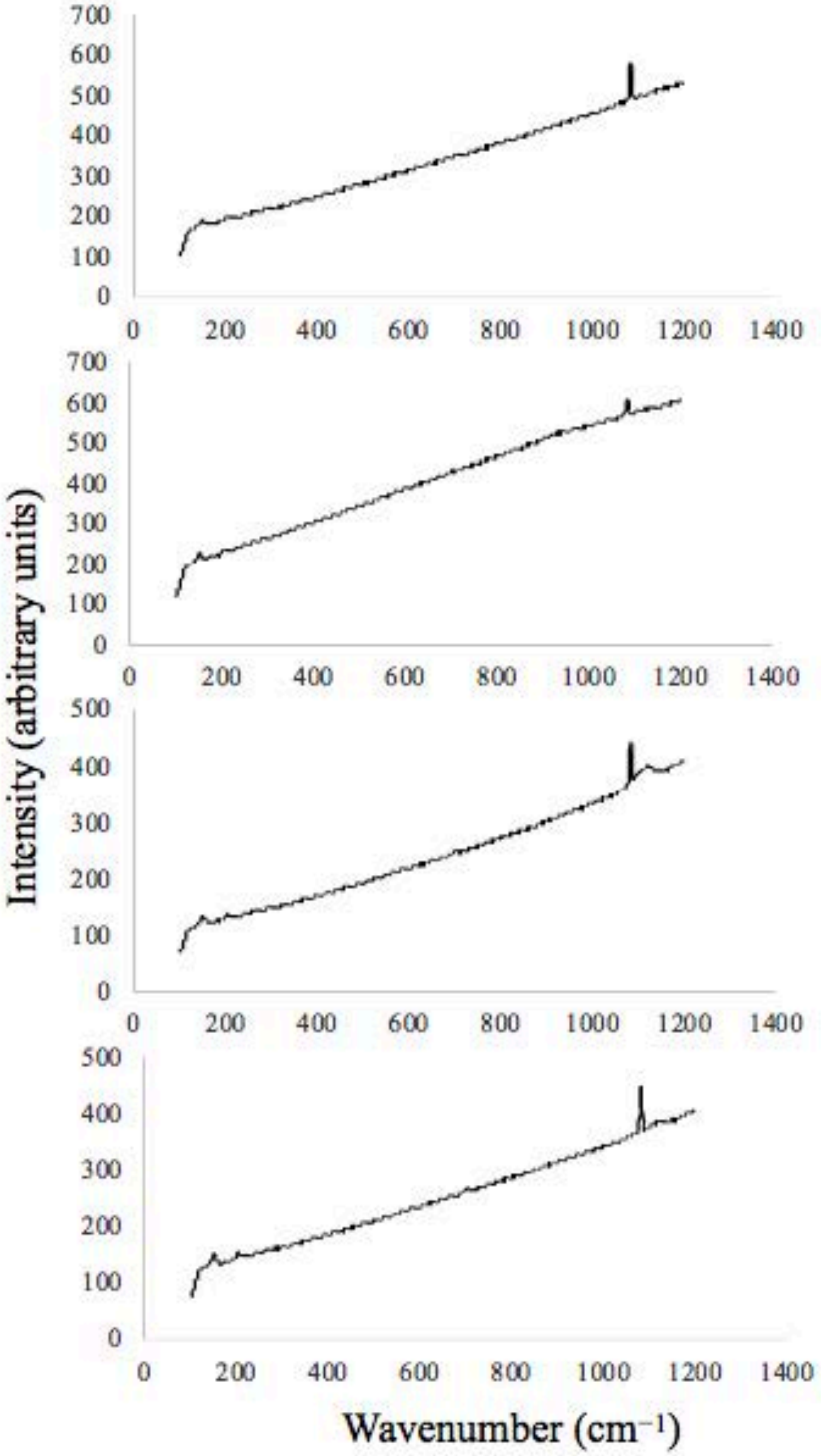


Raman spectra of the posterior shell valve in live-collected *Acanthopleura gemmata* sample LC#5.

Deep Time *Acanthopleura gemmata*



Raman spectra of the anterior shell valve in deep time *Acanthopleura gemmata* sample 60-65cm#1.



Raman spectra of the anterior shell valve in deep time *Acanthopleura gemmata* sample 180-190cm#1.

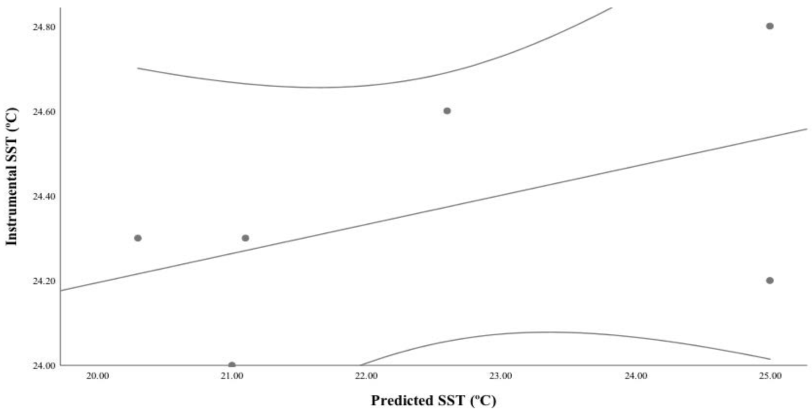
Appendix K – Supplementary Data for Stable Isotope Analyses

Live-Collected *Saccostrea cuccullata*

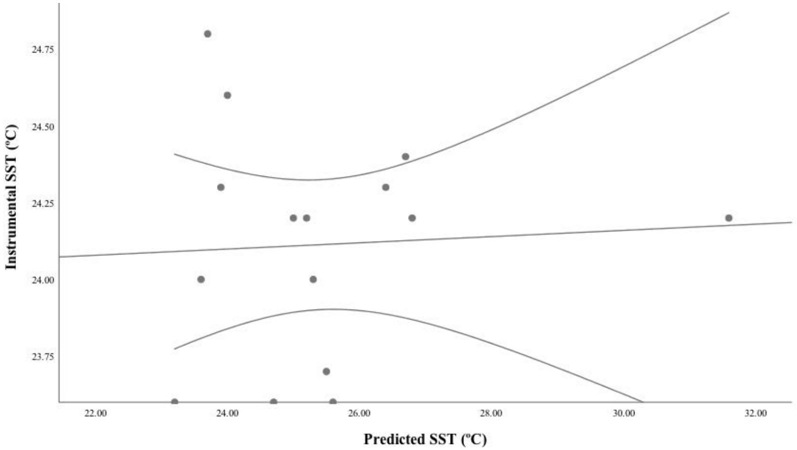
A) Live-collected *Saccostrea cuccullata* LC#2 at the pre-milling stage. B) Showing the area where long-sequence powder samples were extracted. Note grey outline is epoxy resin.

A) Live-collected *Saccostrea cuccullata* LC#4 at the pre-milling stage. B) Showing the area where long-sequence powder samples were extracted. Note grey outline is epoxy resin.

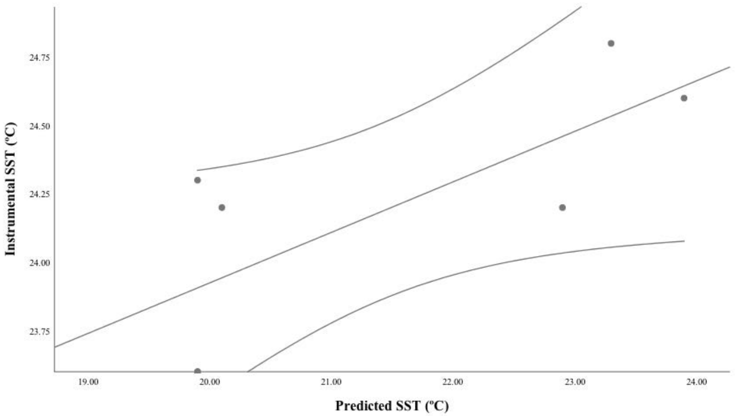
A) Live-collected *Saccostrea cuccullata* LC#6 at the pre-milling stage. B) Showing the area where long-sequence powder samples were extracted. Note grey outline is epoxy resin.



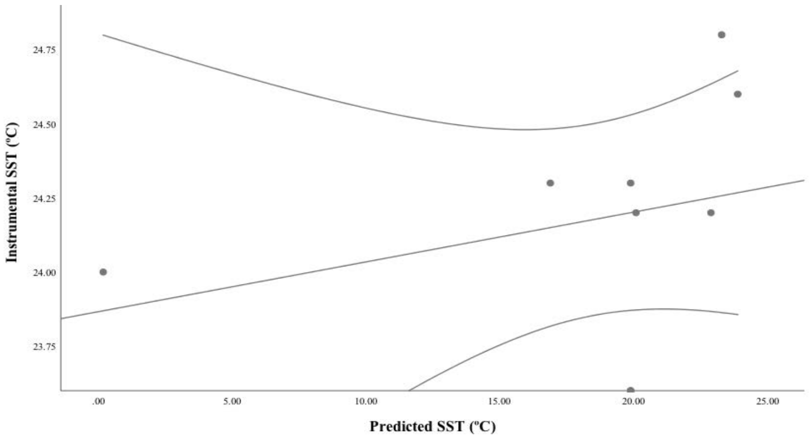
Linear regression scatter plot for live-collected *Saccostrea cuccullata* sample LC#2 (n=6), showing the 95% confidence intervals.



Linear regression scatter plot for live-collected *Saccostrea cuccullata* sample LC#4 (n=15), showing the 95% confidence intervals.



Linear regression scatter plot for live-collected *Saccostrea cuccullata* sample LC#6 (n=7)), showing the 95% confidence intervals.



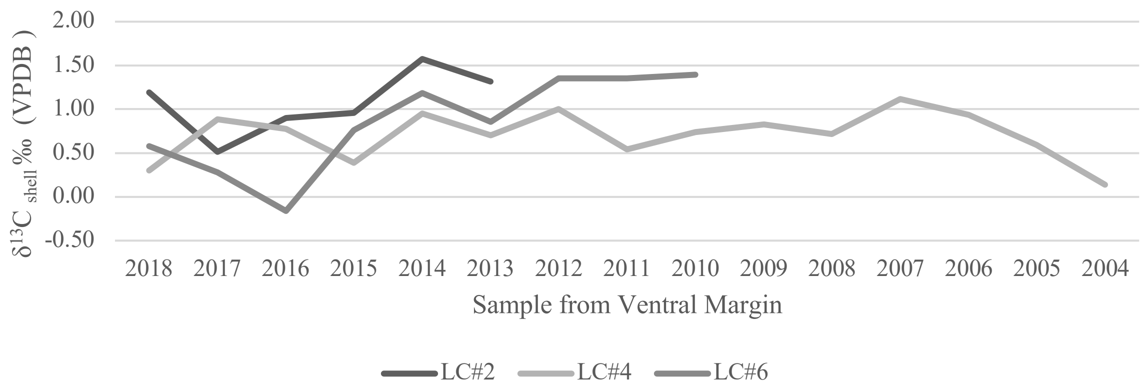
Linear regression scatter plot for live-collected *Saccostrea cuccullata* sample LC#6 (n=9)), showing the 95% confidence intervals.

$\delta^{13}C$ values of *Saccostrea cuccullata*, live-collected from Mazie Bay in September 2018.

	$\delta^{13}C_{shell}$ ‰		
Year	**LC#2**	**LC#4**	**LC#6**
2018	1.20	0.30	0.58
2017	0.51	0.89	0.28
2016	0.90	0.78	-0.16
2015	0.96	0.39	0.76
2014	1.57	0.95	1.19
2013	1.32	0.70	0.86
2012		1.00	1.35
2011		0.54	1.35
2010		0.74	1.40
2009		0.83	
2008		0.72	
2007		1.12	
2006		0.94	
2005		0.59	
2004		0.14	

Descriptive statistics for live-collected *Saccostrea cuccullata* $\delta^{13}C$ values.

			$\delta^{13}C_{shell}$ ‰				
Sample	**n=**	**Mean**	**Median**	**SD**	**Range**	**Min**	**Max**
LC#2	6	1.07	1.07	0.36	1.06	0.51	1.57
LC#4	15	0.7	0.74	0.27	0.97	0.13	1.11
LC#6	9	0.84	0.18	0.54	1.55	-0.16	1.39



Plotted $\delta^{13}C$ values, live-collected *Saccostrea cuccullata*, sample LC#2 (n=6), LC#4 (n=15), LC#6 (n=7) per year of growth.

Deep time *Saccostrea cuccullata*

A) Deep time *Saccostrea cuccullata* 5-10cm#1 at the pre-milling stage. B) Showing the area where long-sequence powder samples were extracted. Note grey outline is epoxy resin.

A) Deep time *Saccostrea cuccullata* 60-65cm#1 at the pre-milling stage. B) Showing the area where long-sequence powder samples were extracted. Note grey outline is epoxy resin.

A) Deep time *Saccostrea cuccullata* 130-135cm#1 at the pre-milling stage. B) Showing the area where long-sequence annual growth increments were carefully pulled out with tweezers. Note grey outline is epoxy resin.

A) Deep time *Saccostrea cuccullata* 190-200cm#1 at the pre-milling stage. B) Showing the area where long-sequence powder samples were extracted. Note grey outline is epoxy resin.

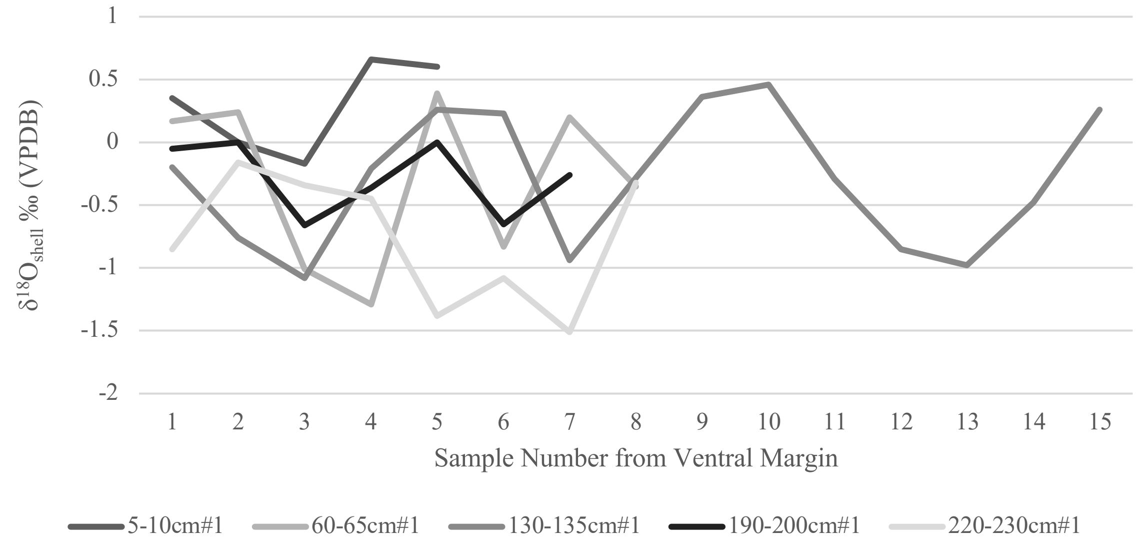
A) Deep time *Saccostrea cuccullata* 220-230cm#1 at the pre-milling stage. B) Showing the area where long-sequence annual growth increments were carefully pulled out with tweezers. Note: gap between the left and right halves of the section, shows a slight discrepancy in image overlay (i.e. at the time of fitting images together, features could not be exactly aligned). Grey outline is epoxy resin.

Descriptive statistics for deep time *Saccostrea cuccullata* $\delta^{18}O$ values. Edges = combined site 1 descriptive statistics.

				$\delta^{18}O_{shell}$ ‰			
Sample	**n=**	**Mean**	**Median**	**SD**	**Range**	**Min**	**Max**
Edges	5	-0.11	-0.05	0.46	1.2	-0.85	0.35
5-10cm#1	4	0.36	0.47	0.37	0.83	-0.17	0.66
60-65cm#1	8	-0.31	-0.09	0.65	1.68	-1.29	0.39
130-135cm#1	15	-0.3	-0.28	0.53	1.54	-1.08	0.46
190-200cm#1	6	-0.33	-0.31	0.28	0.66	-0.66	0
220-230cm#1	8	-0.76	-0.65	0.51	1.35	-1.51	-0.16

$\delta^{18}O$ values and predicted annual sea surface temperatures for deep time *Saccostrea cuccullata*. Sample lost in mass spectrometer = x.

$\delta^{18}O_{shell}$ ‰					Predicted SST ºC				
5-10 cm#1	**60-65 cm#1**	**130-135 cm#1**	**190-200 cm#1**	**220-230 cm#1**	**5-10 cm#1**	**60-65 cm#1**	**130-135 cm#1**	**190-200 cm#**	**220-230 cm#1**
0.35	0.17	-0.2	-0.05	-0.85	17.91	18.69	20.30	19.65	23.12
x	0.24	-0.76	x	-0.16	x	18.39	22.73	x	20.13
-0.17	-1.01	-1.08	-0.66	-0.34	20.17	23.82	24.12	22.30	20.91
0.66	-1.29	-0.21	-0.36	-0.45	16.57	25.03	20.34	20.99	21.39
0.6	0.39	0.26	0	-1.38	16.83	17.74	18.30	19.43	25.42
x	-0.83	0.23	-0.65	-1.08	x	23.03	18.43	22.25	24.12
x	0.2	-0.94	-0.26	-1.51	x	18.56	23.51	20.56	25.99
x	-0.35	-0.28		-0.32	x	20.95	20.65		20.82
x		0.36			x		17.87		
x		0.46			x		17.44		
x		-0.29			x		20.69		
x		-0.85			x		23.12		
x		-0.98			x		23.69		
		-0.48					21.52		
		0.26					18.30		



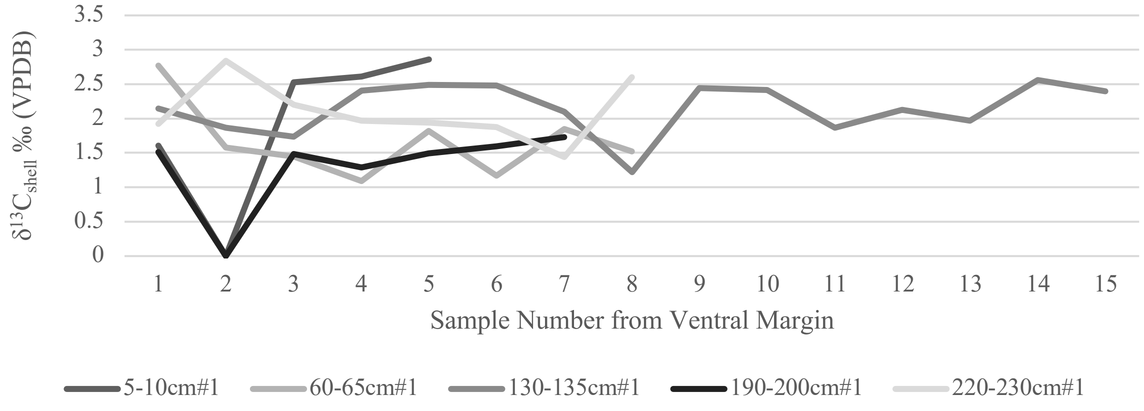
Plotted $\delta^{18}O$ values, deep time *Saccostrea cuccullata*, samples 5-10cm#1 (n=4), 60-65cm#1 (n=8), 130-135cm#1 (n=15), 190-200cm#1 (n=6), 220-230cm#1 (n=8).

δ^{13}C values of deep time *Saccostrea cuccullata*. Sample lost in mass spectrometer = x.

$\delta^{13}C_{shell}$ ‰				
5-10cm#1	**60-65cm#1**	**130-135cm#1**	**190-200cm#1**	**220-230cm#1**
1.61	2.77	2.15	1.51	1.92
x	1.58	1.87	x	2.84
2.53	1.45	1.74	1.48	2.2
2.61	1.09	2.41	1.29	1.97
2.86	1.82	2.49	1.49	1.94
x	1.17	2.48	1.6	1.88
x	1.85	2.1	1.73	1.44
x	1.52	1.22		2.6
x		2.44		
x		2.42		
x		1.87		
x		2.13		
x		1.97		
		2.56		
		2.4		

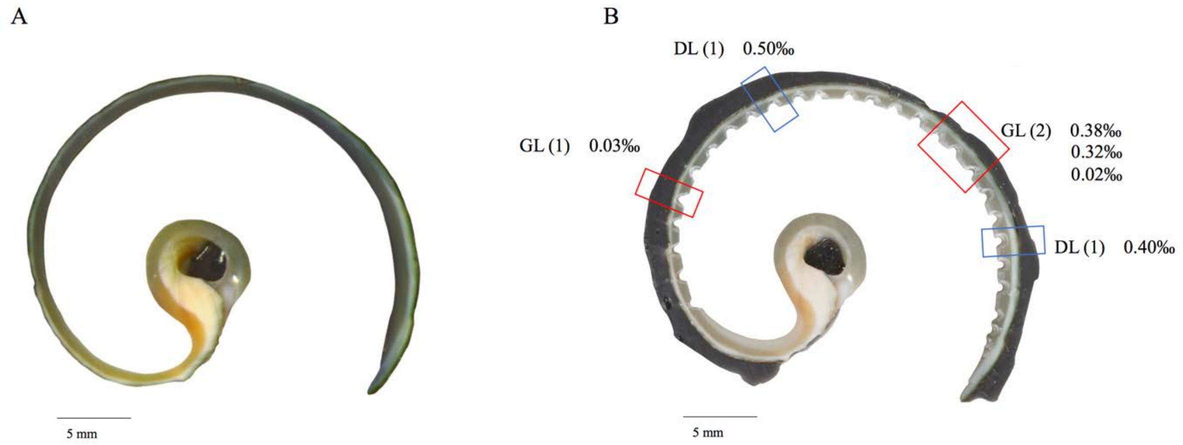
Descriptive statistics for deep time *Saccostrea cuccullata* δ^{13}C values.

$\delta^{13}C_{shell}$ ‰							
Sample	**n=**	**Mean**	**Median**	**SD**	**Range**	**Min**	**Max**
5-10cm#1	4	2.4	2.57	0.54	1.25	1.6	2.86
60-65cm#1	8	1.65	1.55	0.52	1.68	1.08	2.77
130-135cm#1	15	2.15	2.15	0.36	1.34	1.21	2.56
190-200cm#1	6	1.51	1.49	0.14	0.43	1.29	1.72
220-230cm#1	8	2.09	1.95	0.44	1.39	1.44	2.83

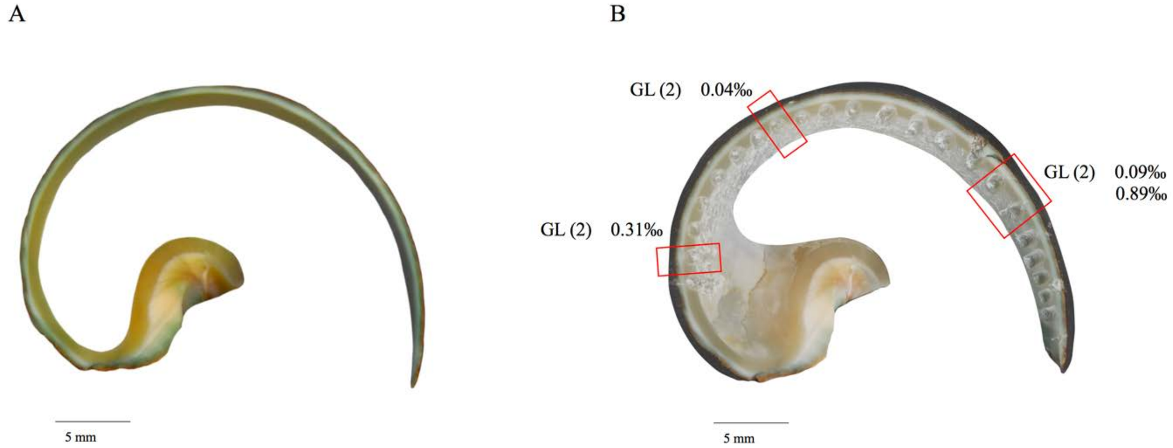


Plotted δ^{13}C values, deep time *Saccostrea cuccullata*, samples 5-10cm#1 (n=4), 60-65cm#1 (n=8), 130-135cm#1 (n=15), 190-200cm#1 (n=6), 220-230cm#1 (n=8).

Live-collected *Lunella cinerea*



A) Live-collected *Lunella cinerea* LC#3 at the pre-drilling stage. B) Showing the area where long-sequence powder samples were extracted. Note grey outline is epoxy resin.

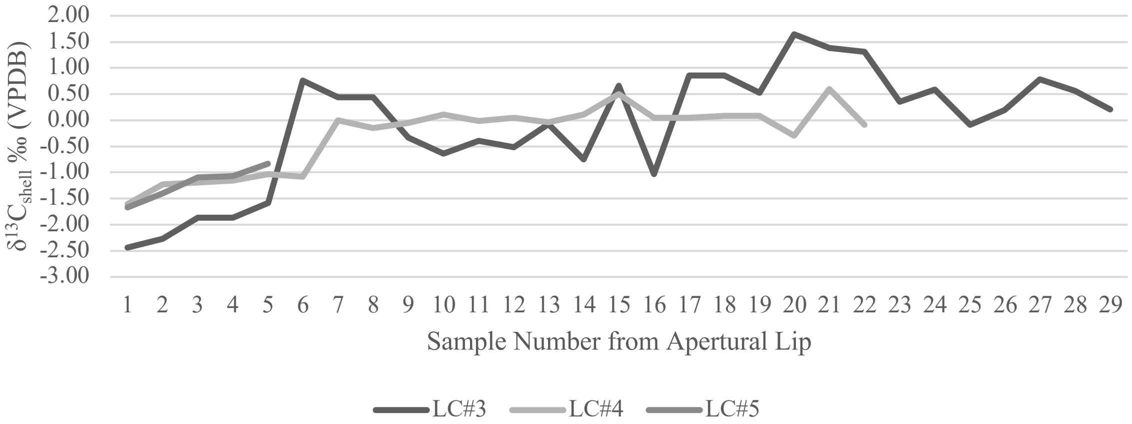


A) Live-collected *Lunella cinerea* LC#4 at the pre-drilling stage. B) Showing the area where long-sequence powder samples were extracted. Note grey outline is epoxy resin.

A) Live-collected *Lunella cinerea* LC#5 at the pre-drilling stage. B) Showing the area where short-sequence powder samples were extracted. Note grey outline is epoxy resin.

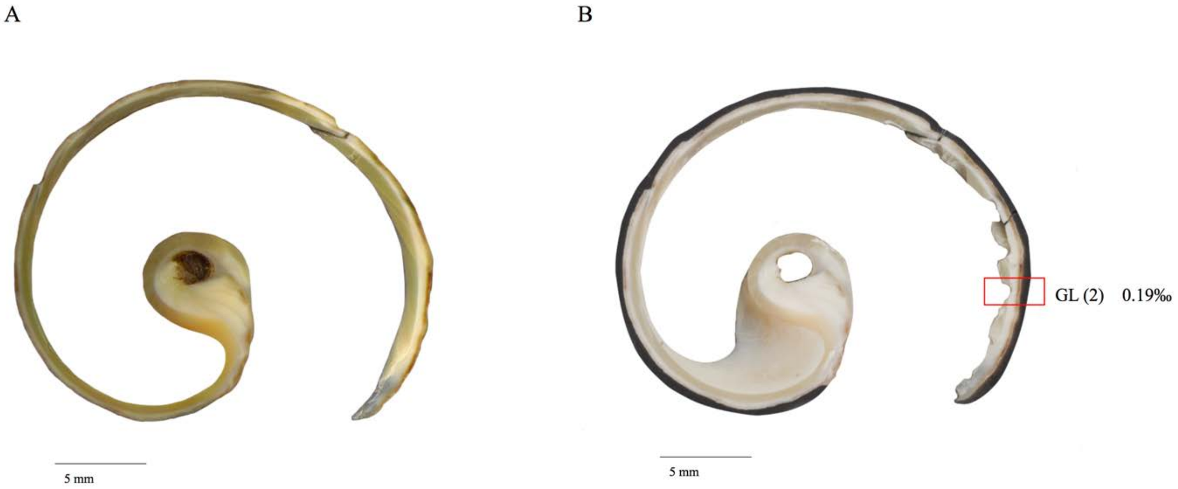
δ^{13}C values of *Lunella cinerea*, live-collected from Mazie Bay in September 2018.

$\delta^{13}C_{shell}$ ‰		
LC#3	**LC#4**	**LC#5**
-2.44	-1.60	-1.67
-2.27	-1.23	-1.40
-1.87	-1.19	-1.09
-1.86	-1.15	-1.06
-1.58	-1.03	-0.83
0.76	-1.08	
0.44	0.00	
0.44	-0.15	
-0.33	-0.05	
-0.64	0.11	
-0.40	-0.01	
-0.52	0.04	
-0.07	-0.04	
-0.75	0.11	
0.66	0.51	
-1.03	0.05	
0.86	0.04	
0.85	0.08	
0.53	0.09	
1.65	-0.29	
1.38	0.60	
1.31	-0.09	
0.36		
0.59		
-0.09		
0.20		
0.78		
0.56		
0.20		



Plotted δ^{13}C values for live-collected *Lunella cinerea* LC#3 (full life-history, n=29), LC#4 (full life-history, n= 22) and LC#5 (edge sample, n=5).

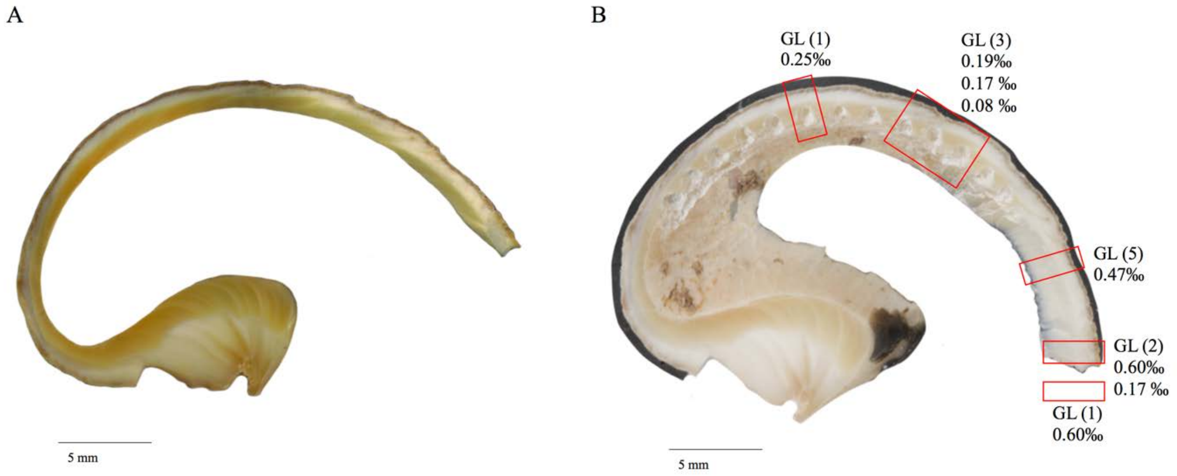
Deep time *Lunella cinerea*



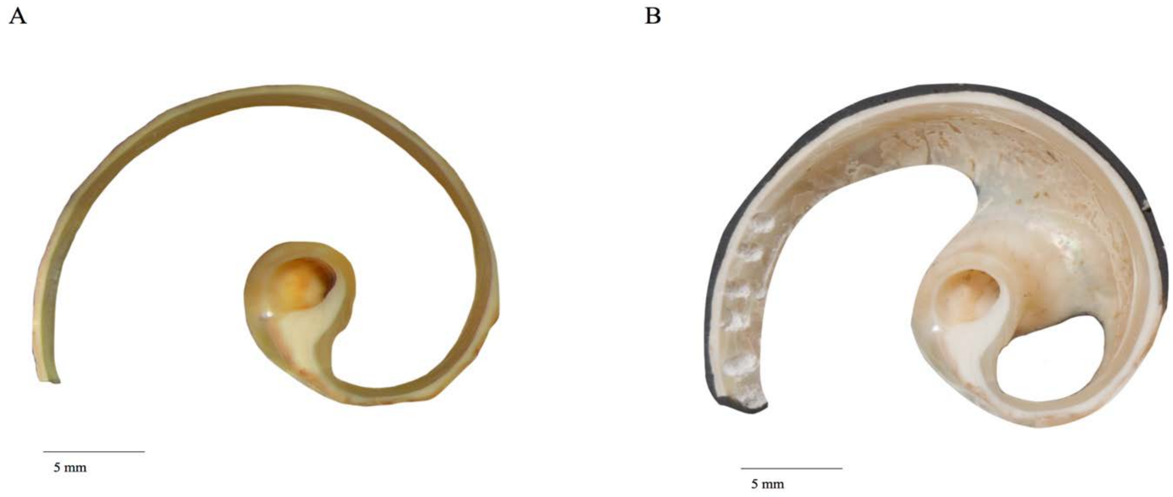
A) Deep time *Lunella cinerea* 5-10cm#2 at the pre-drilling stage. B) Showing the area where short-sequence powder samples were extracted. Note grey outline is epoxy resin.

A) Deep time *Lunella cinerea* 55-60cm#1 at the pre-drilling stage. B) Showing the area where short-sequence powder samples were extracted. Note grey outline is epoxy resin.

A) Deep time *Lunella cinerea* 110-115cm#1 at the pre-drilling stage. B) Showing the area where short-sequence powder samples were extracted. Note grey outline is epoxy resin.



A) Deep time *Lunella cinerea* 170-180cm#2 at the pre-drilling stage. B) Showing the area where long-sequence powder samples were extracted. Note grey outline is epoxy resin.



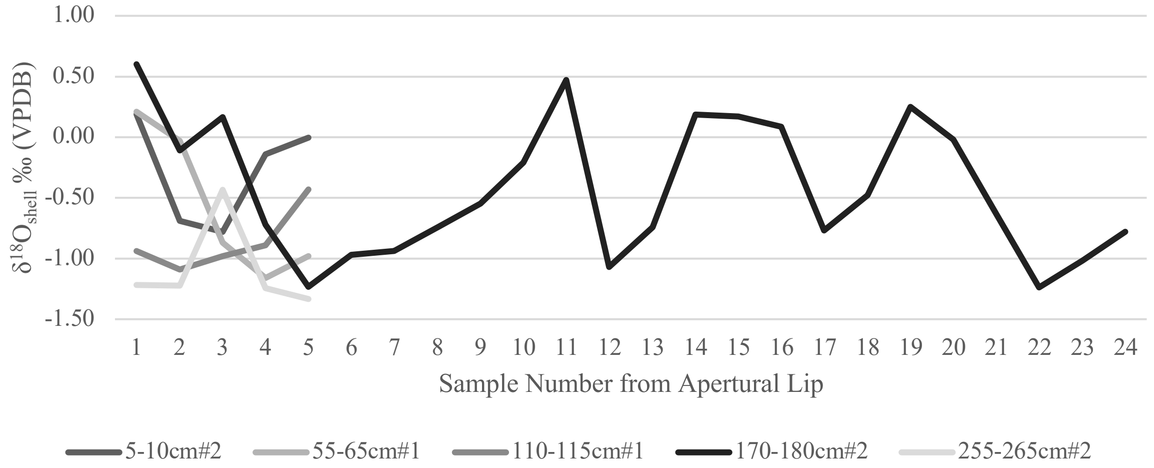
A) Deep time *Lunella cinerea* 255-265cm#2 at the pre-drilling stage. B) Showing the area where short-sequence powder samples were extracted. Note grey outline is epoxy resin.

Descriptive statistics for deep time *Lunella cinerea* δ^{18}O values. Edges = combined site 1 descriptive statistics.

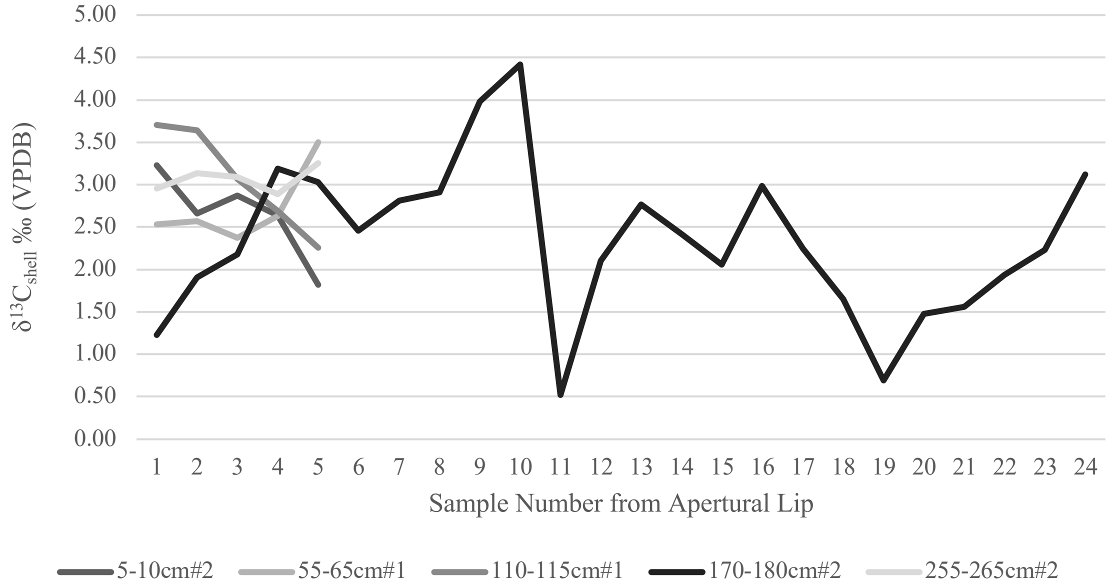
				$\delta^{18}O_{shell}$ ‰			
Sample	**n=**	**Mean**	**Median**	**SD**	**Range**	**Min**	**Max**
Edges	5	-0.23	0.19	0.79	1.82	-1.22	0.6
5-10cm#2	5	-0.28	-0.14	0.42	0.97	-0.78	0.19
55-65cm#1	5	-0.56	-0.87	0.61	1.37	-1.16	0.21
110-115cm#1	5	-0.86	-0.94	0.25	0.66	-1.09	-0.43
170-180cm#2	24	-0.42	-0.59	0.55	1.84	-1.24	0.6
255-265cm#2	5	-1.09	-1.22	0.37	0.9	-1.33	-0.43

δ^{18}O values and predicted annual sea surface temperatures for deep time *Lunella cinerea*.

$\delta^{18}O_{shell}$ ‰					Pred. SST ºC				
5-10 cm#2	**55-60 cm#1**	**110-115 cm#1**	**170-180 cm#2**	**255-265 cm#2**	**5-10 cm#2**	**55-60 cm#1**	**110-115 cm#1**	**170-180 cm#2**	**255-265 cm#2**
0.19	0.21	-0.94	0.6	-1.22	18.6	18.5	23.5	16.8	24.7
-0.69	-0.03	-1.09	-0.11	-1.22	22.4	19.6	24.2	19.9	24.7
-0.78	-0.87	-0.98	0.17	-0.43	22.8	23.2	23.7	18.7	21.3
-0.14	-1.16	-0.89	-0.72	-1.25	20.0	24.5	23.3	22.6	24.8
-0.01	-0.98	-0.43	-1.24	-1.33	19.5	23.7	21.3	24.8	25.2
			-0.97					23.6	
			-0.94					23.5	
			-0.74					22.7	
			-0.55					21.8	
			-0.21					20.3	
			0.47					17.4	
			-1.07					24.1	
			-0.74					22.6	
			0.19					18.6	
			0.17					18.7	
			0.08					19.1	
			-0.77					22.8	
			-0.48					21.5	
			0.25					18.3	
			-0.02					19.5	
			-0.63					22.2	
			-1.24					24.8	
			-1.02					23.8	
			-0.78					22.8	



Plotted δ^{18}O values, live-collected *Lunella cinerea*. Note: sample 170-180cm#2 was drilled for long-sequence data (n=24), sample 5-10cm#2 (n=5), 55-65cm#1 (n=5), 110-115cm#1 (n=5), 255-265cm#2 (n=5).

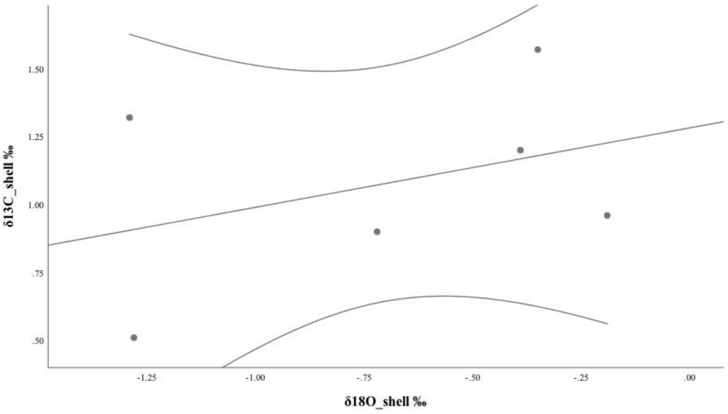


Plotted δ^{13}C values, deep time *Lunella cinerea*. Note: sample 170-180cm#2 was drilled for long-sequence data (n=24), sample 5-10cm#2 (n=5), 55-65cm#1 (n=5), 110-115cm#1 (n=5), 255-265cm#2 (n=5).

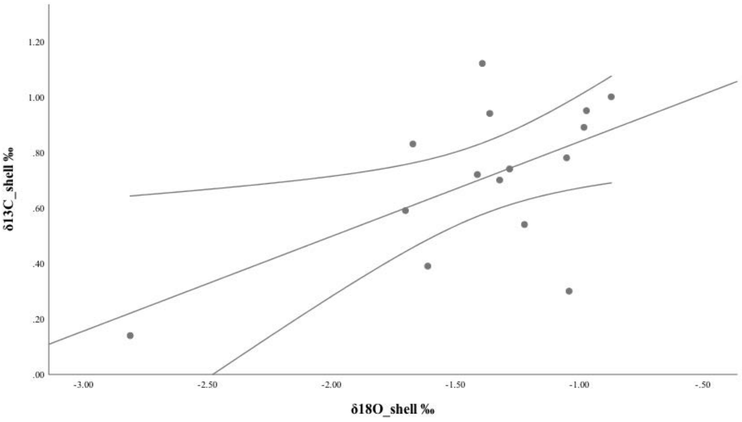
δ^{13}C values of deep time *Lunella cinerea*. Note: sample 170-180cm#2 was drilled for long-sequence data.

$\delta^{13}C_{shell}$ ‰				
5-10cm#2	**55-65cm#1**	**110-115cm#1**	**170-180cm#2**	**255-265cm#2**
3.23	2.53	3.71	1.23	2.95
2.66	2.57	3.64	1.91	3.14
2.87	2.37	3.07	2.18	3.09
2.64	2.63	2.69	3.19	2.89
1.82	3.50	2.26	3.03	3.26
			2.46	
			2.81	
			2.91	
			3.98	
			4.42	
			0.52	
			2.10	
			2.77	
			2.42	
			2.06	
			2.98	
			2.25	
			1.65	
			0.69	
			1.48	
			1.56	
			1.94	
			2.23	
			3.13	

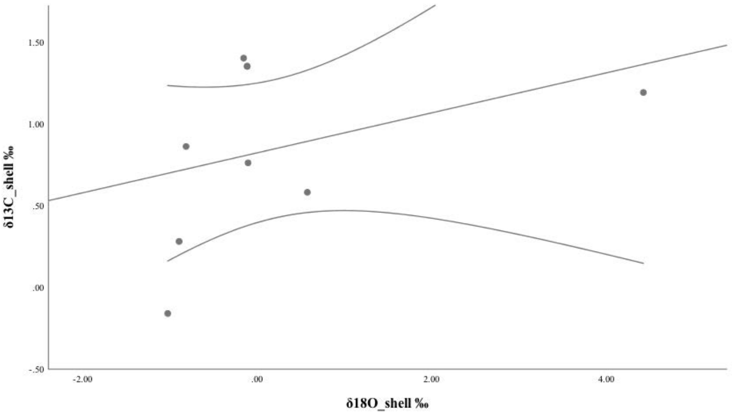
δ^{13}C and δ^{18}O Linear Regressions, *Saccostrea cuccullata* and *Lunella cinerea*



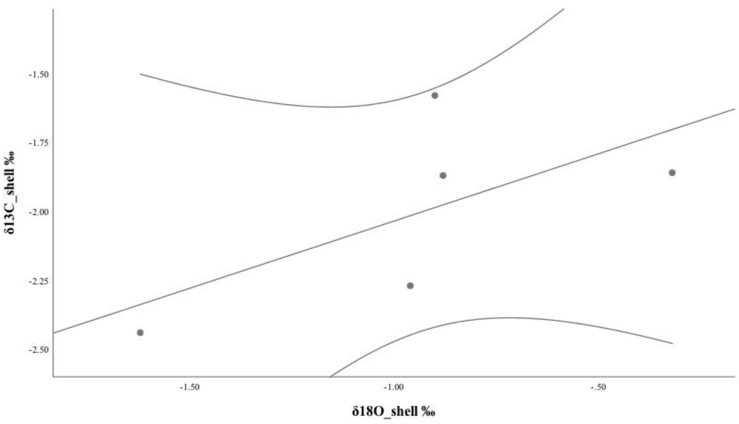
Linear regression scatter plot for live-collected *Saccostrea cuccullata* sample LC#2 (n=6), showing the 95% confidence intervals.



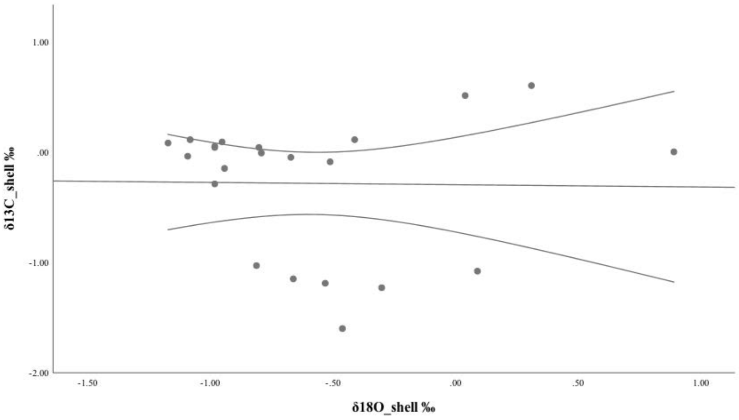
Linear regression scatter plot for live-collected *Saccostrea cuccullata* sample LC#4 (n=15), showing the 95% confidence intervals.



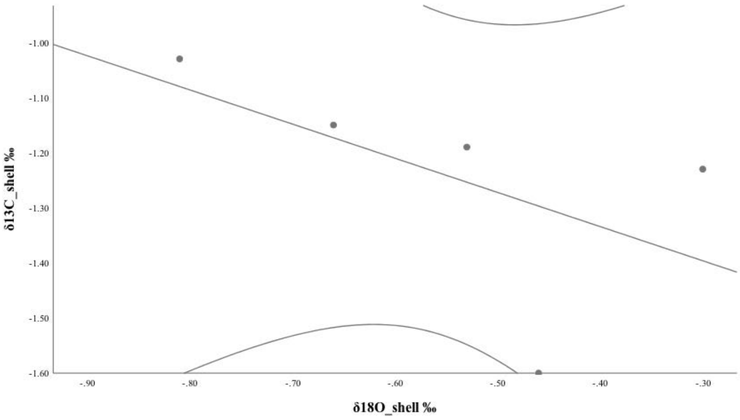
Linear regression scatter plot for live-collected *Saccostrea cuccullata* sample LC#6 (n=9), showing the 95% confidence intervals.



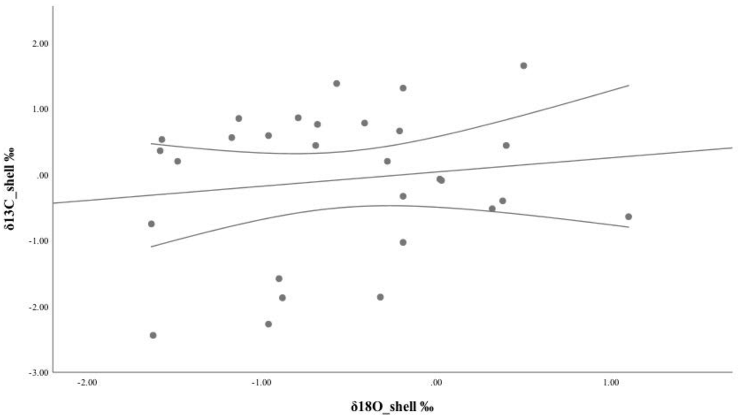
Linear regression scatter plot for live-collected *Lunella cinerea* sample LC#3 (n=5), showing the 95% confidence intervals.



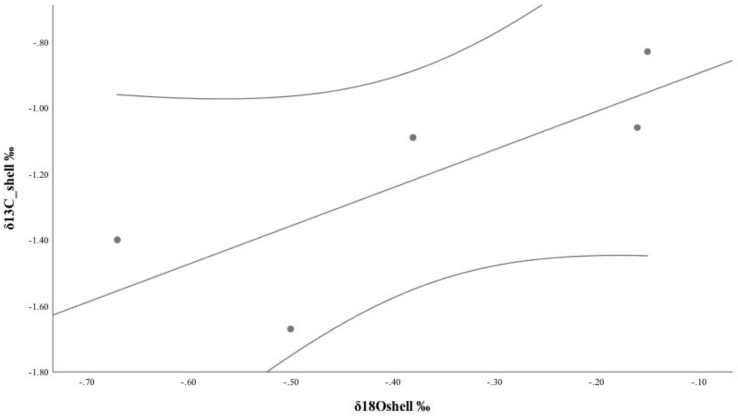
Linear regression scatter plot for live-collected *Lunella cinerea* sample LC#4 (n=22), showing the 95% confidence intervals.



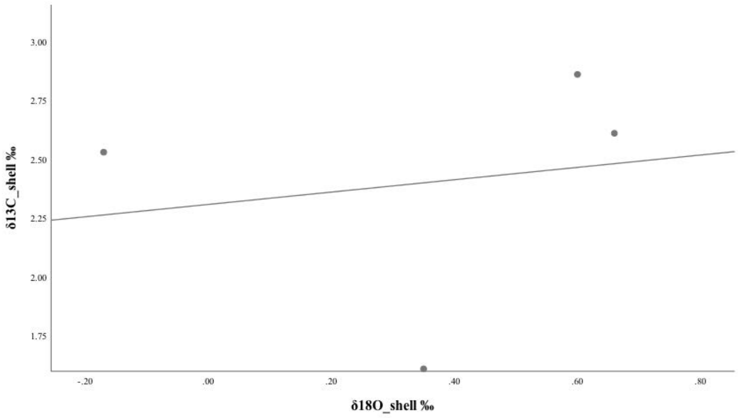
Linear regression scatter plot for live-collected *Lunella cinerea* sample LC#4 (n=5), showing the 95% confidence intervals.



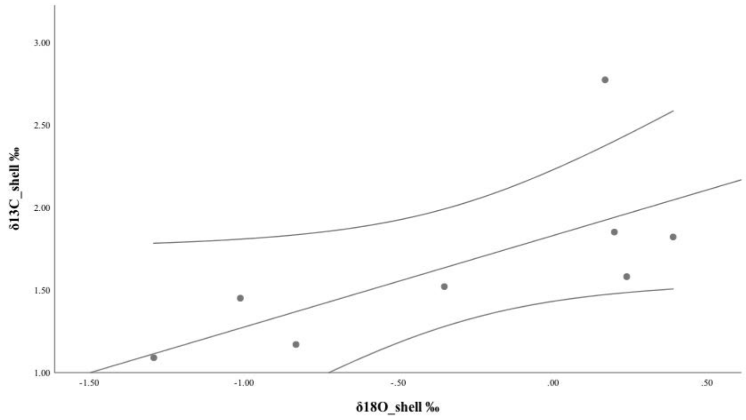
Linear regression scatter plot for live-collected *Lunella cinerea* sample LC#3 (n=29), showing the 95% confidence intervals.



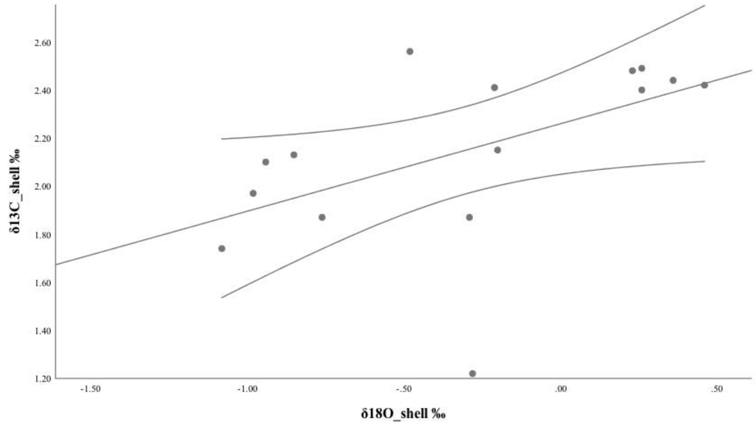
Linear regression scatter plot for live-collected *Lunella cinerea* sample LC#5 (n=5), showing the 95% confidence intervals.



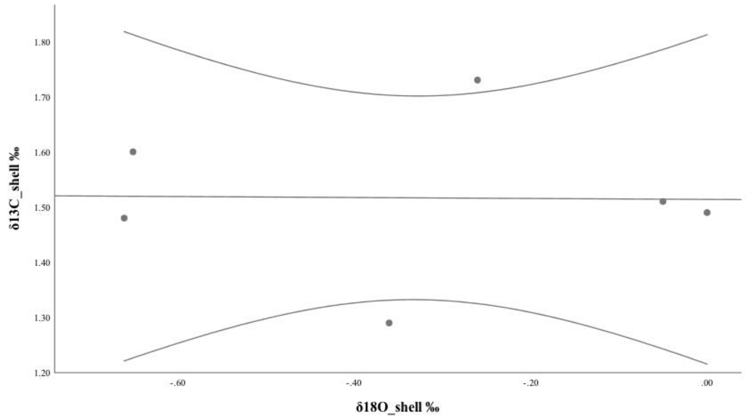
Linear regression scatter plot for deep time *Saccostrea cuccullata* sample 5-10cm#1 (n=4), confidence intervals deliberately not shown.



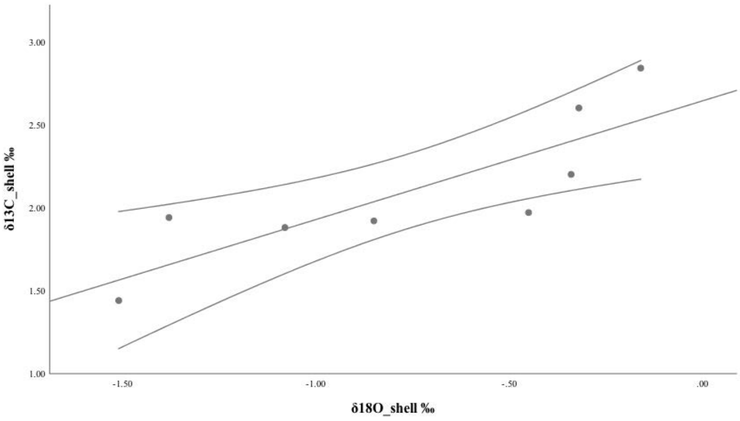
Linear regression scatter plot for deep time *Saccostrea cuccullata* sample 60-65cm#1 (n=8), showing the 95% confidence intervals.



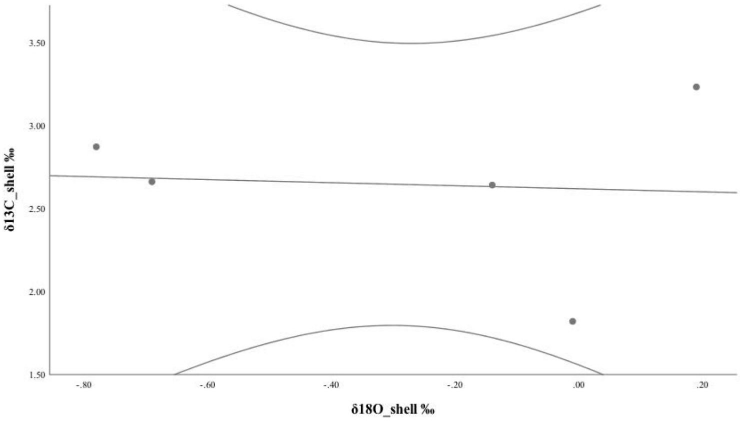
Linear regression scatter plot for deep time *Saccostrea cuccullata* sample 130-135cm#1 (n=15), showing the 95% confidence intervals.



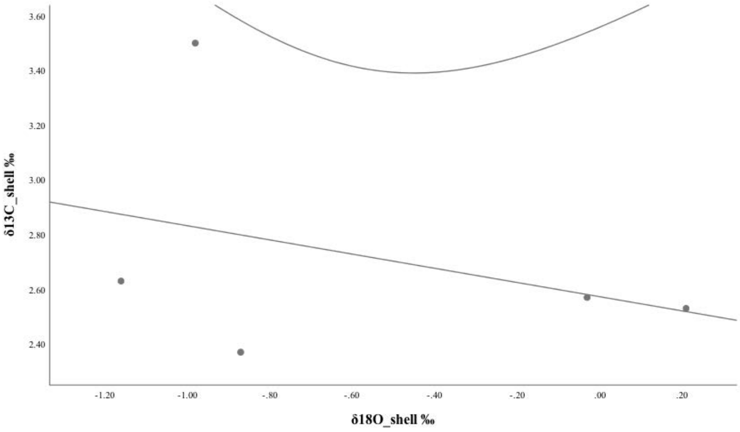
Linear regression scatter plot for deep time *Saccostrea cuccullata* sample 190-200cm#1 (n=6), showing the 95% confidence intervals.



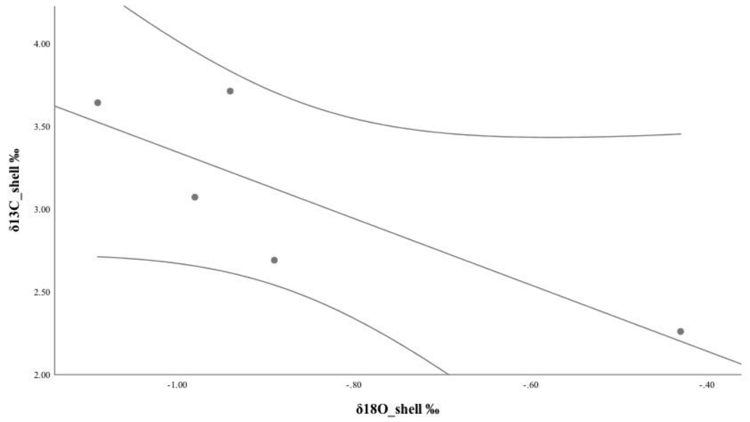
Linear regression scatter plot for deep time *Saccostrea cuccullata* sample 220-230cm#1 (n=8), showing the 95% confidence intervals.



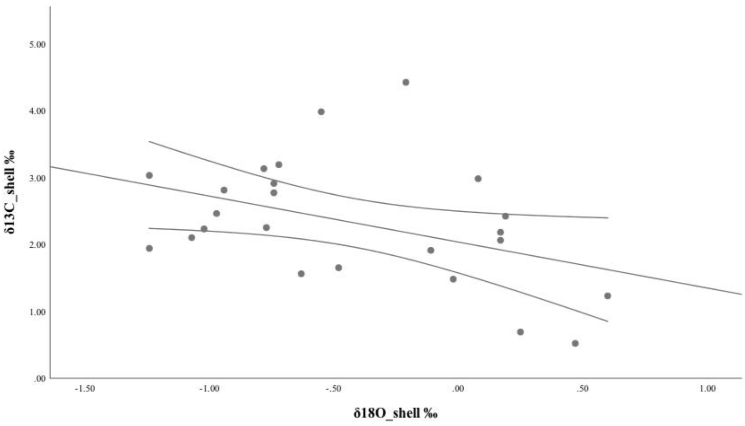
Linear regression scatter plot for deep time *Lunella cinerea* sample 5-10cm#2 (n=5), showing the 95% confidence intervals.



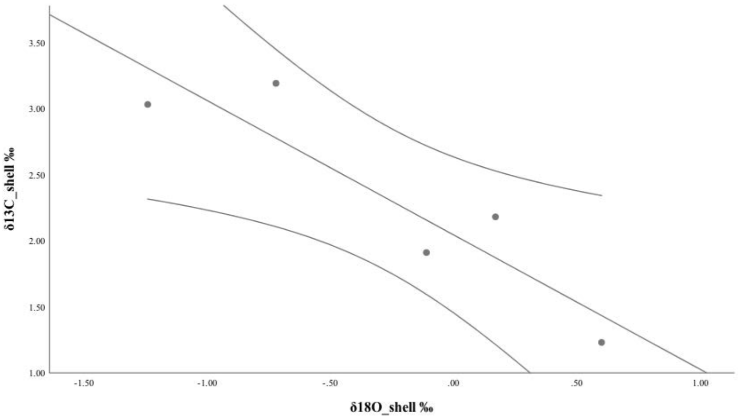
Linear regression scatter plot for deep time *Lunella cinerea* sample 55-60cm#1 (n=5), showing the 95% confidence intervals.



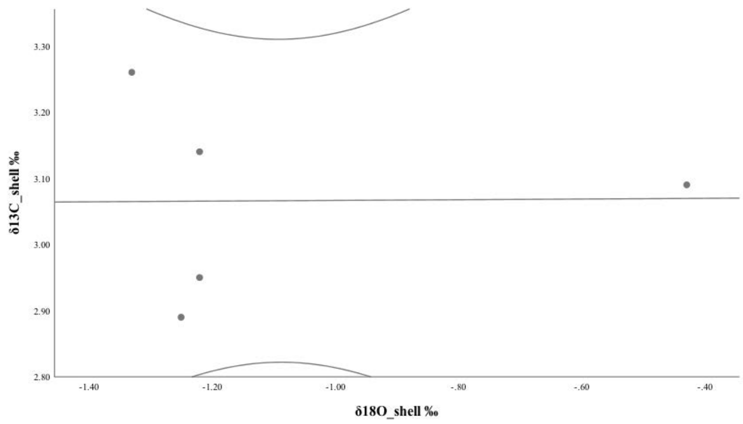
Linear regression scatter plot for deep time *Lunella cinerea* sample 110-115cm#1 (n=5), showing the 95% confidence intervals.



Linear regression scatter plot for deep time *Lunella cinerea* sample 170-180cm#2 (n=24), showing the 95% confidence intervals.



Linear regression scatter plot for deep time *Lunella cinerea* sample 170-180cm#2 (n=5), showing the 95% confidence intervals.



Linear regression scatter plot for deep time *Lunella cinerea* sample 255-265cm#2 (n=5), showing the 95% confidence intervals .