OSTRACODS AS BIOINDICATORS TO RECONSTRUCT PAST ENVIRONMENTAL CONDITIONS AT LAKE ST LUCIA, SOUTH AFRICA

by

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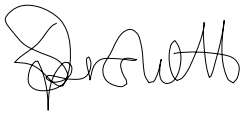
ABSTRACT

Lake St Lucia, situated along the east coast of South Africa, is a highly dynamic system subject to both tidal and freshwater influences with changing environmental conditions. These fluctuating salinity regimes effect the biological communities within the lake, and thus the resilience of the system. Hypersaline conditions have been recorded within St Lucia as a result of severe and prolonged drought events with mass mortalities ensuing. St Lucia is a highly managed system and has recently received a great deal of attention through monitoring programmes, however, few of these encompass long-term changes spanning more than multi-decadal timescales. This underpins the lack in understanding of natural baseline conditions. As salinity is largely variable and the driving factor behind ecosystem functioning, it remains pertinent to gain a long-term understanding of the system. Ostracods, microscopic bivalved crustaceans, have been noted for their sensitivity environmental factors, salinity in particular. These biological indicators can thus offer important insights into past environmental conditions, yet have been under-utilised in the South African context. Here we present a detailed record of palaeosalinity for the Holocene through fossil ostracod analysis of sediment cores retrieved from Lake St Lucia. A 16 m sediment core was extracted from both North Lake and False Bay, and a 12 m sediment core was extracted from Catalina Bay using a piston corer. Core chronology was based on a total of 29 Accelerator Mass Spectrometry radiocarbon age determinations across the three cores. Preservation potential is greatest in the basal region of the cores, with Catalina Bay yielding the highest species diversity and abundance. Fossil records indicate that North Lake illustrates a dominance in brackish-marine ostracod taxa, whilst False Bay depicts a fresher system overall, due to its sheltered landward positioning, and Catalina Bay has a higher marine influence, likely due to its proximity near the estuary mouth. A transfer function was applied to ostracod data to reconstruct palaeosalinity over the Holocene. Results indicate elevated salinities over the early Holocene (~9500-7250 cal yr BP), and ostracod assemblages vastly differing in richness and abundance from those evident in the late Holocene. The early Holocene saw St Lucia as a deep water system with significant marine influence through various tidal inlets, and hence records reflect a high marine dominance. Ostracods appear to thrive in times of increased marine influence as higher water volumes would have been conducive to continual flow and mixing between basins, facilitating ostracod movement. As Lake St Lucia transitioned from a deep water system to the shallow estuarine system evident today, environmental conditions appear less favourable to ostracods found in

North Lake and Catalina Bay. A shallower system is more at risk of desiccation and sediment reworking via wind turbulence, both of which will also hinder fossil success and preservation. Fossil records reflect the transition from marine influenced assemblages to estuarine ostracod assemblages occurred around 7000-6000 cal yr BP, the early to mid Holocene. Today, decreased marine influences are heightened by anthropogenic interventions and modifications, and has consequently put extra pressure on an already stressed ecosystem. Hypersaline events, recently noted in St Lucia literature, are not evident in the ostracod record, likely the results of time averaging through sediment mixing. However, a low species diversity experienced in North Lake and Catalina Bay over the late Holocene is indicative of unstable environmental conditions. As there is significant focus on St Lucia's management, and in particular its mouth and the relinking to the sea, this study will aid in the decision-making process by providing insight on environmental conditions at a multi-millennial scale.

PREFACE

The research contained in this dissertation was completed by the candidate while based in the discipline of Geography, School of Agriculture, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Westville Campus, South Africa. This research was financially supported by the NRF. The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.



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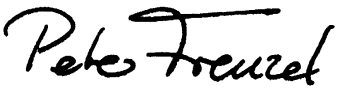

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c.	approximately
Ga	billion years
cal yr BP	calendar years before the present
^{14}C yr BP	uncalibrated radiocarbon age
cm/y	centimetres per year
psu	practical salinity unit
MAT	Modern Analogue Technique
MinDc	Minimum Dissimilarity Coefficient
RMSEP	Root Mean Square Error of Prediction
RMSE	Root Mean Square Error
WAPLS	Weighted Average Partial Least Squares
KZN	KwaZulu-Natal
ENSO	El Niño-Southern Oscillation
CONISS	Constrained Sum of Incremental Squares
AMS	Accelerator Mass Spectrometry
°C	degrees Celsius
µm	micrometre
cm	centimetre
cm^3	cubic centimetre
km	kilometre
km^2	square kilometre
N	North
S	South
LP	low preservation

CHAPTER ONE

INTRODUCTION

Climate change is defined as the changes in a climatic state that are identified, statistically, by the changes in the variability or mean of its properties and typically persist for extended periods (IPCC, 2014). According to the IPCC (2014) definition, such changes may be attributed to natural variability or anthropogenic activity. South Africa has been classified as a region with increased vulnerability to climate change and variability (Schulze, 2011). One such area that has been identified as exceptionally vulnerable are estuaries and lagoons (IPCC, 2007). Surrounding floodplains, saltmarshes and open water are included within this zone as estuaries are dependent on these systems for their functionality (Cilliers and Adams, 2016). The most significant impacts on estuaries, resulting from climate change, are illustrated in the physical mixing characteristics resulting from changing freshwater runoff patterns, increased water temperatures affecting the primary production of the system altering oxygen, light and carbon availability for estuarine species (IPCC, 2007), and sea level rise, changing ocean circulation patterns and the projected increase of storm frequencies altering the sediment dynamics and the geochemical processes within the system (James *et al*., 2013).

Lake St Lucia, situated along the north eastern coastline of South Africa, is Africa's largest estuarine lake and a designated Ramsar wetland of international importance (Porter, 2013), on the basis that it supports critical habitats for a range of species (Van Niekerk and Turpie, 2012). This system is highly dynamic, constantly shifting between fresh and hypersaline states, thus enabling it to support a variety of plant-animal combinations and ensuring its rich biological diversity (iSimangaliso Wetland Park, 2011). St Lucia has been identified as an area vulnerable to climate change, with changes already evident in terrestrial-based hydrological processes, ocean-based physical processes and in the processes operating between the land and sea interface (Mather *et al*., 2013). Climate change, coupled with the large increase in anthropogenic activities taking place within this area, pose threats to the successful functioning of the estuary (Raw *et al*., 2013). The variability of the system, combined with awareness around well-documented anthropogenic influences, has generated significant research interest largely focussed on recent changes within the system (e.g. Taylor *et al*., 2006; Cyrus *et al*.,

2011; Carrasco and Perissinotto, 2012; Whitfield *et al*., 2013; Perissinotto *et al*., 2014; Zikhali *et al*., 2014). Because the majority of these studies were conducted post 1940, there is limited understanding of natural ecosystem functioning prior to significant human impacts. It is therefore imperative that long-term environmental records be established, which may also aid in informing management practices to promote ecosystem restoration, recovery and preservation (Froyd and Willis, 2008).

A long-term understanding is attainable through palaeoenvironmental studies, which have the ability to express how natural systems responded to the changing climates and may also yield insight into ecosystem response to future change (Walker and Pellatt, 2008). In the absence of direct evidence, palaeoenvironments are studied through the application of environmental proxies which are capable of providing important feedback on ecosystem processes (Sayer *et al*., 2010). These proxies range from geochemical proxies (e.g. Zhang *et al*., 2016), to sedimentological proxies (e.g. Doerschner *et al*., 2016), fossilized plant remains like charcoal and pollen (e.g. Parkington *et al*., 2000), glaciology (e.g. Jennings *et al*., 2016), dendrochronology (e.g. Battipaglia *et al*., 2015), and the fossilized biological remains of diatoms, foraminifera and ostracods (e.g. Gomes *et al*., 2017; Strachan *et al*., 2014; Pint *et al*., 2015). Environmental conditions may affect proxies differently, with the weaknesses in one proxy being compensated for in another (Kiage and Liu, 2006). Despite the vast array of proxies available, southern Africa is fairly in the potential of high resolution proxy archives, such as those of tree rings and ice cores (Verschuren, 2003). Furthermore, a significant portion of southern Africa is too dry to support microfossil preservation (Fitchett *et al*., 2017). This has left the records of palaeoenvironmental reconstruction relatively scarce and patchy, often with low temporal resolution (Chase and Meadows, 2007). Lacustrine systems within southern Africa do, however, have the potential for high resolution records of past climate change through the study of their sedimentary records (Verschuren, 2003). Whether the climatic trends are naturally or anthropogenically induced, long-term signals will be chronologically recorded within the limnic sequence, thus allowing environmental reconstruction over long timescales, and underpinning the field of palaeolimnology (Bitusik *et al*., 2009). Lacustrine sediments within St Lucia have the potential to preserve biological proxies (e.g. Gomes *et al*., 2017) that may be used to provide insight into long-term environmental changes. One such proxy that has been underutilised within the southern African context is that of ostracods.

The class Ostracoda, represents a group of microscopic, aquatic crustaceans typically 1-2 mm in size, found in both marine and freshwater environments (Martens, 2003). Ostracods are geographically and environmentally diverse and are thus particularly useful in both palaeo- and modern environmental studies (Lorenschat and Schwalb, 2013). Prevailing environmental conditions affect ostracods in several ways including abundance, morphology, shell geochemistry, and their presence or absence within a particular system (Decrouy *et al.*, 2012). Habitat characteristics affecting ostracods include the energy level, the size and depth of the water body, the types of aquatic plants present, texture of the sediment, predation, and food availability (Holmes *et al.*, 2010). An ostracod shell is composed of calcium carbonate therefore allowing for excellent preservation within alkaline lake sediments (Park and Cohen, 2011). Furthermore, their relatively high diversity and abundance in brackish water systems renders them statistically relevant, and as they are particularly sensitive to salinity (Frenzel and Boomer, 2005) there is the potential to yield valuable palaeoenvironmental information about St Lucia. This study will use ostracods as an environmental proxy to explore past environmental conditions in Lake St Lucia. This will contribute to a more comprehensive understanding of palaeoenvironmental conditions experienced during the Holocene, and the natural responses of the system to the effects of global change.

1.1 Aim and objectives

The aim of this study is to reconstruct past fluctuations in lake water chemistry in Lake St Lucia using ostracods as a biological indicator. The specific objectives will be to:

i. quantify downcore fossil ostracod associations from sediment cores collected in the three main basins of Lake St Lucia;
ii. infer past environmental conditions experienced at Lake St Lucia based on the finding from the fossil assemblages;
iii. reconstruct past salinity fluctuations within the lake using a transfer function based on modern distribution data; and
iv. understand long term natural fluctuations in water chemistry and habitat structure to inform current management practices.

CHAPTER TWO
LITERATURE REVIEW

This chapter will introduce the study of palaeolimnology and associated methodologies. In particular, the chapter will focus on the ability of lake sediments to preserve important environmental information within a chronological sequence. It will provide an overview of the field of palaeolimnology, the methodological steps involved in the palaeolimnic approach, and the relevant proxies used in palaeolimnology. Ostracoda, a potential biological proxy, will then be discussed in detail. This includes the origin of ostracods, environmental parameters known to affect them, the use of ostracods in chemical and isotopic analyses, and the limitations associated with using ostracods as biological proxies. It will highlight the preservation, sampling and preparation techniques involved in ostracod analyses, what constitutes an ostracod assemblage, and how to quantitatively record ostracod species.

2.1 Palaeolimnology

Global climate change is documented as an additional and intensifying driver behind ecosystem variability (Dallas and Rivers-Moore, 2014). The globally observed changes in the trends in humidity, precipitation, run-off patterns and drought have suggested that the southern African region is on a negative trajectory in regards to the changes relating to climate change (IPCC, 2007). This emphasizes the need for a more detailed account of the palaeoenvironment as a means to the understanding of past natural variability, and predicting future climate change (IPCC, 2014).

Palaeoenvironmental reconstructions are attainable through the application of palaeolimnology. Palaeolimnology is defined as the interdisciplinary science that examines the physical, chemical and biological properties of lacustrine sediments, thereby producing high resolution time-series data of environmental change at different timescales (Saulnier-Talbot, 2016). Palaeolimnology provides us with a historical overview against which present conditions and predicted future changes can be assessed (Battarbee *et al*., 2005). Lake systems incorporate the interactions between the hydrosphere, geosphere, biosphere and atmosphere,

and are thus suited to cross-boundary research studies like those of land-water or water-air interfaces (Saulnier-Talbot, 2016). Materials from terrestrial and atmospheric deposits are absorbed into lake sediments and later preserved to form a chronological sequence reflecting naturally occurring climate change or anthropogenically induced events (Blockley *et al*., 2007).

Although palaeolimnology is not a new field of study, its potential in solving environmental problems and the advantages a long term perspective provides, is not yet fully acknowledged (Sayer *et al*., 2010). Within the southern African context, palaeoenvironmental reconstructions commenced relatively late in comparison to the rest of the world, with initial studies being limited by chronological uncertainties and lack of proxy data (Fitchett *et al*., 2017). Subsequently, the increase in affordable, high-precision dating opportunities and available proxy collections has largely aided in contemporary palaeoenvironmental studies (Meadows, 2014). The aridity of southern Africa however, has also limited potential palaeo-archives and in many cases, narrowed down the research potential to the more humid wetland areas in the eastern region (Fitchett *et al*., 2017).

In order for palaeolimnogical approach to be successful, eight basic methodological steps should be followed, and have been summarised as follows (Smol, 2008):

i. Study site selection: This may be based on a site-specific problem or it may be more general with the aim of providing basic information for management strategies (Smol, 2008). It is important to consider whether the site is a deep or shallow lake and whether it has several inputs, via marine or freshwater connections, or not as these factors will influence the type of material deposited within the system (Verschuren, 2003). Due to low energy levels, deep lake basins form a natural trap for proxy materials because sediment is rarely transported after it has settled into the lake bed (Smol, 2008). Conversely, shallower lakes and fast flowing rivers are often at risk for sediment redistribution due to wind and water flows, which may prove problematic for palaeolimnological studies (Frew, 2014). If however, core sites are strategically chosen and care is given during interpretation, such studies remain viable. It is important to keep in mind, permission to access the land may need to be obtained from the relevant authorities, especially if the site falls within a protected area (Frew, 2014).

ii. Coring site selection: Since palaeolimnological analyses are incredibly time-consuming, generally a single, or few sediment cores will be analysed (Smol, 2008). Thus it is imperative that the core(s) will be representative of the processes acting within the system (Smol, 2008). A successful core site needs to yield a continuous, undisturbed and representative sequence (Glew *et al*., 2001). Therefore central, deeper areas are generally preferred over shallow areas as shallower parts are more susceptible to bioturbation and mixing, especially in windy areas (Smol, 2008). Very steep localities should also be avoided as slumping is a risk, making interpretations difficult (Verschuren, 2003). Remote imaging or characterisation of the subsurface is an integral part of the site selection process and is conducted in sedimentary basins prior to coring and drilling (Scholz, 2001). Digital seismic reflection technology has been key in modernising the field of subsurface analysis and stratigraphy, thereby significantly increasing the understanding in the evolution of lacustrine basins (Scholz, 2001). Factors affecting sediment distribution are climate, topography and flow rates, which result in three zones being defined within the system: the erosion zone, transportation zone, and the accumulation zone (Blais and Kalff, 1995). The accumulation zone is of the most value in palaeolimnology as the sediments offer a continuous and complete record of environmental change (Blais and Kalff, 1995). Any undisturbed accumulated sediment should reflect the oldest deposits at the deepest part of the lake overlain by progressively younger material, according to the law of superposition (Blockley *et al*., 2007). Sediment accumulations can either be of autochthonous or allochthonous origin. Autochthonous refers to material that originated within the system, such as certain biological remains and chemical precipitates, and in contrast, allochthonous material is that which is washed or blown into the system, such as eroded soil or clay particles and pollen grains (Smol, 2008).

iii. Core collection: This largely depends on chosen site locality, the sediment type, and the length and temporal resolution that one wishes to achieve. Retrieving a continuous, unmixed and uncontaminated sediment core is the first and most critical step in what can be a rather extensive process (Glew *et al*., 2001). Errors made during this step can seldom be corrected after-the-fact and therefore the success of a project, and the lengthy analyses that follow, depend on the recovery of a decent sample (Glew *et al*., 2001). The three main requirements in core collection are listed by Hvorslev (1949) as: having no disturbance to the sediment structure, no changes in the water content, and no changes in the sediments chemical composition. The type of coring equipment used

will largely depend on the conditions surrounding the core site environment such as its accessibility, available man power, as well as the funds available (Frew, 2014). Examples of different coring methods include gravity corers, box corers, cable-operated or rod driven piston corers, vibracorers, percussion corers and pneumatic corers (Glew *et al*., 2001). Gravity corers are amongst the simplest coring devices to use as they are driven into the ground vertically before closing the top of the tube and extracting the core. They can be removed manually or with mechanical aid in more compact sediment. Box corers (such as an Ekman Grab) are generally limited to surface sampling where sediment is retained by closing off the bottom of the box by rotating the jaws. Piston corers (driven by rods) comprise of a cable and piston construction, a core tube and drive head, and rods, whereas cable-operated corers have a driving weight that aids in driving the core into the sediment in one smooth movement. Piston corers do need stable platforms for deployment. Another commonly used device is the vibracorer. Vibracorers are used when unconsolidated sediments need to be collected from difficult conditions (e.g. sand lenses) that cannot be cored with piston corers, for example. Vibracorers consist of a cement vibrator that is powered by a gasoline engine. These components are readily available and it is a fairly inexpensive tool. Furthermore, the vibracorer is light and mobile, can be used off multiple platforms, and only needs two people to operate it.

iv. Core sectioning: When attaining sections for specific temporal resolutions, it is important to remember that the subsamples may be required for dating, isotopic and geochemical analyses, as well as biological investigations (Smol, 2008). As many of these processes are destructive, there may not be sufficient material for analysis if the subsamples are at very close intervals (Smol, 2008).

v. Dating: Establishing a chronology is vital as an age-depth profile allows for timing and trends to be investigated (Smol, 2008). The changes in sediment texture and/ or colour are visible to the naked eye and are often the reason behind selecting specific sections to date (Jeter, 2000). Dating techniques measure the amount of decay of radioisotopes that occur naturally, with the most common forms being lead (^{210}Pb), caesium (^{137}Cs) and radiocarbon (^{14}C) dating techniques (Verschuren, 2003). ^{210}Pb is used to date recent sediments up to ~150 years and is the most frequently used method for younger materials (Sert *et al*., 2016). ^{210}Pb is a natural radioisotope that is produced constantly via the planets natural processes, and also decays constantly with a half-life of 22.26 years (Sert *et al*., 2016). However, not all isotopes are naturally occurring, with ^{137}Cs

being an example of a manufactured isotope from the nuclear industry (Smol, 2008). This isotope aids in pinpointing specific time periods within a sequence. Longer sequences usually use the technique of ^{14}C dating, a carbon isotope formed in the atmosphere due to cosmic rays with a half-life of 5730 years (Smol, 2008). Contamination is a risk with this dating technique because of reworking, through fungal growth or rootlets, or by incorporating 'old carbon' (Blockley *et al*., 2007). Species found living within the atmosphere and in water will yield differing ^{14}C ages because of a reservoir effect (Facorellis and Vardala-Theodorou, 2015). Because of global variations in carbon reservoirs, it is imperative that ^{14}C ages are placed into a calendar timescale comprising of various ^{14}C calibration records that have been independently dated: IntCal13 (Reimer *et al*., 2013) for Northern Hemisphere samples and SHCal13 (Hogg *et al*., 2013) for Southern Hemisphere samples.

vi. Proxy data: This is a major step with a vast array of environmental indicators available pertaining to chemical, biological and physical information (Smol, 2008). This is by far the most time consuming step, and these data are used in all subsequent analyses and interpretations (Smol, 2008). Proxies will be discussed in further detail in section 2.1.1 below.

vii. Data interpretation: Significant advances in data interpretation have been seen in the past few decades. Commonly used ordination techniques are correspondence analysis or principal component analysis, with non-metric multidimensional scaling and principal coordinate analysis being the less frequently used analyses (Legendre and Birks, 2012). These simple ordination techniques are used to recognise the main gradients within assemblage data, and to interpret and assess the gradients according to the species loadings depicted on the ordination axes (Legendre and Birks, 2012). Studies now also include transfer functions derived from a training dataset and surface-sediment calibrations (Sayer *et al*., 2010). A range of environmental variables have been reconstructed from microfossil data using transfer functions (Telford and Birks, 2009). Examples are illustrated in the dinoflagellate-salinity transfer function produced by de Vernal *et al*. (2005), foraminifera-sea level transfer function presented by Strachan *et al*. (2014), benthic foraminifera-salinity transfer function conducted by Sejrup *et al*. (2004), an ostracod-water temperature transfer function developed by Viehberg (2006), and ostracod-conductivity transfer function produced by Mischke *et al*. (2007) and a diatom-salinity transfer function produced by Zong *et al*. (2010).

viii. Data presentation: Data needs to be represented in such a manner that it is accessible to scientists, decision- makers as well as the general public (Smol, 2008). It needs to be both scientific and communicative (Birks, 2012). There are several statistical software packages that can be used to represent complex stratigraphical data series, with the more commonly used ones being Tilia (Grimm, 1990), C2 (Juggins, 2007) and Psimpoll (Bennett, 1994). As this step is highly complex and computationally demanding, it is vital that a palaeolimnologist understand both the numerical methodology and the nature of palaeolimnology, as well as understanding any numerical problems created by palaeolimnological data (Birks, 2012).

2.1.1 Palaeolimnic proxies

The range of environmental proxies available is extensive, as is the type of archival materials preserving those (Meadows, 2014). Some of the richest archives however, are preserved within limnic sequences (Walker and Pellat, 2008). The ability to preserve both environmental processes and variables make lake sediments incredibly valuable sources of environmental information (Saulnier-Talbot, 2016).

Pollen has been the most commonly used proxy for palaeoenvironmental reconstructions within southern Africa with examples of this evidenced in studies by Meadows and Baxter (2001), Scott *et al*. (2003), Finch and Hill (2008), Neumann *et al*. (2008, 2010, 2011) for example. These studies all involved pollen analyses from cores taken within lake and wetland systems as a means to reconstructing past environmental conditions experienced within the area. Meadows and Baxter (2001) retrieved a core from Klaarfontein Springs, Western Cape, Scott *et al*. (2003) from Wonderkrater spring in Limpopo, Finch and Hill (2008) from Mfabeni Peatland on the Maputaland Coastal Plain, Neumann *et al*. (2008) extracted a core from Lake Sibaya, KZN, Neumann *et al*. (2010) from Lake eTeza, KZN and Neumann *et al*. (2011) a core from Princess Vlei, Western Cape.

In the more recent decades, there has however been a shift within South Africa to include an increased suite of proxies such as foraminifera, diatoms, speleothems, isotopic analyses and geochemistry (Fitchett *et al*., 2017). Foraminifera have been used to detect sea level changes

from lagoon and salt marshes in the eastern and western Cape (e.g. Franceschini *et al*., 2005; Strachan *et al*., 2014; Strachan *et al*., 2015). Diatoms have been utilised in the reconstruction of past environmental change within the region of KZN (e.g. Bate and Smailes, 2008; Finné *et al*., 2010; Stager *et al*., 2013; Kirsten and Meadows, 2016; Gomes *et al*., 2017). Speleothems are another important source of palaeoclimate information for South Africa, with successful reconstructions from the Northern Province and the Northern Cape (e.g. Talma and Vogel, 1992; Holmgren *et al*., 1999; Finch *et al*., 2001; Pickering, 2015). Isotopic and geochemical analyses are increasingly being used on sediment cores, fossilised remains and speleothems to reveal more information pertaining to the environment (Wündsch *et al*., 2016; Fitchett *et al*., 2017).

A relatively new proxy in the southern African context is that of ostracods. Ostracods may prove suitable indicators in certain environments such as Lake St Lucia because they illustrate a higher preservation potential in alkaline waters over diatoms (Boomer *et al*., 2003), and they exhibit a higher abundance and diversity over foraminifera in meso- and oligohaline environments (Frenzel and Boomer, 2005). Overall, the use of a multi-proxy approach allows for numerous independent signals of environmental change to be identified from complementary proxy data sources, aiding validation of inferences (Saulnier-Talbot, 2016).

The ability of lake sediments to preserve environmental and anthropogenic interactions within a chronological sequence is invaluable. If appropriate methods are followed, from core site selection through to data presentation, a wealth of high-resolution data can be produced. Proxy data, preserved within a palaeolimnological sequence, aids in reconstructing environments, which help contextualise contemporary environmental changes and allow for future predictions to be made. In the following section we focus on Ostracoda, a relatively new and valuable addition to the suite of available proxies.

2.2 Ostracoda

Ostracods are microscopic bivalved crustaceans belonging to the group of meiofauna (Karanovic, 2012). The body of an ostracod resembles that of a shrimp, and its casing that of a

bivalve mollusc, resulting in the common name ‘seed shrimp’ (Griffiths and Holmes, 2000). The exact origin of ostracods is not known, but evidence indicates their presence throughout the Palaeozoic, Mesozoic and Cenozoic eras (Griffiths and Holmes, 2000). Although the morphologies of early crustaceans also remains unclear, by the Ordovician period marine ostracods were definitively present and identifiable (Caporaletti, 2011). The five identified orders were: Leperditicopida and Palaeocopida, which went extinct during the Devonian and the late Triassic, Myodocopida and Platycopida, which are still present in marine settings today, and Podocopida, which incorporate numerous modern marine and all non-marine assemblages (Griffiths and Holmes, 2000). Ostracods originated in marine systems and moved on to colonise continental systems very early on (Griffiths and Holmes, 2000). Significantly higher diversity is evident in marine ostracods in comparison to continental diversity (Frenzel and Boomer, 2005).

Despite the increased interest in ostracods in Quaternary palaeoenvironmental reconstruction, it is still the very early stages of an evolving discipline (Frenzel and Boomer, 2005). Ostracods are found in most aquatic environments and because of their broad ecological tolerances, they are key representatives within a system (Karanovic, 2012). The soft body of an ostracod is encased in a carapace, formed by a left and right valve, with a hinge along the dorsal margin (Martens *et al.*, 2008).

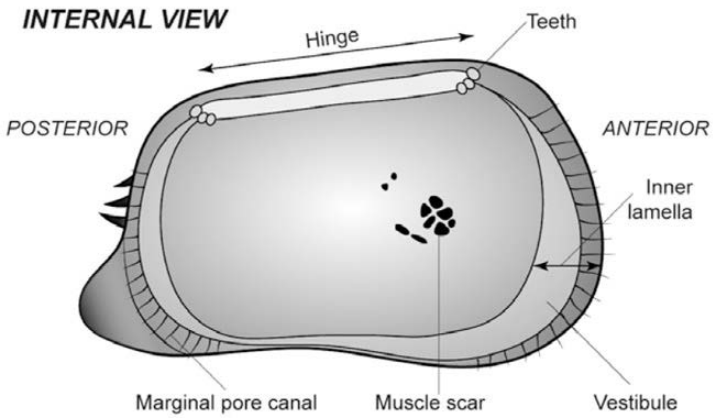

Figure 1.1: Basic anatomical structure of an ostracod (Williams *et al.*, 2015).

Valves are very useful in palaeontological work because their low-magnesium calcite composition allows for excellent preservation within sediments, especially in alkaline lakes (Holmes *et al*., 2010). They are of taxonomic value because of morphological differences in shape, size, ornamentation and the position and pattern of muscle scars (Karanovic, 2012). Furthermore, their calcareous shells are informative archives for trace element geochemistry, as well as oxygen and carbon isotope analyses as they contain information pertaining to environmental conditions at the time of deposition (Cusminsky *et al*., 2011).

2.2.1 Environmental parameters

Environmental parameters are known to affect ostracod assemblages, diversity and abundance resulting in a unique response, and therefore providing important insight into environmental change. The various environmental parameters discussed here include salinity and hydrochemistry, climate and temperature, sedimentation and substrates, oxygen, and pollution.

2.2.1.1 Salinity and hydrochemistry

Ostracods are present across broad salinity ranges, from freshwater systems to marine conditions, often exhibiting a diversity of species (Frenzel and Boomer, 2005). Salinity is the main factor controlling ostracod distribution, affecting them through its ionic composition, concentration and variability (Keatings *et al*., 2010). As levels exceed a species' salinity optimum, there may be a reduction in the overall size of the individuals (Karanovic, 2012). An example of this is seen in freshwater and marine species appearing smaller in brackish water systems than they would in a freshwater or marine system, respectively (Karanovic, 2012). Furthermore, certain marine ostracods show a decreased shell ornamentation in low salinity environments whilst certain euryhaline species show a decreased shell ornamentation in highly saline environments (Keatings *et al*., 2010). An example of this is *Limnocythere floridensis*, a euryhaline freshwater species that demonstrates decreased ornamentation in saline environments (Frenzel and Boomer, 2005).

The pH of a system is also known to have an effect on ostracods and their valve preservation (Kim *et al*., 2015). The pH level of a water body can determine ostracod distribution as well as the population density as it effects their growth and reproductive processes (Griffiths, 1992).

Environments with low pH values can decrease both the growth and reproductive rates and increase the mortality rates of ostracods (Kim *et al*., 2015). Furthermore, ostracod preservation potential is hindered in acidic waters as acidity will destroy their calcite shells after death (Boomer *et al*., 2003). Noding of the vales has also been linked to the pH of the system (Frenzel and Boomer, 2005).

2.2.1.2 Climate and temperature

Over recent decades, studies conducted on ostracod morphology, ecology and shell chemistry have proven very effective tools for understanding climate variability (Schwalb, 2003). This includes long term climate changes stemming from orbital cycles, rapid climate changes throughout deglaciation periods, as well as the impacts on sea level changes, palaeoceanography and limnology (Frenzel and Boomer, 2005). The Mutual Ostracod Temperature Range (MOTR) method was developed by Horne (2007) using the Nonmarine Ostracod Dataset in Europe (NODE) to directly obtain past air temperature estimates through the comparison of ostracod distributions to January and July minimum and maximum temperatures. MOTR is a non-analogue method which involves the use of calibrated temperature ranges (determined by a range of species distributions) and an interpolated climate model, within a GIS (Geographical Information System) (Horne, 2007). There are a few species whose temperature tolerances are known, but these records are minimal (Frenzel and Boomer, 2005). However, successful studies have been conducted in Recent taxa using their geographic distribution and temperature tolerances for palaeoenvironmental reconstructions (e.g. Hunt *et al*., 2010; Lorenschat and Schwalb, 2013). Furthermore, temperature is also a determining factor in the ornamentation and calcification of valves with geochemical techniques even allowing for ostracod valves to be used as a palaeothermometer (e.g. Cronin *et al*., 2000).

2.2.1.3 Sedimentation and substrate

Sediment grain size does not have a significant effect on ostracod assemblages, however a study by Ruiz *et al*. (2013) demonstrated that decreased particle size decreased the survival rate of freshwater ostracods. Sedimentation rates however, are known to affect ostracods. Lakes and their surrounding catchments that have high erosion rates, and thus higher sedimentation rates, have illustrated a reduced richness in ostracod species (Ruiz *et al*., 2013). The recognition

of certain substrates being a factor that affects ostracod distribution has been discussed in early literature, however none of these observations were robust enough to be scientifically sound, with few proving correct (Griffiths and Holmes, 2000). It is only through the use of multivariate statistical analyses that progress has been made in ecological studies to allow for substrate-ostracod associations to be made bearing some objective meaning (Griffiths and Holmes, 2000). An example of this is illustrated in a local study by Martens and Tudorancea (1991) who found *Limnocythere inopinata* to have an affinity toward soft sediment in Lake Zwai, Ethiopia. There are, however, problems associated with this as certain ostracods may occur within and upon sediments, and may also be found at varying depths depending on seasonality (Griffiths and Holmes, 2000). Furthermore, available food and oxygen, sedimentation and water flows may also cause ostracods to move through the different sediment layers (Smith and Delorme, 2010). Lastly, in an attempt to avoid predators, free-swimming ostracods will burrow into the sediment (Smith and Delorme, 2010). Macrophytes alter the water and sediment characteristics within a system and thus, have been noted to effect ostracod communities (Rossetti *et al*., 2004). Some species are said to favour macrophytes as their preferred habitat and use them as refugia from predators (Rossetti *et al*., 2004). Published data on this topic is relatively rare however, and mainly limited to European marine ostracod species (Frenzel *et al*., 2005).

2.2.1.4 Oxygen

Although the occurrence of ostracods within a system is not dependent on oxygen concentrations, many taxa are not able to survive in anoxic environments (Frenzel and Boomer, 2005).Whilst some taxa may illustrate a tolerance toward slightly oxygen deficient systems, ostracod eggs, housed within the carapace, are not protected from anoxia (Frenzel and Boomer, 2005). The protection of ostracod eggs is critical for their abundance and distribution (Griffiths and Holmes, 2000).

2.2.1.5 Pollution

In general, ostracod diversity and abundance decreases in the presence of pollution, with certain species having increased sensitivity over others (Keatings *et al*., 2010). The impacts associated with pollution do not always necessarily affect ostracods directly, with an example of increased organic pollution causing decreased oxygen levels as bacteria breakdown the organic matter,

and thus cause a decrease in ostracod abundance (Frenzel and Boomer, 2005). Laboratory studies are also underway testing the effects of herbicides, heavy metals and oil contamination on ostracods (e.g. Ruiz *et al*., 2013). Ostracods appear to be slightly more sensitive than amphipods, copepods and prawns to herbicides and pesticides (such as DDT and dioxin), which seem to accumulate in the soft tissues of ostracods under low concentrations, and cause immobilisation and death with increasing concentrations (Ruiz *et al*., 2013). Heavy metal pollution tests illustrated ostracod death in soils polluted with zinc, and in high copper concentrations and acidic waters (Ruiz *et al*., 2013). In oil contaminated sediments, ostracods also illustrate a higher sensitivity than amphipods (Ruiz *et al*., 2013).

2.3 Chemical and isotope analysis of ostracods

The reconstruction of palaeoenvironments and climates, in a marine or non-marine setting, is commonly achieved through the standard techniques of stable isotope and trace element analysis (Viehberg, 2005). This technique can be applied to both sediments and fossil organisms (Viehberg, 2005). Isotope analysis in ostracods started in the 1980s due to the favourable characteristics ostracods displayed (Caporaletti, 2011). These characteristics include valves that are easily separated from the sediments, low-magnesium calcite valves that are well preserved, high abundances in marginal-marine and non-marine settings, and valves that reflect the discrete environmental characteristics of the ambient waters (Gouramanis *et al*., 2015). An ostracod will moult eight to nine times in its growth from juvenile to adult status and with each moult, a pair of valves are shed that can be used for stable isotope and trace element analysis (Smith and Delorme, 2010). Although brackish water systems have largely varying environmental parameters, it will be the existing environmental parameters at the time of calcification that are reflected in the shell chemistry (Gouramanis *et al*., 2015). As certain taxa may prefer specific salinity and temperature conditions for mineralisation of their shell, it is important to consider that the shell chemistry will reflect a signal that is species specific, which needs to be addressed when reconstructing palaeoenvironments (Frenzel and Boomer, 2005). Keatings *et al*. (2002) recommend that a minimum of four valves per sample are used for chemical analysis to gain useful mean values. If juveniles are selected, it is recommended that between four and six valves are used as they are of a smaller size (Caporaletti, 2011).

Stable isotopes refer to atoms that possess the same amount of protons with a differing number of neutrons, and do not decay (Caporaletti, 2011). Changes occur in isotopic records as a result of biological, physical and chemical processes (Caporaletti, 2011). Two oxygen isotopes are frequently used in palaeoclimatic studies: ^{16}O and ^{18}O. The main controlling factor of these isotopes is the global climate in the open oceans, and local changes in environmental conditions are responsible for marginal areas (Leng and Marshall, 2004). Within lacustrine systems, the composition of the oxygen isotopes is dependent on the prevailing precipitation:evaporation (P-E) ratio, and therefore on salinity and temperature, the $\delta^{18}O$ content of groundwater and river input, the catchment area and other factors (Steinman and Abbott, 2013). Furthermore, complexities arise as temperature will also affect the P-E ratio, as well as precipitation (yielding its own isotopic composition), and thus it is imperative to have a basic understanding of the lake systems hydrology (Caporaletti, 2011). ^{13}C and ^{14}C are stable carbon isotopes with ^{14}C being a radioactive carbon isotope. These isotopes are influenced by several factors including photosynthesis, temperature, salinity, upwelling, and the exchanges between water and the atmosphere (Meyer *et al*., 2011). As the factors influencing carbon isotopes are more diverse, interpretation is harder than that of stable oxygen isotopes (Caporaletti, 2011).

Trace elements may be analysed to determine environmental conditions, with the main trace elements being Na, Sr, Mg, Ba and K (Frenzel and Boomer, 2005). For example, the ratio Mg/Ca can be used for interpreting palaeotemperature and the ratio Sr/Ca is often influenced by salinity (Karanovic, 2012). A more recent approach to improve environmental reconstructions is to use both the trace element and isotopic analyses in conjunction with one another (Griffiths and Holmes, 2000). An example is illustrated in the study by Kulkoyluoglu *et al*. (2015) which included the integration of stable isotope and trace element signatures in the hopes of correcting the composition of the oxygen isotope from the effects of temperature to produce a reliable record.

2.4 Limitations

There are several difficulties associated in the interpretation of ostracod assemblages. These may be due to taphonomic redeposition or alteration of ostracod valves, poor knowledge of ostracod autoecology, and uncertainty around the actualistic approach used for old fossil groupings (Frenzel and Boomer, 2005). Furthermore, juveniles can be particularly hard to

identify to species level, especially if there are no adult representatives within the association (Meisch, 2000). The genus *Candona* is an example of this. Certain ostracods also possess asymmetrical valves (genus *Physocypria* for example) and if the valves are not articulated, it may seem as if they belong to a different species (Griffiths and Holmes, 2000). Within sexual populations there may be valve differences between male and female individuals so care needs to be taken not to mistake them for different species (Karanovic, 2012). Variations in ecophenotypes may also lead to problems as it causes the alteration of the shape, ornamentation and size of the valves, which may lead to identification problems, evidenced in the genus *Ilyocypris* for example (Holmes, 2001). Cryptic speciation is another problem with ~40 cryptic species being noted in cosmopolitan ostracods from Europe and North Africa (Karanovic, 2015). Evolutionary and statistical tests, such as the Automatic Barcode Gap Discovery, have been developed to identify genetically distinct but morphologically similar populations, however, it has little application in practical recognition of species (Karanovic, 2015). Other problems encountered with isotope analysis are due to the uncertainty associated with the changing environmental effects on valve chemistry and morphology, as well as the uncertainty surrounding the effects of certain chemicals used for the pre-treatment of the valves during sampling processes (Boomer *et al*., 2003). Problems may occur in the preservation, sampling and preparation techniques employed; these issues are addressed in further detail in section 2.5.

2.5 Preservation, sampling and preparation

Despite the widespread geographical distribution of ostracods, not every ecosystem can effectively preserve their fossil assemblages (Keatings *et al*., 2010). Preservation may also depend on carapace biomineralization as weakly calcified carapaces have a poor preservation potential when compared to the more robust carapaces, evident in many marine species. Other issues may be encountered with poorly calcified or thin valves that are at risk of dissolution, fracturing or crushing right after death. Techniques employed throughout these processes will also effect fossil valves.

In order to ensure unbiased samples and results, several issues need to be addressed during the sampling and preparation processes. Important factors to consider are sample size, sieve size, chemical analyses, and the physical methods employed for disaggregation (Griffiths and Holmes, 2000). Sample size needs to be large enough to yield a significant number of

specimens to ensure statistical relevance (Viehberg, 2006). However, it is also important to keep in mind that an increase in sample size means an increase in the time averaging effect and thus a loss in temporal resolution (Boomer *et al*., 2003). Holmes *et al*. (2010) recommend 300 specimens as a sufficient ostracod count size per sample. Sieve sizes are important as the sieves need to be small enough to retain juveniles as well as adults, and certain taxa have very small adult forms (Holmes, 2001). Generally, a sieve size of 150 μm is sufficient enough to retain adult ostracods (Smith and Delorme, 2010). For sediment disaggregation, unconsolidated silts and sands only require a gentle wash with water, whilst marls and clays require a weak chemical treatment (Caporaletti, 2011). Hardened lithologies require more powerful chemicals such as hydrogen peroxide, however this increases the risk of corroding the valves (Caporaletti, 2011). If the remaining sample is dirty, ostracods with a smoother carapace may be preferentially picked as they separate easier from the sediment than the more ornamented carapaces (Boomer *et al*., 2003).

2.6 Ostracod assemblages: modern analogues, generalist and specialist species

Once recovering and sorting has been done, initial interpretations can be made using generic and suprageneric evidence to draw broad conclusions about the environment at the time of deposition (Griffiths and Holmes, 2000). When looking at fossil material, a modern analogue can be evident from a species level upwards, depending on the stratigraphic range of the taxon and the age of the material (Boomer *et al*., 2003). In keeping with the principle of uniformitarianism, ostracod assemblages depict their environment at the time of deposition, and if the ecological tolerances and preferences have been established for their current modern relatives, inferences surrounding past environmental characteristics can be made (Dügel *et al*., 2008).

Ostracods are found throughout all aquatic environments, from fresh to saline systems, however several species are known for having increased sensitivity to certain environmental parameters, and are thus considered specialist species (Dügel *et al*., 2008). There are also several generalist species, especially in many freshwater systems, which occupy a much broader niche (Griffiths and Holmes, 2000). Consequently, the negative and changing environmental conditions that affect species richness may not be detected because of these species dominating within a system (Dügel *et al*., 2008). An opportunistic species will flourish

in environmentally stressed systems, such as those with fluctuating salinities or temperatures, and is usually evident in the fossil record by the dramatic increase of a certain species that is better adapted to the newly developed, stressed conditions (Boomer *et al*., 2003).

2.7 Ostracod species: abundance, age, sex and valve ratios

Once the sample has been classified to species level, it is possible to determine the diversity of the ostracod assemblage. A simple species diversity can be evaluated using standard ecological approaches (Maher *et al*., 2012). Abiotic and biotic factors will cause changes in ostracod diversity, however the timescale over which changes occur is an important factor to consider (Allen and Dodson, 2011).

There are five ways to quantitatively record ostracod species: absolute abundance, relative abundance, adult:juvenile ratio, male:female ratio and the valve:carapace ratio. All species within the same sample need to be counted using the same method (Griffiths and Holmes, 2000). Absolute abundance records the total number of valves, with a single valve = 1 or a double valve (carapace) = 2 for example (Boomer *et al*., 2003), relating it to a given sediment volume or sampling area. Relative abundance is a simple calculation and is usually expressed as a percentage of a species within an assemblage as a means to determining rarity or dominance (Boomer *et al*., 2003). The adult:juvenile ratio depicts the population age structure and is an important ratio for assessing life and death assemblages, as well as transportation (Holmes, 2001). Very little attention has been given to the male:female ratio (in species capable of sexual reproduction. In a marine environment, a 1:1 male to female ratio is indicative of the K-strategy in relatively stable environmental conditions, whereas ratios with higher values for females are indicative of the r-strategy during times of unstable environmental conditions (Boomer *et al*., 2003). The valve:carapace ratio may be affected by biological controls such as the strength of each species hinge and their mode of life (Frenzel and Boomer, 2005). Methods in which a sample is collected and sampled may also affect the ratio (Holmes, 2001). The portion of adult:juvenile and valve:carapace found within the sediment can be indicative of the wave energy conditions, enabling the physical conditions at the time of deposition to be established (Keatings *et al*., 2010). High energy environments will erode or remove small juvenile valves, cause valve discolouration and completely destroy several of them before preservation is possible (Keatings *et al*., 2010).

2.8 Ostracods within the African literature

Within the African context, there are fewer available studies that use ostracods as the biological proxy for palaeoenvironmental reconstruction, in comparison with the rest of the world. North and East Africa do provide some palaeoenvironmental context through the application of ostracod analysis (e.g. Keatings *et al*., 2010; Park and Cohen, 2011; Schön *et al*., 2013; Schmit *et al*., 2013), however, southern Africa appears to have a higher portion of studies focussed purely on the descriptive and taxonomic aspects of ostracods (e.g. Martens *et al*., 1996; Martens, 2003; Wouters, 2003; Matzke-Karasz and Martens, 2005)

Keatings *et al*. (2010) conducted a study focussing on past human–environment interactions in Lake Qarun, Egypt. Ostracod occurrence was found to be dependent on solute composition related to land use within the catchment. *Cyprideis torosa* coincided with times of thriving agriculture and *Limnocythere inopinata* dominated during times of economic and environmental decline. This provided the necessary evidence to deduce anthropogenic influences before the times of detailed and instrumental observation records. In another study, compiled by Park and Cohen (2011), the palaeoecological responses of ostracods to changing lake levels in the early Late Pleistocene were determined for Lake Malawi, East Africa. Park and Cohen (2011) correlated the taphonomic variables of the seven identified ostracod genera against the palaeoecological changes within their communities to delineate the lake level lowstands and highstands. In another study from East Africa, Schön *et al*. (2013) illustrated the cryptic diversity of *Romecytheridea* in Lake Tanganyika. This study analysed the mitochondrial 16S DNA of ostracods from four different regions of the lake. Their findings revealed highly differentiated genetic populations, while the genetic markers of their nuclear genome appeared almost identical. This led to the conclusion that the populations were cryptic species with allopatric distributions. In North Africa, a recent study by Schmit *et al*. (2013) has observed the present environmental and geographical parthenogenesis in the ostracod *Eucypis virens*. Schmit *et al*. (2013) linked the contemporary environmental parameters with the reproductive modes of *E. virens*, and proposed that the geographical parthenogenesis reveals the capability of asexual populations to rapidly colonise a system, and the high adaptability of the sexual populations to changing hydroperiods.

In the context of the southern African subregion, Koen Martens has played a vital role in contributing to the identification and describing of ostracods, evidenced in papers from the Western Cape (Martens *et al*., 1996; Martens, 2003) and Northern Cape (Matzke-Karasz and Martens, 2005). Martens *et al*. (1996) contributed to the discovery of two new ostracod species, *Ilyodromus viridulus* and *Limnocythere inopinata* that were recorded for first time within the African continent. *Ilyodromus viridulus* is a freshwater species that was introduced from Australia and is considered an alien. *Limnocythere inopinata* is a benthic ostracod usually found in moderate to high salinities but has been noted in freshwater environments. Martens (2003) revealed the presence of the ostracod *Liocypris grandis* in the Western Cape, a species on the Red Data List and previously thought to be extinct. Following the construction of an airport at Stompneus, this ostracod could not be found again in any surrounding vleis, and hence the reasoning behind its believed extinction. This species is classified as a giant ostracod usually measuring over 5 mm in length. It was originally described in 1924 and then re-described by Martens (2003) after being documented in a temporary pool 200 km away from its original locality. This giant ostracod was then further examined, through micro-sectioning, to fully explore the soft parts of the body to produce a detailed record by Matzke-Karasz and Martens (2005). In a study by Wouters (2003), material was analysed from a previous field sampling trip to Lake St Lucia conducted by Martens in 1994. Although only six ostracods were found within the sample, it still acknowledges their presence within the study site of this paper, False Bay, Lake St Lucia. Wouters (2003) used valves, as well as the soft parts of three male ostracods to identify them as *Cyprideis torosa*, which subsequently led to the extension of the species range. It is important to note that Wouters (2003) has identified that Hartmann (1974) had reported the genus *Cyprideis* as absent along South Africa's eastern and southern coast as it is replaced by the genus *Sulcostocythere* in the region. Wouters (2003) study has proven that this is in fact not true and that *Cyprideis* species co-occur with *Sulcostocythere knysnaensis*.

2.9 Global palaeoenvironmental studies using ostracods as proxy data

Several successful palaeoenvironmental reconstructions, achieved using ostracods as the proxy, are evident around the world. Studies areas range from Lebanon to Pantagonia to China.

Develle *et al*. (2010) conducted a study in Lake Yammoûneh, Lebanon, using ostracods to reconstruct palaeolake oxygen isotope records. Oxygen isotope signatures were found to be affected by temperature and rainfall. Through $\delta^{18}O$ isotopic analysis of ostracod valves, this study was able to reveal that the changes in the lake water during the Holocene were linked to changing sea surface isotopic water composition and further amplified by increased rainfall inland. The changes in lake water over the Last Glacial Maximum are because of the temperature effect on the isotopic composition of rainfall. Limitations did however occur within the study as no one taxon was present throughout the length of the core and thus, the three most abundant taxa were selected for isotopic analysis. Furthermore, the lake is currently dry and therefore no monitoring schemes can be implemented and no calibration of modern material could be executed.

A study focussing on environmental changes during the late Quaternary, inferred by fossil ostracods within a lake system, has been successfully conducted by Cusminsky *et al*. (2011). A sediment core was extracted from Lago Cardiel, a lacustrine basin in Patagonia. Six ages were determined using tephrachronology and AMS (Accelerator Mass Spectrometry) radiocarbon dating. A nearby basin, Laguna Cari-Laufquen, had been previously sampled in 1988 with two radiocarbon ages determined. A total of 38 localities in the two basins were analysed for modern ostracod assemblages using canonical correspondence analyses as the multivariate statistic. From these samples, ostracod-based transfer functions were developed for palaeoenvironmental information. The Ca:pH ratio and salinity were determined to be the two major factors affecting ostracod distribution. Subsequently, this allowed for wet and dry periods to be established with the overall conclusion of a dry Late Pleistocene with significantly more humid conditions being experienced during the early to middle Holocene, and the overall decrease in the lake levels characterising the late Holocene.

Another successful study, complied by Chunlian *et al*. (2013), assessed the palaeoenvironmental changes over the late Quaternary period in South China using ostracods and stable isotope analysis. A core was extracted from the Pearl River Delta and dated using standard radiocarbon techniques. The most commonly occurring ostracod, *Bicornucythere leizhouensis*, was used for $\delta^{13}C$ and $\delta^{18}O$ isotopic analyses throughout the length of the core,

with the results corresponding with salinity variations. Four stages were identified, with the aid of lithology, to deduce the changes in sea level over the Late Quaternary.

2.10 Conclusions for using ostracods as proxies

Ostracods are evident in the fossil record as far back as the Palaeozoic era with notably higher diversities displayed in marine species. Their excellent preservation potential and sensitivity to various environmental parameters render them useful biological proxies for environmental change. Isotope analyses conducted on ostracod valves reveal important environmental information. As with all scientific investigations, there are the associated limitations however, specific, unbiased sampling methods need to be pursued throughout the entire preservation, sampling and preparation techniques to ensure robust scientific findings, and reduce the risk of encountering such problems. An ostracod assemblage is made up of various species, all indicating specific environmental conditions, which can be quantitatively recorded in several ways. Although palaeoenvironmental studies using ostracods are few within the African region, several studies using ostracods for palaeoenvironmental reconstructions have proven successful in other parts of the world. This, coupled with available evidence of their preservation potential, leaves much potential for future studies and the application of ostracods as a method for reconstructing palaeoenvironments within South Africa.

CHAPTER THREE

LAKE ST LUCIA

Lake St Lucia, part of iSimangaliso Wetland Park, is the world's oldest protected estuary, having been proclaimed as a Game Reserve in 1885 (Bainbridge, 1993). In 1986, this site was declared a Ramsar Wetland of International Importance, and later appointed as a UNESCO World Heritage Site on the basis of natural, cultural and historical value. The 350 km^2 shallow estuarine system, with a water depth averaging only 1 m, is situated on the east coast of South Africa, KZN, on the Maputaland Coastal Plain. Accounting for 80% of all estuarine habitats in southern Africa, Lake St Lucia has been deemed the single most important nursery ground for several estuary-associated fish species and many invertebrates, as well as being home to crocodiles, hippopotamus, and a rich aquatic birdlife (Porter, 2013). This chapter will discuss the geology and geomorphic evolution of Lake St Lucia and its physico-chemical properties. It will explore the past, present and future management strategies employed within the system. Lastly, it will review the palaeoecological literature available for the Holocene era.

3.1 Geology

The St Lucia Estuary basin falls within the boundary of an extremely variable terrestrial environment and the high energy Indian Ocean coastline, with the geology representing more than 3.2 Ga of the earth's history (Botha *et al*., 2013). The five dominant river catchments in the region comprise of the larger Mkhuze River in the north and Mfolozi River in the south, in addition to the smaller Nyalazi, Mzinene and Hluhluwe rivers. The oldest rocks in the area represent 3.2 Ga Kaapvaal craton granites overlain by 2.9 Ga Pongola Supergroup volcanic and sedimentary rocks (Botha *et al*., 2013). The Permo-Triassic Karoo Supergroup sedimentary succession (approximately 260-210 Ma) are superimposed unconformably over the basement rocks (Botha *et al*., 2013). The current dune systems that form the Eastern Shores of St Lucia link to 300 000 years of climatic variability, whereas the unconsolidated dune cover along the coastal plain of Maputaland results from the long-term evolutionary connection between the littoral marine environment, the terrestrial coastal dune and wetland environment, and the eroding catchments (Botha *et al*., 2013).

3.2 Geomorphic Evolution

The late Pleistocene (c. 127 000/126 000 – 11 784 yr BP) saw the last glacial cycle responsible for shaping the landscape through various geomorphological processes (Wright *et al*., 2000). The evolution of St Lucia is in accordance with many coastal estuaries whereby the marine transgression or regression cycles, connected to fluctuating Quaternary glacio-eustatic sea levels, created incised bedrock valleys that were subsequently infilled following the Holocene marine transgression (Whitfield *et al*., 2013). This has ultimately resulted in the development of three basins: North Lake, False Bay and South Lake.

Sedimentation due to the infilling of the Pleistocene valleys of North Lake depicts a cycle of lowstand to transgressive infilling of mixed tide- and wave dominated estuary conditions (Benallack *et al*., 2016). As the coastal barrier developed, the water was impounded within North Lake, drowning the interfluves, transforming the estuary into a back-barrier lagoon and altering the dominant form of sedimentation to that of the eroded underlying sediment of the migrating tidal channels (Benallack *et al*., 2016). Continued barrier growth led to the tidal outlet at Leven Point constricting and the subsequent lateral infilling (Benallack *et al*., 2016). False Bays' incised fluvial channels were filled slowly as the direct marine influence was deflected by the Nibela Peninsula, and the prevailing estuarine conditions formed a cycle of mixed tide- and wave dominated sedimentary conditions (Benallack *et al*., 2016). This process repeated itself several times, in response to the slowing and renewed sea levels (Benallack *et al*., 2016). Sediment supply and accumulation within the lake has caught up with the rapidly rising sea level resulting in the transformation of the once deep-water system, to a much shallower estuarine system (Humphries *et al*., 2016). It is estimated that the lagoon previously covered approximately 912 km² of land, and in conjunction with the 253 km² of inundated Mfolozi River wetland, it covered an area of roughly 1165 km² along the coastline, and extended 112 km N-S (Botha *et al*., 2013). Through the late Holocene there has been a reduction by 60% of the area of the lake, which is currently only 60 km in length, covering a total area of 350 km² (Taylor *et al*., 2006).

Generally speaking, sandy substrates and less turbid waters characterise the eastern parts of the lake (Botha *et al*., 2013). In the northern reaches, sedimentation is uniform and pelagic (Botha *et al*., 2013). Bird Island to Selley's Lake, along the Eastern Shores, consist of fine-grained

sand with much coarser sand being found in the shallower eastern shoreline (Botha *et al*., 2013). The dominating fine silts and clays in the False Bay and North Lake areas coincide with the low-energy conditions, due to the lacking fluvial and tidal currents, promoting a calm suspension setting (Benallack *et al*., 2016). The south lake typifies traction sediment transport with the islands having areas of suspension sedimentation (Botha *et al*., 2013).

3.3 Physico-chemical properties

The physico-chemical conditions present in St Lucia represent the most extreme conditions seen in South African estuaries, and are influenced by cyclone-induced flood events and prolonged periods of drought conditions (Whitfield *et al*., 2013). Flood conditions have been recorded in 1955, 1963, 1975, 1984 and 1987 with periods of drought being recorded from 1949-1951 and 1968-1972, with the more recent droughts experienced from 2002-2012 (Perissinotto *et al*., 2013) and 2015-2016 (Humphries *et al*., 2016). Freshwater input has been singled out as the most pertinent factor influencing physico-chemical conditions such as temperature, mouth state, water depth and salinity, which in turn influence biotic communities and thus determine habitat and species distribution throughout the entire lake system (Adams *et al*., 2013). Despite the spatial and seasonal variability in freshwater input, additional stressors are noted in the anthropogenic alterations to flow manipulation and groundwater extractions (Humphries *et al*., 2016).

Spatial variability between the various basins is characteristic of St Lucia (Cyrus *et al.*, 2011). Each section of the system assumes a unique identity through the intricate interactions of the physico-chemical parameters (Perissinotto *et al*., 2013). Of importance are the contrasts between freshwater versus marine inflows in determining salinity gradients, deep versus shallow areas in determining temperature, salinity and light penetration, and exposed versus sheltered basins as the oxygen concentration and turbidity is affected (Perissinotto *et al*., 2013). A reversed salinity gradient is characteristic of Lake St Lucia as most of the freshwater supply is in the mouth and the Narrows region (Carrasco and Perissinotto, 2012). Temporal variability is also an important factor. Temporal changes occurring over time are demonstrated in the cyclical dry and wet phases, while temporal changes over shorter timescales are demonstrated by the changes in seasonality, both of which affect salinity and temperature (Cyrus *et al*., 2011).

As St Lucia is a very shallow system with a very large surface area:volume ratio, it is particularly sensitive to any variations in the balance of freshwater gains and losses (Bate and Smailes, 2008). During wet phases (increased freshwater inflow), the environmental parameters within the system are relatively similar and thus form a homogenous entity (Whitfield and Taylor, 2009). During dry phases (reduced freshwater inflow) however, habitat distribution is largely determined by water depth and salinity (Whitfield and Taylor, 2009). The current shallowness of St Lucia results in the poor circulation and mixing of the water with the reduced freshwater inflows causing the flow between basins to become discontinuous (Perissinotto *et al*., 2013). Severe dry phases will result in the system basins becoming fragmented and separated from one another (Taylor *et al*., 2006). As the Mfolozi and Mpate rivers generally keep a steady supply of freshwater to the lower reaches of the estuary, the northern reaches often experience hypersaline conditions and very low water levels (Whitfield and Taylor, 2009). This produces a reversed depth profile as well as the reversed salinity gradient creating an array of unique habitats (Perissinotto *et al*., 2013). In comparison to South Lake, North Lake exhibits a greater surface area:volume ratio which may also be the reasoning for the reversed salinity gradient within the system (Humphries *et al*., 2016).

Salinity is one of the most influential factors within an estuary as it affects almost every organism, with stenohaline species tolerating a limited salinity range and euryhaline species tolerating a much larger range (Perissinotto *et al*., 2013). Salinity levels exceeding 60 and those below 15 are linked to mass mortalities in estuarine-dependent marine species, whilst typical estuarine species have a much broader threshold (Carrasco and Perissinotto, 2011). Historically, a quasi-decadal cycle in salinity was experienced in St Lucia (Perissinotto *et al*., 2013). During an open mouth phase, the southern areas of the lake are essentially marine due to the influence of the tide, with this influence extending up towards the northern reaches of the system during periods of low freshwater input (Carrasco and Perissinotto, 2012). Equally so, during wet phases due to increased freshwater into the system, the system will become less saline even with continued tidal influences (Perissinotto *et al*., 2013). Superimposed on these conditions are the effects of seasonality. Lake St Lucia falls within the boundaries of the summer rainfall zone and precipitation is hence influenced by the southern regions of the Inter Tropical Convergence Zone and thunderstorms moving in an easterly direction (Holmgren *et al*. 2003). Mean annual rainfall at St Lucia ranges from 1200 mm at the mouth to 625 mm at Lister's Point (Humphries *et al*., 2015). The rainy season, from October to April, will see an

increased inflow of freshwater runoff resulting in meso/oligohaline conditions (closed mouth) or euhaline/marine conditions (open mouth) in the Narrows and the mouth region (Perissinotto *et al*., 2013). Lake basin conditions may, however, remain hypersaline, especially in False Bay (Perissinotto *et al*., 2013). As rainfall ceases, water loss via evaporation results in extreme hypersaline conditions (>300) (Whitfield and Taylor, 2009). Evaporation is a natural and powerful process with mean annual evaporation rates accounting for up to 1470 mm (Hutchison and Midgley, 1978). Because rainfall in the area is seasonal, typically the rivers in the catchment area will flow during the summer months, and are reduced to groundwater seepage during winter, which only constitutes 6-7% of the lakes water balance overall (Humphries *et al*., 2016). St Lucia is a large system, and thus, several different salinity states may be present at any one time (Whitfield *et al*., 2012).

Humphries *et al*. (2016) focussed on geochemical analysis of sediment cores extracted from each of the three basins within St Lucia. Results indicate a marked increase in salinity over the past 2000 years in North Lake and False Bay, with ~1100 and ~1750 cal yr BP showing two distinct peaks in both basins. False Bay yielded Na/K ratios that were six times higher than those of North Lake indicating that the basin had been subjected to higher degrees of desiccation, perhaps resulting from the small catchments and surface runoff of the rivers that drain into it (Humphries *et al*., 2016). The freshwater seepage that drains into the northern reaches from the Mkhuze River helps to ameliorate the saline conditions found within North Lake (Humphries *et al*., 2016). Catalina Bay, in the southern reaches, indicated less saline conditions because it has the deepest basin, receives a steady water supply form the Narrows and a considerable amount of groundwater from the eastern shores, hence buffering it against the effects of desiccation (Humphries *et al*., 2016). El Niño-Southern Oscillation (ENSO) influences climatic variability within the Southern Hemisphere and has been noted as the driving force of the drought in the St Lucia area (Rouault and Richard, 2003). This evidenced in the records of Humphries *et al*. (2016) who concluded that St Lucia illustrated increased desiccation at ~1100-1700 cal yr BP, corresponding with peak ENSO activity. Further details of this study are provided in the palaeoenvironmental review later in the chapter.

3.4 Management of St Lucia

Lake St Lucia is a highly managed system with a long history of anthropogenic influences noted from the mid-1800s right through to the present day (Perissinotto *et al*., 2014). A great deal of this manipulation surrounded the freshwater inputs and the mouth region. Subsequent management strategies have focussed on the rectification of previous decisions to try restore Lake St Lucia to a healthy, functional estuarine system, and alleviate the effects and overall deterioration resulting from prolonged drought conditions (Whitfield and Taylor, 2009).

1850 – 1950

The mid 1800s saw the settlement of hunters and traders in the St Lucia area because of the hunting opportunity it presented (Taylor, 2013). Towards the late 1800s however, the significant decrease in animal numbers prompted the implementation of the first management strategy proclaiming part of St Lucia as a Game Reserve in 1885, rendering it one of the oldest protected areas in Africa (Bainbridge, 1993). In 1902, the possibility of constructing a harbour produced the first map of the Mfolozi-St Lucia area, but it was deemed inappropriate due to the mouth variability and improbability of it remaining deep enough (Taylor, 2013). 1911 marked the beginning of sugar cane farming on the Mfolozi floodplains (iSimangaliso Wetland Park, 2011). After floods in 1918 and 1925, the management strategy moved to incorporate a more respectful consideration toward flooding and floodplains, thus farmers relocated to higher ground, where they remain today (iSimangaliso Wetland Park, 2011). During the 1932 drought, the joint Mfolozi-St Lucia mouth closed and water started backing up behind the berm, resulting in the flooding of low-lying floodplains, affecting the sugar plantations (Cyrus *et al*., 2010). As a means of alleviating this, local farmers decided to breach the mouth and masses of sediment were washed out to sea resulting in an intense scouring effect (Whitfield *et al*., 2012). Each breaching event did, however, led to the rejuvenation of the St Lucia lake system (Whitfield and Taylor, 2009). In response to this back-flooding, local farmers excavated drainage systems (Wilson’s Drain and Warner’s Drain), damaging the natural filtration system and changing the sediment deposition site from the upper to the lower reaches of the floodplain, 30 km eastward (Carrasco and Perissinotto, 2012). From the 1930s toward the 1940s, drought conditions saw the increased narrowing of the St Lucia mouth and the Mfolozi River diverting naturally to join the St Lucia system, thereby resulting in the freshening of the system (Whitfield and Taylor, 2009). Superimposed on to the already evident impacts of drought, was

the further abstraction of water from the system for irrigation purposes by local farmers (Stretch and Maro, 2013).

Early 1950s – late 1960s

The prolonged drought conditions and silting up of the estuary led to the closure of the combined Mfolozi-St Lucia mouth in May 1951 (iSimangaliso Wetland Park, 2011). Several experts were brought to St Lucia to advise on a plan moving forward, which saw the opening of Mfolozi mouth in 1952 (Whitfield *et al*., 2013). Their next focal point was the St Lucia Estuary, and in 1955, after years of dredging, the mouth was breached only to close again eight days later (Taylor, 2013). Several attempts to stabilise both the Mfolozi and St Lucia mouths were made by driving railway lines into the sand as a means of preventing them from merging or drifting northward, but these proved unsuccessful (Taylor, 2013). Intensive dredging operations were maintained with the St Lucia mouth finally opening again in 1956, flushing out the entire system (Taylor, 2013). This led to the rejuvenation and return of thriving conditions in the St Lucia system up until the late 1960s (Whitfield and Taylor, 2009).

Late 1960s – early1970s

A severe drought was experienced from 1968-1972 causing the closure of both the Mfolozi and St Lucia mouths in 1970 (Whitfield and Taylor, 2009). This resulted in increased salinities within the system and the development of salt tolerant communities, and a subsequent loss in biodiversity (Carrasco and Perissinotto, 2012). As the water level in the St Lucia system had fallen below sea level, once the mouth was dredged open there was a significant marine influx, creating a salinity gradient comprising of marine salinity levels near the mouth and salinity concentrations three times that of seawater in the northern reaches of the lake (Whitfield and Taylor, 2009). As a means of temporarily combatting the effects of the drought, water was diverted from the Mfolozi into St Lucia through the Back Channel during the period of 1970-1973 (Taylor, 2013). Similarly, the St Lucia Conservator at the time thought an excavation through the swamp near the Mpempe Pan of the Mkhuze River would be effective in capturing the water from Mkhuze River into St Lucia and a canal was excavated in 1971 (Taylor, 2013). Following the end of the drought, increased water flows through the channel caused erosion that led to the draining of the Mpempe Pan (iSimangaliso Wetland Park, 2011). An earth wall

was built to try and rectify the situation several times in 1974, 1979 and 1985, but was breached each time by flood events in 1975, 1984 and 1985 respectively (Ellery *et al*., 2003). To this day, millions of rands have been spent in trying to repair the damage caused by this excavation (Whitfield and Taylor, 2009).

Early 1970s – mid 1980s

The mid 1970s saw the formation of a hydrological model and the concept of the Link Canal (Whitfield and Taylor, 2009). This entailed the linking of the Mfolozi to St Lucia as means of bringing freshwater into St Lucia and thus reducing the duration of extreme saline conditions in times of drought (Taylor, 2013). Construction of the Link Canal commenced in 1975, however, shortly after the completion of the first stage, flood waters associated with Cyclone Domoina severely damaged the canal (Whitfield and Taylor, 2009). After assessing the damage caused by the cyclone, flaws in the concept became evident and the canal was never repaired or used (Taylor, 2013).

Mid 1980s – 2000

During January/ February of 1984, Cyclone Domoina passed through the lakes catchments bringing a significant increase in rain with flood peaks reaching 167 000 m^2s^{-1} in the Mfolozi River (Whitfield and Taylor, 2009). As the water from the floodplain of the Mfolozi reached St Lucia, it split northward to flow into the lake and southward to flow out into the sea (Taylor, 2013). Subsequently, the flow was reversed in the Narrows as a significant volume of water flowed in from the Mkhuze catchment and all water was directed south in a seaward direction washing away the hard structures at the estuary mouth (Patrick and Ellery, 2006). Cyclone Imboa hit the coast two weeks after Domoina, resulting in remarkably high seas, coinciding with high tides and thus causing further damage through erosion and dune undercutting (Taylor, 2013). New management strategies were sought, and it was agreed that the best way forward was to move toward more natural coastal processes and avoid further canalizations and diversions in the Mfolozi River (Taylor, 2013). The two mouths were to be left separated but no hard structures were to be built for mouth stability, and natural spits/bars were to be allowed to form (Whitfield and Taylor, 2009). Dredging became essential as long as the

Mfolozi remained separated from St Lucia, as the St Lucia mouth would eventually close during periods of low rainfall (Whitfield *et al*., 2013).

2000 – present

The year 2001 saw a significant increase in rainfall, however, rainfall reduced considerably thereafter causing rivers to stop flowing and resulting in a notable drop in lake level (Cyrus *et al*., 2011). With this drought onset, the mouth of St Lucia closed in 2002 and a decision was taken to leave the mouth closed, expecting the drought to last no longer than five years (Taylor, 2013). Other than the drop in the water level of St Lucia, other responses to the drought were evident in the vegetation expansion onto exposed beaches, groundwater-dependent habitats flourished, mass fish mortalities as the loss in connection to the sea prevented the movement required for recruitment, and in the inability of the estuary to function as a nursing ground (Whitfield *et al*., 2013). As salinity concentrations intensified, reaching concentrations above 200 in the northern reaches of the lake, a halotolerant food chain was established (Carrasco and Perissinotto, 2012). By 2006, 80% of St Lucia was dry and exposed (Taylor, 2013).

The July of 2012 saw the change in management strategy towards encouraging the re-linking of the Mfolozi with St Lucia, and with increased rains brought the opening of St Lucia to the sea (iSimangaliso Wetland Park, 2013). This was a pivotal shift in the management strategy that had been in place for the past 62 years and had largely focussed on keeping the two systems separate (iSimangaliso Wetland Park, 2013). The current status in St Lucia is dire with 2015 being the year of lowest recorded rainfall since the 1920s, leaving 90% of lake bed exposed (iSimangaliso Wetland Park, 2016a). The salinity readings in the little water remaining are five times higher than that of the seawater with estuarine species having a salinity tolerance of only two to three times that of seawater, and thus having devastating effects on the biological communities with species recovery remaining slow (iSimangaliso Wetland Park, 2016a).

3.5 Future Management

Focus now remains on preventing any further degradation to the St Lucia system, and in maintaining the link between the Mfolozi and St Lucia as the Mfolozi is responsible for 60% of the freshwater input into St Lucia (iSimangaliso Wetland Park, 2016b). This will help to

ensure that St Lucia will have a freshwater supply during drought periods (Whitfield *et al*., 2013). However, this in turn brings with it an increased sedimentation influx. This issue will need to be addressed as the Mfolozi catchment has a reduced natural sediment trapping ability due to the previous canalisation (Whitfield *et al*., 2013). Sediment fills into the estuary when it is washed down through the catchments or washed into the system during flood tides and often requires dredging to remove (Whitfield and Taylor, 2009). During previous periods of a joint Mfolozi-St Lucia mouth, a strong river flow washed sediment out into the ocean during ebb tides, again highlighting the importance of maintaining the link between St Lucia and the Mfolozi (Taylor, 2013). A contract was recently signed with Cyclone Engineering Projects (Pty) Ltd after 2010, and saw a multi-disciplinary research team working together to find the best possible solutions to address the hydrological problems St Lucia faces (iSimangaliso Wetland Park, 2016b). The aim of Cyclone Engineering is to remove 100 000 m^3 of dredge spoil that was previously dumped (1952-2000) in the path of the Mfolozi River, obstructing its flow into St Lucia (iSimangaliso Wetland Park, 2016b).

3.6 Palaeoenvironmental studies spanning the Holocene

As St Lucia is a highly managed system with an impressive record detailing the events over the past 150 years, there have been several ecological studies conducted within the system, many of which describe the responses of the biota to anthropogenic alterations (e.g. Taylor *et al*., 2006; Whitfield and Taylor, 2009; Cyrus *et al*., 2011; Carrassco and Perissinotto, 2012; Whitfield *et al*., 2013; Perissinotto *et al*., 2014). These studies however, only provide a very brief glimpse into the recent biological and physico-chemical changes that have occurred within the system, and yield the results of an already highly managed system. This emphasizes the need for a long term perspective to establish the natural functioning of the system prior to human intervention.

A few long-term datasets have been very recently produced providing important information pertaining to palaeoenvironmental conditions at St Lucia (e.g. Benallack *et al*., 2016; Humphries *et al*., 2016; Gomes *et al*., 2017). Benallack *et al*. (2016) produced the first high resolution seismic study, identifying seven seismic units, within the St Lucia system. This was achieved by analysing the geochemical and sedimentological information from 300 line kilometres of single channel high resolution Boomer seismic reflection data. While the

profiling was conducted in all three basins, focus remained on North Lake and False Bay. This study has revealed valuable information on the formation of St Lucia that was once an open lagoon affected by sea level high- and lowstands. As sea levels rose, a coastal barrier (along the eastern side of North Lake) started to develop and grow. The slowing of the rising sea level and continued dune accretion finally resulted in the closure of Leven Point, the only inlet that still connected North Lake to the sea. Benallack *et al*. (2016) have noted that this occurred around 7123-6235 cal yr BP and created a back-barrier environment with calmer, estuarine conditions. Because of the Nibela Peninsula, False Bay was more sheltered from tidal effects seen in North Lake, and hence the changes toward a more low energy system are evident as early as 8355 cal yr BP.

In a study by Humphries *et al*. (2016), geochemical (SiO_2, Al_2O_3 and Fe_2O_3) and mineralogical analyses were used to identify dry periods within St Lucia. The results from the Na/K ratios pointed to periods of increased salinity, especially over the past 2000 years in North Lake and False Bay. A distinct phase, noted at ~1100 and 1750 cal yr BP, is evident in North Lake as well as False Bay. Additionally, through scanning electron microscopy they were able to identify halite as the dominating mineral within these regions, indicating mineral precipitation during dry, evaporative conditions. Furthermore, a distinctive increase in grain size within these regions was noted and is likely the result of deflation of the coarser material from exposed shorelines during low lake water periods. Humphries *et al*. (2016) has also noted the possibility of a depositional hiatus in both North Lake and False Bay, indicated by radiocarbon dating, which reinforces their idea of an extensive dry period and deflation associated with an exposed bed. This deduction is further substantiated by the accumulation of shell debris that overlies the halite enriched regions, indicating mass die-offs of Mollusca under hypersaline conditions. The Na/K ratio of False Bay was significantly higher than that of North Lake, indicating a more severe desiccation period. South Lake illustrated the lowest Na/ K values and lacked halite enriched regions. Humphries *et al*. (2016) have concluded that because of the similarity between North Lake and False Bay, system-scale processes act between the sub-basins. The onset of a system wide desiccation period is evident by the persisting Na/ K enriched seismic reflectors, which consequently point a significant change in the hydroclimate of St Lucia. These findings, noted by Humphries *et al*. (2016), coincide with similar lacustrine records in the tropical Pacific that indicated a definitive increase in El Niño activity. ENSO is the most important driver of inter annual climate variability within the Southern Hemisphere and is often

noted as the causing agent of drought within the region (Richard *et al*., 2001). As this study identified ~1100-1700 cal yr BP as the period most affected by drought, which correlated to the period of maximum ENSO activity, it was able to provide evidence that the extensive dry periods experienced in St Lucia were likely the result of El Niño events.

Gomes *et al*. (2017) used diatom assemblages and sulphur isotope geochemistry ($\delta^{34}S$) to determine the changes in basin geomorphology resulting from the changing sea level, barrier aggradation and lagoonal development. The focus of this study was restricted to the sediment cores extracted from North Lake and False Bay. Diatom reconstructions were used to successfully identify the past ~6000 years of geomorphic evolution, in North Lake, that was controlled by sea levels. Furthermore, diatom reconstruction coupled with $\delta^{34}S$ enabled three phases to be identified in North Lake and False Bay; an initial Holocene marine transgression, a mid-Holocene highstand, and the development of a back barrier and consequent infilling. Gomes *et al*. (2017) has however noted that there are issues relating to diatoms poor preservation potential within a shallow lake environment, in accordance with several other studies.

The state of knowledge on St Lucia may be summarised as follows. The Lake St Lucia system was formed by the fluctuations in climatic variability and sea levels. The early Holocene saw a substantially larger and deeper system, but through the process of sedimentation the lake has been reduced to less than half its original size, with a water depth of less than one metre. This shallowness causes the system to be particularly sensitive to water losses through evaporation and results in extreme physico-chemical properties, with salinity being the most influential. A range of management strategies have been employed, dating back to the 1800s, resulting in significant alterations and the subsequent deterioration of the system. Focus now remains on preventing further system degradation and its successful restoration. It is important to recognise that the majority of the research conducted in St Lucia was carried out post 1950, which is after the biggest anthropogenic interference of diverting the Mfolozi away from St Lucia (Whitfield and Taylor, 2009). This means that a large portion of research was conducted on a severely impaired system and thus very little is actually known about the natural behaviour of the system before interference, emphasizing the need for a longer ecological perspective. This is attainable through the application of palaeolimnological studies, which provide insights into the ‘natural’

functioning of the system and allow for more informed management strategies for Lake St Lucia's restoration. Successful palaeolimnological studies are already evident by Humphries *et al*. (2016) and Gomes *et al*. (2017) and backed by the geological study from Benallack *et al*. (2016). As Lake St Lucia is an alkaline system, it hosts favourable conditions for ostracod preservation, rendering them a viable biological proxy choice for palaeoenvironmental reconstruction. Furthermore, their short lifespan, high abundance, distinct shell morphology and sensitivity to environmental parameters add to their success as a biological proxy. Because St Lucia is fed by freshwater systems as well as a marine input, the differing salinities should be reflected in ostracod communities, preserved within the palaeolimnic sequences, and hence making it possible to deduce the natural functioning of the system prior to anthropogenic interference. Spatial and temporal variability exists throughout the lake, and the study of ostracods within the different basins could provide an advanced overview of the different factors acting within the system.

CHAPTER FOUR

METHODOLOGY

3.1 Field sampling

An extensive program of seismic profiling was conducted in Lake St Lucia in January 2014. The method involved the collection of 300 line kilometres of single-channel high resolution Boomer seismic reflection data using a Design Projects Boomer and a 20 element hydrophone array (Benallack *et al*., 2016). These data were used to target sites for coring within the main depositional basins, based on the maximum depth of sediment infill.

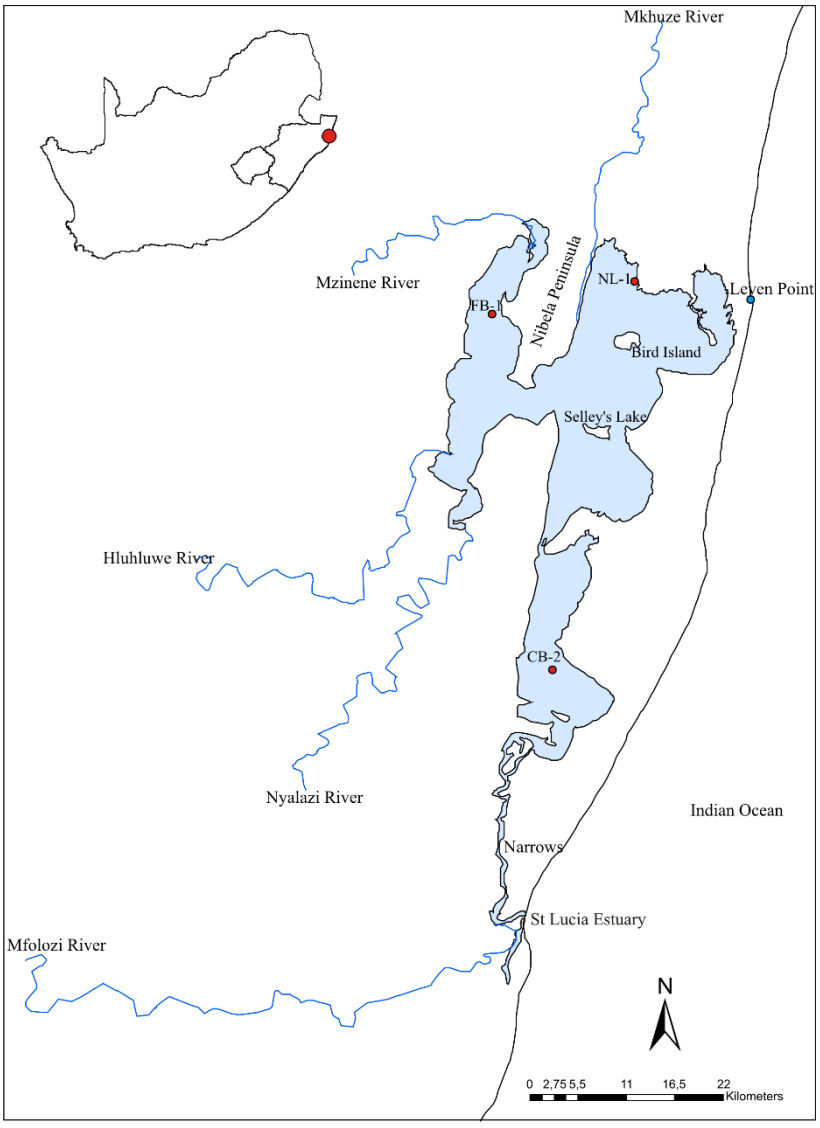

Figure 3.1.1: Site map of Lake St Lucia depicting the three coring sites North Lake (NL-1), False Bay (FB-1) and Catalina Bay (CB-2).

Following the seismic profiling, three ~12 m sediment cores were extracted from the main depocentres of Lake St Lucia: NL-1 (-27.933130°, 32.498410°), FB-1 (-27.942861°, 32.395583°) and CB-2 (-28.209805°; 32.440273°). The cores were extruded in 2 m sections using a piston corer equipped with a percussion system, deployed from a UWITEC coring platform. The NL-1 and FB-1 cores were then extended to approximately 16 m in length in July 2014. Each 2 m core section was capped and sealed within the core liner, wrapped in plastic sheeting and clearly labelled before being transported back to the University of the Witwatersrand for cold storage and analysis.

Figure 3.1.2: Key stages of fieldwork at Lake St Lucia and subsequent subsampling: a) the UWITEC barge and coring platform on False Bay (Photo credit L. Pillay); b) manual operation of the piston corer; c) upon meeting resistance, the piston corer was fitted with a percussion drill system allow further penetration; d) each 2 m section of core was extracted by winch (Photo credit L. Pillay); e and f) subsamples being taken for proxy analysis and dating for various project partners.

3.2 Laboratory analysis

3.2.1 Subsampling and stratigraphic description

Each core was sectioned vertically using an angle grinder to split the core liner, and a wire fed through the length of the core to separate them. Each section was carefully cleaned and photographed. Stratigraphic descriptions were performed according to Troels-Smith (1955), with the aid of the Munsell soil colour chart. Subsamples were extracted for proxy analysis and dating by each research group.

3.2.2 Radiocarbon dating

According to visual changes in sediment characteristics, a series of samples were extracted for AMS radiocarbon dating at Beta Analytic Incorporated, Florida, USA. 29 sediment samples were selected across the three cores with 26 being bulk sediment samples and 3 shell samples. Sample pre-treatment involved the removal of contaminants, overnight drying at 100 °C and acid washes. Shell samples underwent acid etching. The resulting ^{14}C ages were used, in conjunction with the age modelling software of 'bacon' and 'clam', to produce age-depth models for each core. Age-depth modelling is used as means of estimating the calendar ages of the depths within the core, based on a selected number of dated samples and an assumption as to how the sediment deposit has accumulated between the dated sample depths (Blaauw, 2010). The relationship between the calendar ages and ^{14}C is non-linear, thus a calibration curve is required (Blaauw and Christen, 2011). This study will use the Southern Hemispheric calibration curve SHCal13 (Hogg *et al*., 2013). 'Bacon' is used to produce Bayesian age-depth models using advanced, robust numerical methods and is not overly concerned by outlying dates whereas 'clam' is used to produce a classical age-depth models with a greater option for exploring the possibilities of outliers and hiatuses, for example, through the various model choices (Blaauw, 2010). As a result, Bayesian models were plotted in 'bacon' (Blaauw and Christen, 2011) and illustrated the best age-depth models for NL-1 and FB-1, and 'clam' was used to plot a series of models for each core; linear interpolation, linear regression, smooth spline and loess (Blaauw 2010). The linear interpolation model produced in 'clam' was selected as the best age-depth model for CB-2.

3.2.3 Ostracod analysis

Roughly 10 cm^3 subsamples, taken at 10 cm intervals down the length of the cores, were used for ostracod analysis totalling 113 samples from NL-1, 117 samples from FB-1, and 104 samples from CB-2. Sediment samples were sieved through a 200 μm and 63 μm mesh sieve using distilled water so as not to affect the shell chemistry. Samples were dried in an oven, overnight, at 80°C. All samples were placed into labelled plastic bags, for ostracod analysis at a later stage. The 200 μm samples were picked for ostracods as any ostracod valves found within the 63 μm samples are likely to be juveniles, making interpretation difficult (Keatings *et al*., 2010).

Where dried samples were fairly large and sandy in composition, the method of floatation was employed (Griffiths and Holmes, 2000). Floatation involved pouring the dried sample, bit by bit, into a beaker filled with water and allowing the bulk sediment to sink to the bottom whilst the enriched sediment (containing ostracod valves) would float at the top. The water from the beaker was then poured through a 63 μm mesh sieve as a means to retaining the enriched sediment, whilst being careful not to let the bulk sediment leave the bottom of the beaker. All enriched sediment remaining in the sieve was then washed, using distilled water, into a separate dish. This process was repeated until the entire sample had been through the process of floatation. The enriched sediment and remaining bulk sediment were then dried in separate dishes, following the same methods described above. Once dry, samples were placed in labelled plastic bags before being analysed under the microscope. Several bulk sediment samples were analysed microscopically for ostracods to ensure that the method of floatation had worked correctly and that no ostracods were present in the bulk sediment. As these sandy samples were generally quite large, a dry splitter was used to divide them into smaller sized sample aliquots to allow for easier picking.

Dried samples were inspected for ostracods at an appropriate magnification, using a Leica stereomicroscope (Holmes *et al.*, 2010). A moistened paintbrush was used to pick ostracod valves out of the dry samples before placing them on a counting slide. Where possible, 350 ostracod valves were picked from each sample (Griffiths and Holmes, 2000). If a sample contained less than the minimum count, all valves were picked (Viehberg, 2005). Both ostracod carapaces and single valves were counted as viable specimens. Broken valves were

not counted if identification was not possible. All ostracods were identified and recorded with the aid of relevant literature by Benson and Maddocks (1964), Hartmann (1974), Dingle (1992, 1993), Dingle and Honigstein (1994) and Martens *et al*. (1996), and with personal communication with Dr Peter Frenzel and Stephanie Meschner. For further ostracod verification, the scanning electron microscope facility at the University of Jena was used when accessible. Ostracod species have been grouped into five ecological groupings: freshwater, brackish, brackish-marine, marine and euryhaline species. Each grouping was established with the aid of the World Register of Marine Species (WoRMS) and via personal communication with Dr Peter Frenzel and Stephanie Meschner.

Figure 3.2.1: Key stages of laboratory work: a) sieving the samples through 200 µm and 63 µm mesh sieves; b) samples placed into an 80° oven for drying; c) dried samples placed into marked plastic bags for analysis; d) counting tray used with an evenly distributed sample; e) picking of a samples with the aid of microscopy; f) slides containing picked ostracods; g) a sample being poured into a beaker with the bulk sediment settling at the bottom and the enriched sediment floating at the top, illustrating the method of floatation; h) the enriched sediment being poured through a 63 µm mesh sieve; i) bulk sediment remaining in the beaker; j) both the enriched and bulk sediment drying; k) dry splitter used to split large samples.

3.3 Data analysis and presentation

Stratigraphic plots for NL-1, FB-1 and CB-2 were plotted in C2 v 1.7.7 (Juggins, 2007) and Psimpoll v 4.263 (Bennet, 1994). Stratigraphic plots produced in C2 form the main plot for interpretation and only employ samples containing 50+ valves as this is considered to be statistically significant. Zones were identified through the application of Constrained Sum of Incremental Squares (CONISS; Grimm, 1987), a stratigraphically constrained ordination technique, and applied to the C2 dataset. For support data, all fossil data were used in the stratigraphic plots produced in Psimpoll, with the accompanying CONISS derived zones. A flexible significance level was adopted to indicate the relative abundance or presence/ absence of a species. If less than 20 ostracod valves were present in a sample, a dot was placed to mark their presence. If a sample contained less than 50 individuals, taxa with less than 10% were marked by a presence/ absence dot; in samples containing less than 100 specimens, taxa with less than 7% were marked by a presence/ absence dot; samples with less than 200 specimens, taxa with less than 3% were marked by a presence/ absence dot; in samples containing less than 300 specimens, taxa with less than 2% were marked by a presence/ absence dot; and in samples containing 500+ specimens, taxa with less than 1% were marked by a presence/ absence dot.

A regional training dataset, containing modern ostracod analogue data from various sites along the east coast of South Africa (Meschner *et al*., unpublished data; Appendix E) was used to produce an ostracod-salinity transfer function. Six ostracod species recorded within this study are present within the training dataset; *Perissocytheridea estuaria, Sulcostocythere knysnaensis, Australoloxoconcha favornamentata, Aglaiella westfordensis, Cytherella* spp. and *Cytheridea.* A Weighted Averaging Partial Least Squares (WAPLS) model with the leave one out cross-validation bootstrapping method was chosen. Transfer functions are a mathematical representation used for describing inputs and outputs, and because of their ability to quantify the relationship between a selected environmental variable and an environmental proxy, they are important in the understanding of palaeoenvironmental changes (Telford and Birks, 2009). Downcore palaeosalinity estimations produced by the transfer function were plotted in C2, alongside the ostracod stratigraphic plot. Salinity ranged from 8 to 27 psu in North Lake with a RMSEP (root mean square error of prediction) is 6.86 and the r^2_{boot} is 0.56; from 8 to 28 psu in False Bay with a RMSEP=6.83 and a r^2_{boot}=0.56; and from 14 to 37 psu in Catalina Bay with a RMSEP=6.62 and the r^2_{boot}=0.59. The Modern Analogue Technique

(MAT) was then applied to the dataset, in C2, to determine the minimum dissimilarity coefficient (MinDC) values for all fossil data. The RMSE=7.61 and r^2=0.43. MinDc values falling within the 5th percentile were rendered a 'good' fit, values falling within the 10th percentile were rendered a 'close' fit and samples falling within the 20th percentile were rendered a 'poor' fit (Watcham *et al*., 2013). The modern analogue closeness is plotted alongside palaeosalinity. Ostracod salinity ranges, for both living species and empty valves, have been tabulated in Appendix F.

To test the relationship strengths between environmental variables and ostracods, principal component analyses were performed in PAST; a statistical software package designed for palaeontological data (Hammer *et al*., 2001). Samples with less than 2% of ostracods present, and ostracods not found in at least three samples were excluded to reduce statistical noise (Pint *et al*., 2015).

CHAPTER FIVE

RESULTS

This chapter will cover the core chronology and associated age-depth models for North Lake, False Bay and Catalina Bay. The various statistical analyses used, and the reconstruction of downcore stratigraphic plots and palaeosalinity for each core are illustrated.

5.1 Chronology

A series of basic age-depth models, based on linear interpolation, linear regression, smooth spline and loess models, were plotted using 'clam' classical age modelling software. NL-1 and FB-1 indicate stratigraphically consistent results with the exception of two age inversions for NL-1 (96 cm and 1563 cm; Table 5.2), and a single age inversion for FB-1 (65 cm; Table 5.3). These age inversions have been manually designated as outliers for the age models (Appendix C2; Appendix C3). CB-2 has two age inversions (100 cm and 718 cm), the latter of the two has not been excluded as it overlaps with the error range of the adjacent overlying age (Table 5.4; Figure 5.4). The linear interpolation models (Figures 5.4; Appendix C2a; Appendix C3a) are a good fit and are the least complex, however, the manual exclusion of outliers leave them open to subjectivity. The linear regression models are a fair fit for NL-1 and FB-1 because of their linearity, though are not suitable for CB-2 because of the change in sedimentation rate at 242 cm (Appendix C2b; Appendix C3b; Appendix C4a). The smooth spline age model appears acceptable for FB-1 but is not a plausible fit for NL-1 and CB-2 without the manual designation of outliers (Appendix C2c; Appendix C3c; Appendix C4b). The same applies for the loess models, whereby the model illustrates a plausible fit, however, with the manual designation of outliers the model defies the law of superposition (Blockley *et al*., 2007) (Appendix C2d; Appendix C3d; Appendix C4c).

The Bayesian models, produced in Bacon, illustrate the best age-depth model for NL-1 and FB-1 as no outliers have to be manually selected, ruling out any subjectivity in the model (Figure 5.2 and 5.3). Because of the abrupt change in sedimentation in CB-2 (242 cm) the Bayesian model did not perform well for this core (Appendix C4d) and thus, the linear interpolation, produced in 'clam', was decided on as the most appropriate age-depth model

(Figure 5.4). The AMS radiocarbon age determinations used in the age-depth models are tabulated below (Table 5.2).

Table 5.2: Calibrated and uncalibrated AMS age determinations for the North Lake sediment core.

Lab Code	Depth (cm)	Material	^{14}C age (yrs BP)	Error (±yrs)	95% Probability Range (cal yr BP)	Calibration Curve
Beta-423921	22.5	Sediment	1140	30	937-947 (3.9%)	ShCal13
					953-1060 (91.1%)	
Beta-405603	28.5	Sediment	1170	30	957-1074 (95%)	ShCal13
Beta-423922	47.5	Sediment	2130	30	1998-2152 (95%)	ShCal13
Beta-387868	96	Sediment	1430	30	1271-1351 (95%)	ShCal13
Beta-423923	148.5	Sediment	2220	30	2095-2134 (13%)	ShCal13
					2141-2310 (81.9%)	
Beta-386293	290	Sediment	2490	30	2359-2545 (54.9%)	ShCal13
					2556-2619 (15.7%)	
					2629-2703 (24.4%)	
Beta-405604	577	Sediment	3980	30	4249-4274 (4.6%)	ShCal13
					4281-4445 (80.4%)	
					4474-4479 (0.8%)	
					4481-4514 (9.1%)	
Beta-386294	897	Sediment	5090	30	5664-5673 (1.4%)	ShCal13
					5684-5685 (0.2%)	
					5711-5905 (93.3%)	
Beta-373289	1185	Sediment	5410	30	6007-6082 (21.7%)	ShCal13
					6101-6159 (22.8%)	
					6169-6278 (50.4%)	
Beta-405605	1478	Shell	7350	30	8025-8180 (95%)	ShCal13
Beta-386295	1563	Shell	6830	30	7582-7678 (95%)	ShCal13

AMS dating of the North Lake sediment core yields a Holocene basal age of 7350 ^{14}C yr BP (8025-8180 cal yr BP) (Table 5.2). The age-depth model depicts a linear sediment accumulation rate averaging 0.17 cm/yr (Figure 5.2). Two age inversions are evident at 96 cm and 1563 cm (Table 5.2). A total of 11 radiocarbon dates were produced using nine bulk sediment sub-samples and two shell sub-samples (Table 5.2).

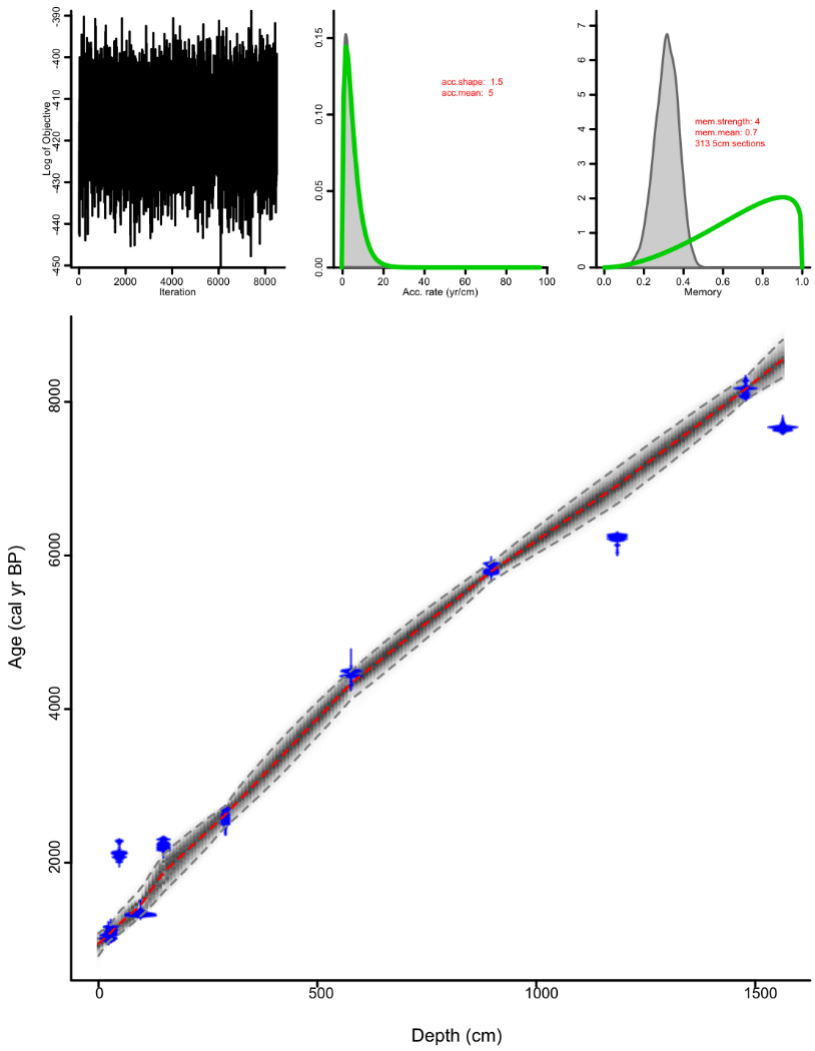

Figure 5.2: Bayesian age-depth model for North Lake.

Table 5.3: Calibrated and uncalibrated AMS age determinations for the False Bay sediment core.

Lab Code	Depth (cm)	Material	^{14}C age (yrs BP)	Error (±yrs)	95% Probability Range (cal yr BP)	Calibration Curve
Beta-423919	30	Sediment	1420	30	1191-1207 (4.2%)	ShCal13
					1267-1322 (87.8%)	
					1334-1347 (2.8%)	
Beta-423920	55	Sediment	1460	30	1283-1362 (95%)	ShCal13
Beta-405600	65	Sediment	1280	30	1069-1188 (72.3%)	ShCal13
					1211-1265 (22.6%)	
Beta-387867	187	Sediment	1870	30	1702-1834 (95%)	ShCal13
Beta-386290	316	Sediment	2800	30	2776-2944 (95%)	ShCal13
Beta-405601	691	Sediment	3830	30	3998-4036 (4.2%)	ShCal13
					4078-4291 (90.8%)	
Beta-386291	896	Sediment	4570	30	5048-5197 (61%)	ShCal13
					5212-5310 (33.9%)	
Beta-373287	1186	Sediment	5030	40	5606-5767 (72.7%)	ShCal13
					5807-5890 (22.2%)	
Beta-405602	1350	Shell	5290	30	5922-6031 (60.4%)	ShCal13
					6039-6119 (24.8%)	
					6149-6177 (9.7%)	
Beta-386292	1591	Sediment	7560	30	8210-8261 (12.8%)	ShCal13
					8295-8402 (82.1%)	

The basal age of FB-1 is 7560 ^{14}C yr BP (8295-8402 cal yr BP) (Table 5.3). There are ten radiocarbon dates of which nine are bulk sediment sub-samples and one shell. A single inverted age occurs at 65 cm (Table 5.3). The linear sediment accumulation is very similar to that of NL-1, with an average of 0.18 cm/yr (Figure 5.3).

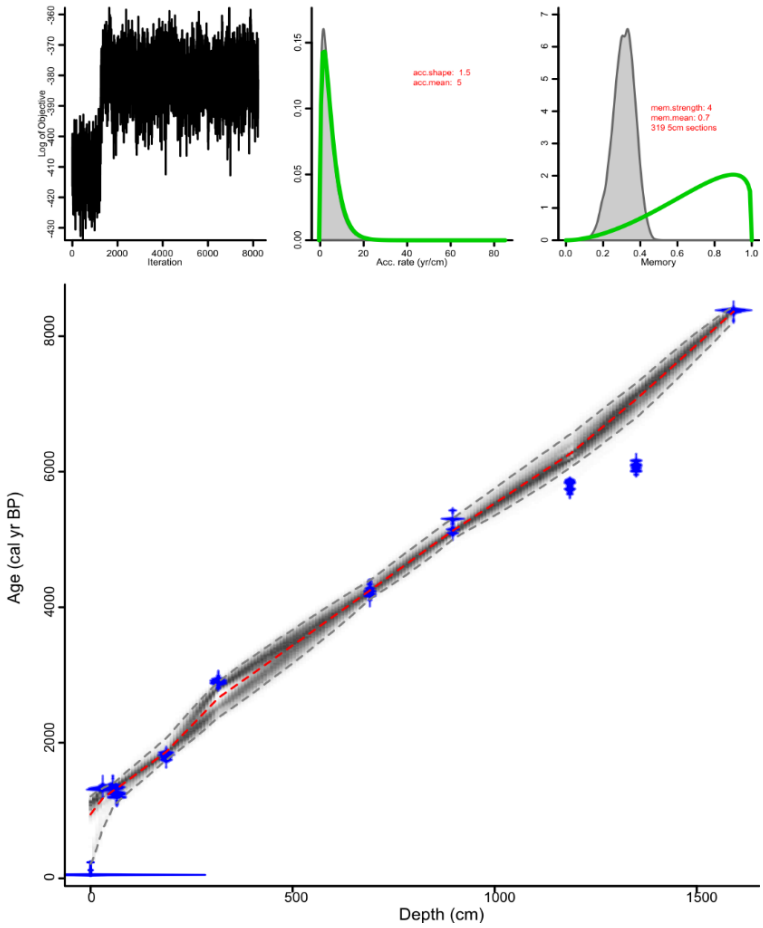

Figure 5.3: Bayesian age-depth model for False Bay.

Table 5.4: Calibrated and uncalibrated age determinations for the Catalina Bay sediment core.

Lab Code	Depth (cm)	Material	^{14}C age (yrs BP)	Error (±yrs)	95% Probability Range (cal yr BP)	Calibration Curve
Beta-405598	50	Sediment	1780	30	1578-1717 (95%)	ShCal13
Beta-387866	100	Sediment	1370	30	1185-1253 (50.8%)	ShCal13
					1257-1298 (44.2%)	
Beta-405599	170	Sediment	3570	30	3698-3898 (95%)	ShCal13
Beta-386286	242	Sediment	6400	40	7176-7219 (9.6%)	ShCal13
					7238-7342 (63.8%)	
					7347-7417 (21.6%)	
Beta-386287	541	Sediment	7610	30	8333-8421 (95%)	ShCal13
Beta-423918	718	Sediment	7500	30	8192-8360 (95%)	ShCal13
Beta-386288	945	Sediment	7910	30	8554-8777 (92.7%)	ShCal13
					8835-8858 (1.8%)	
					8924-8930 (0.4%)	
Beta-386289	1254	Sediment	8460	30	9319-9353 (6.2%)	ShCal13
					9401-9523 (88.8%)	

Of the three cores, Catalina Bay has the oldest basal age of 8460 ^{14}C yr BP (9401-9523 cal yr BP) (Table 5.4). Eight bulk sediment sub-samples were analysed for radiocarbon dating and two age reversals are evident at 100 cm and 718 cm (Table 5.4). The age determination at 100 cm is younger than expected, and is thus designated as an outlier within the age model. . This age reversal (100 cm; 1370 ^{14}C yr BP) is marked by an X (Figure 5.4). The age reversal occurring at 718 cm overlaps with the calibrated error range of the adjacent sample and therefore has not been excluded.

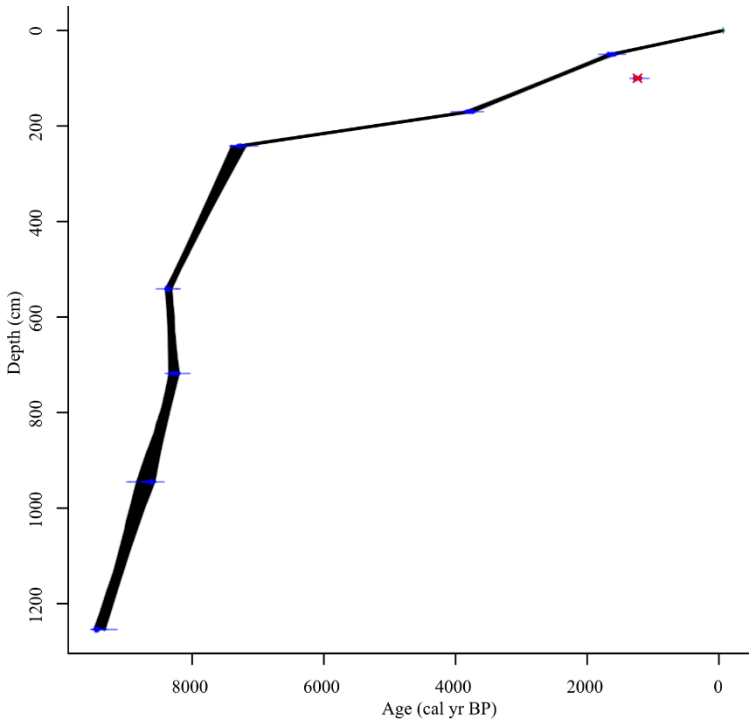

Figure 5.4: Linear interpolation age-depth model of Catalina Bay. The outlier is indicated by an X at 1370 14C yr BP (1185-1253 cal yr BP).

There are two distinct sections with different sediment accumulation rates evident in this core. The top ~250 cm of CB-2 indicates a very slow sediment accumulation rate with an average of 0.04 cm/yr and covers a substantial time period of ±5640 years (Figure 5.4). This is followed by a distinct change toward a more rapid sediment accumulation rate averaging 0.10 cm/yr through to the base of the CB-2 core (Figure 5.4). Although this rapid accumulation happened over a short space of time of only ±2100 years, it accounts for the majority of the length CB-2 (242-1254 cm) (Figure 5.4).

5.5 Ostracoda stratigraphy

From a total of 28 recorded ostracod species identified between the three cores NL-1, FB-1 and CB-2, 23 species are present within North Lake (Appendix B4) and generally persist throughout the length of NL-1 (Figure 5.6; Appendix A2). Amongst the more prominent species are the brackish ostracods *Australoloxoconcha favornamentata* and *Aglaiella westfordensis* (Plate 5.5.2: 20-21; Plate 5.5.4: 35-37), *Sulcostocythere knysnaensis* (Plate 5.5.1: 1-3) a brackish-marine ostracod, and *Cyprideis* spp., a euryhaline ostracod (Plate 5.5.2: 22-24).

False Bay has 17 identified ostracod species and illustrates a higher ostracod presence nearer the younger section of the core (Figure 5.5.1.2; Appendix A3). FB-1 is the only core to present a freshwater species, *Sclerocypris clavularis* (Plate 5.5.3: 33-34). There are 23 identified ostracod species in Catalina Bay (Appendix B4; Appendix A4) with this core displaying a higher ostracod presence in the basal section (Figure 5.5.1.3; Appendix A1). North Lake and Catalina Bay display higher ostracod diversity and abundance in the basal region of the core whereas False Bay illustrates high ostracod concentrations nearer the present day. All cores have greyed out low preservation zones, indicating areas of very low ostracod abundances. False Bay exhibits a single large area of low preservation (Figure 5.3.2), whilst North Lake and Catalina Bay exhibit several smaller low preservation zones (Figures 5.3.1 and 5.3.3).

The five ecological groups of ostracods found within the three cores include: freshwater, brackish, brackish-marine, marine and euryhaline species. However, there are no freshwater species are present within North Lake. Ostracods have been tabulated according to their ecological grouping with the associated family, genus and species names recorded below. The majority of the recorded ostracods are marine species.

Table 5.5: Ostracod taxa classification according to the five associated ecological groupings.

Ecological grouping	Taxon
Freshwater	CYPRIDIDAE: *Sclerocypris clavularis* (Sars, 1924)
Freshwater	CYPRIDIDAE: *Heterocypris salina* (Brady, 1868)
Brackish	LOXOCONCHIDAE: *Australoloxoconcha favornamentata* (Hartmann, 1974)
Brackish	CANDONIDAE: *Aglaiella westfordensis* (Benson and Maddocks, 1964)
Brackish	LEPTOCYTHERIDAE: *Callistocythere eulitoralis* (Hartmann, 1974)
Brackish-marine	CYTHERIDEIDAE: *Sulcostocythere knysnaensis* (Benson and Maddocks, 1964)
Brackish-marine	TRACHYLEBERIDIDAE: *Mutilus dayii* (Benson and Maddocks, 1964)
Brackish-marine	CYTHERURIDAE: *Cytherura* (Sars, 1866)
Brackish-marine	XESTOLEBERIDIDAE: *Xestoleberis* spp.
Marine	LEPTOCYTHERIDAE: *Mediocytherideis (Sylvestra) ochracea* (Brady, 1890)
Marine	TRACHYLEBERIDIDAE: *Mutilus* sp.
Marine	TRACHYLEBERIDIDAE: *Pseudokeijella lepraloides* (Dingle, 1992)
Marine	CYTHERELLIDAE: *Cytherella* sp.
Marine	LOXOCONCHIDAE: *Palmoconcha* sp.
Marine	HEMICYTHERIDAE: *Aurila* sp.
Marine	CANDONIDAE: *Aglaiocypris* aff. *eulitoralis* (Hartmann, 1974)
Marine	CYTHERIDAE: *Cytheridea*, gen. et spp. inc
Marine	HEMICYTHERIDAE: *Neocaudites* spp.
Marine	TRACHYLEBERIDIDAE: *Ruggieria* sp.
Marine	KRITHIDAE: *Krithe* sp.
Marine	LOXOCONCHIDAE: *Bonnyannella* sp.
Marine	LOXOCONCHIDAE: *Loxoconcha* cf. *algicola*
Euryhaline	CYTHERIDEIDAE: *Cyprideis* spp.
Euryhaline	CYTHERIDEIDAE: *Perissocytheridea estuaria* (Benson and Maddocks, 1964)

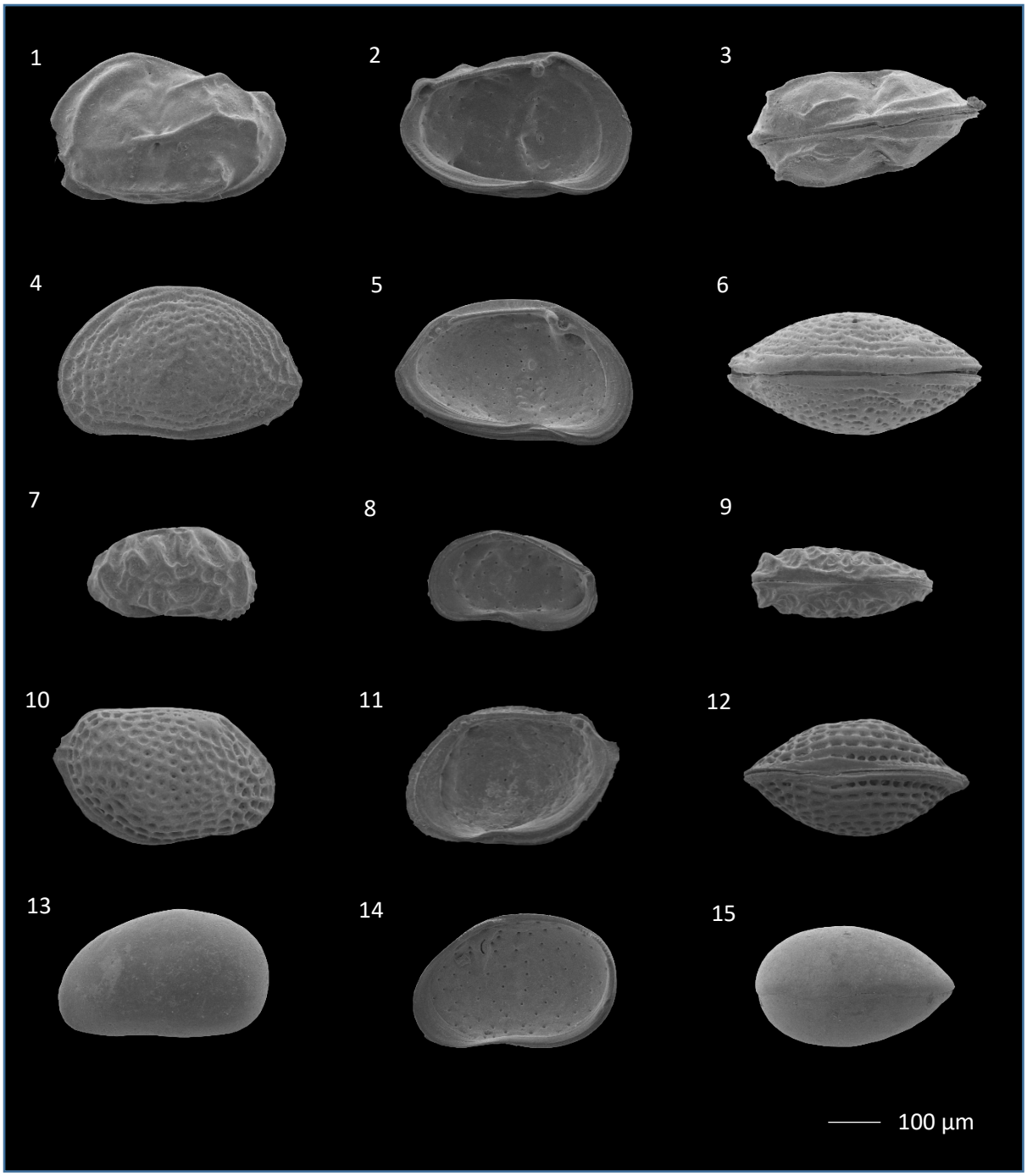

Plate 5.5.1: Sulcostocythere knysnaensis (1-3); *Mutilis dayii* (4-6); *Callistocythere eulitoralis* (7-9); *Loxoconcha* cf. *algicola* (10-12) and *Xestoleberis* spp. (13-15). *S. knysnaensis*: 1. Left valve, external view. 2. Left valve, internal view. 3. Dorsal view. *M. dayii*: 4. Left valve, external view. 5. Left valve, internal view. 6. Dorsal view. *C. eulitoralis*: 7. Right valve, external view. 8. Right valve, internal view. 9. Dorsal view. *L. algicola*: 10. Right valve, external view. 11. Right valve, internal view. 12. Dorsal view. *Xestoleberis* spp.: 13. Left valve, external view. 14. Right valve, internal view. 15. Dorsal view.

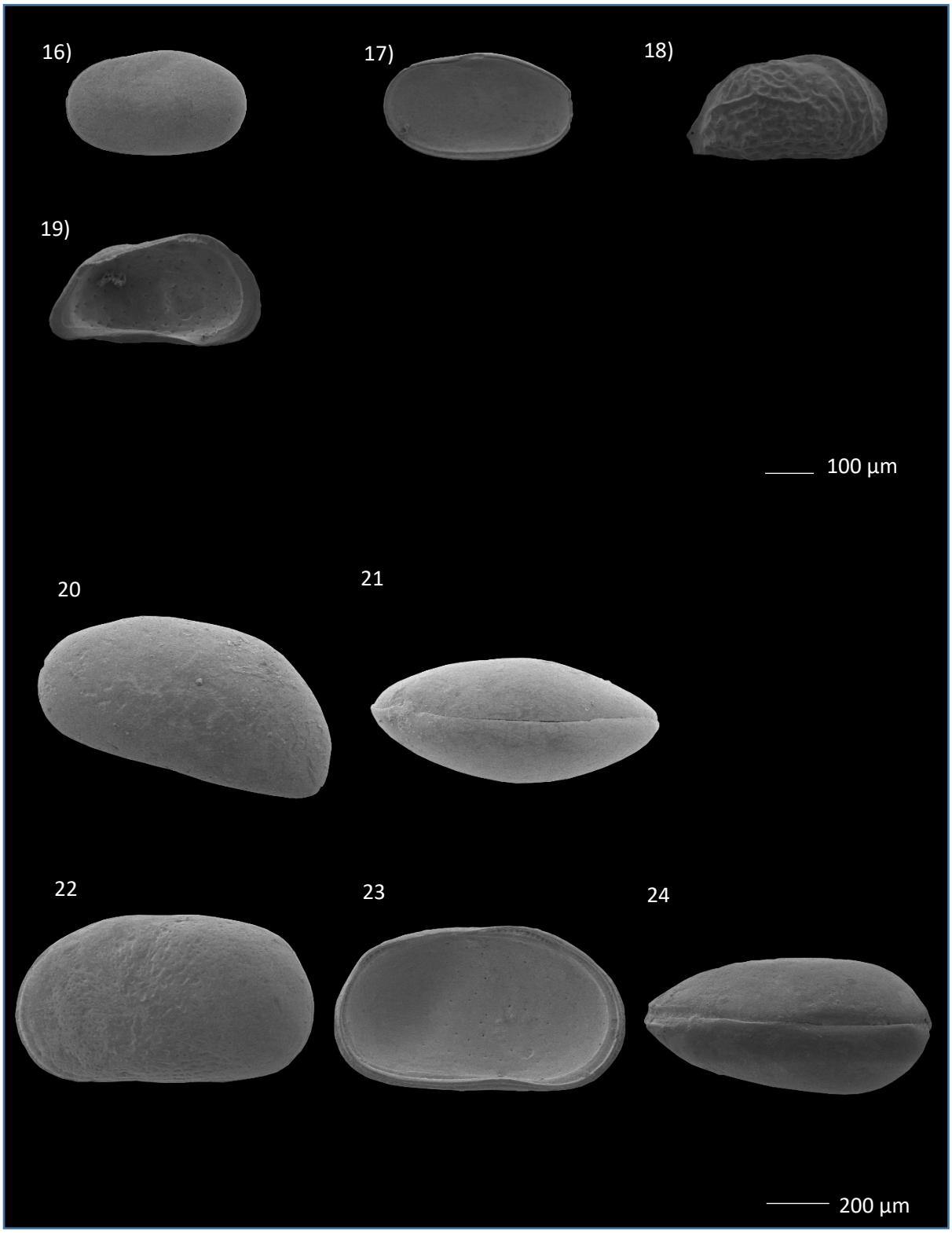

Plate 5.5.2: Cytherella spp. (16-17); *Perissocytheridea estuaria* (18-19); *Aglaiella westfordensis* (20-21) and *Cyprideis* spp. (22-24). *Cytherella* sp.: 16. Right valve, internal view. 17. Left valve, internal view. *P. estuaria*: 18. Right valve, external view. 19. Left valve, internal view. *A. westfordensis*: 20. Left valve, external view. 21. Dorsal view. *Cyprideis* spp.: 22. Right valve, external view. 23. Left valve, internal view. 24. Dorsal view.

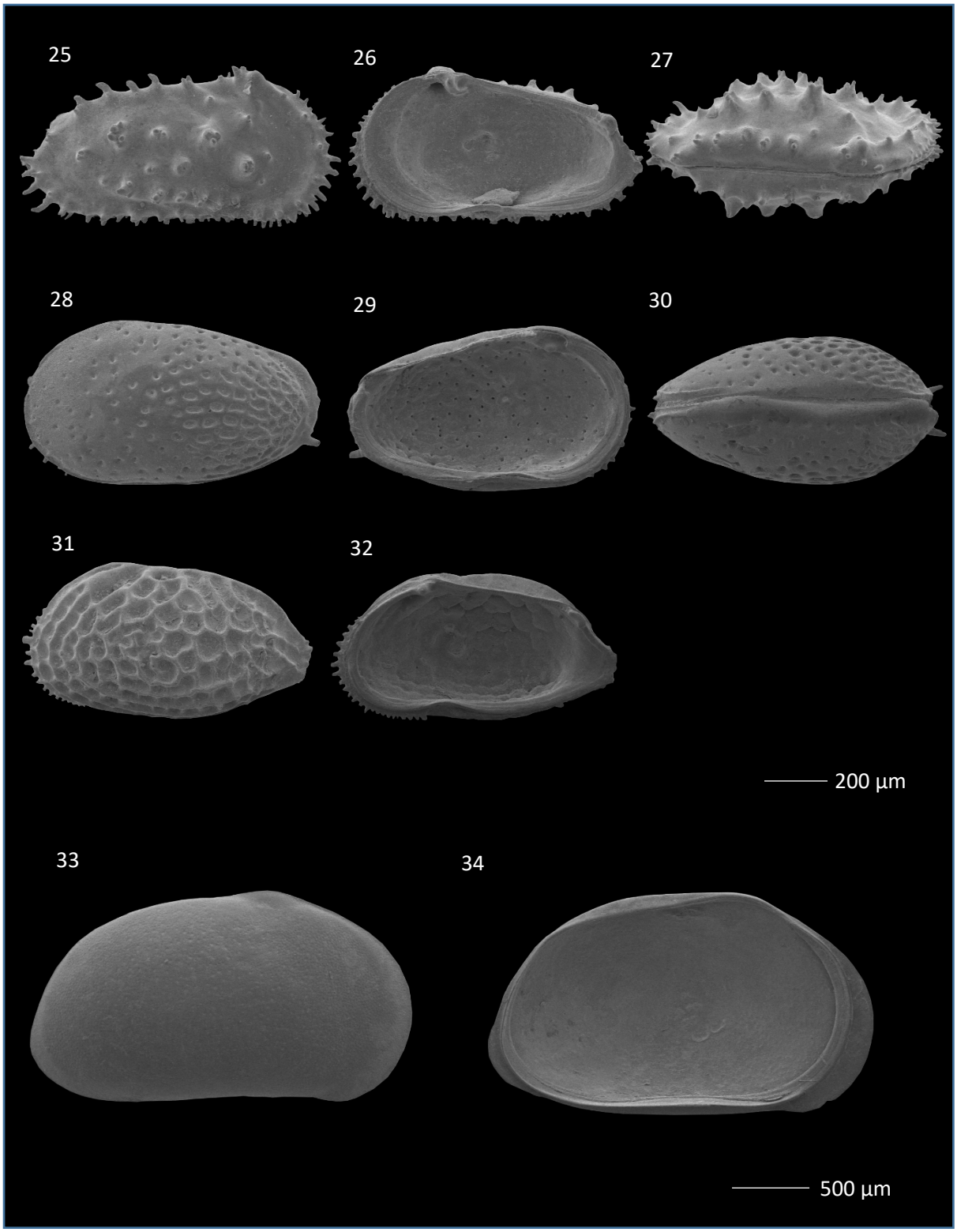

Plate 5.5.3: Neocaudites spp. (25-27), *Ruggieria* sp. (28-30); *Pseudokeijella lepraloides* (31-32) and *Sclerocypris clavularis* (33-34). *Neocaudites* spp.: 25. Right valve, external view. 26. Right valve, internal view. 27. Oblique dorsal view. *Ruggieria* sp.: 28, Left valve, external view. 29. Left valve, internal view. 30. Dorsal view. *P. lepraloides*: 31. Left valve, external view. 32. Right valve, internal view. *S. clavulans*: 33. Right valve, external view. 34. Left valve, internal view.

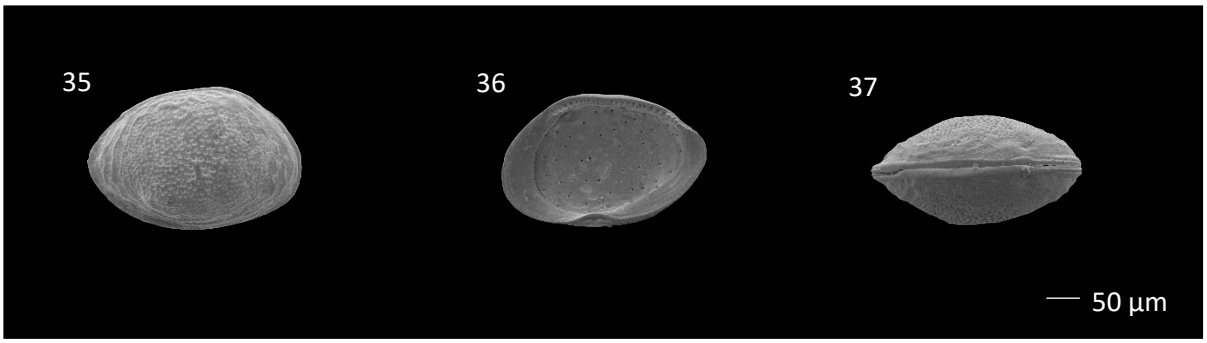

Plate 5.5.4: Australoloxoconcha favornamentata (35-37). *A. favornamentata*: 35. Right valve, external view. 36. Right valve, internal view. 37. Dorsal view.

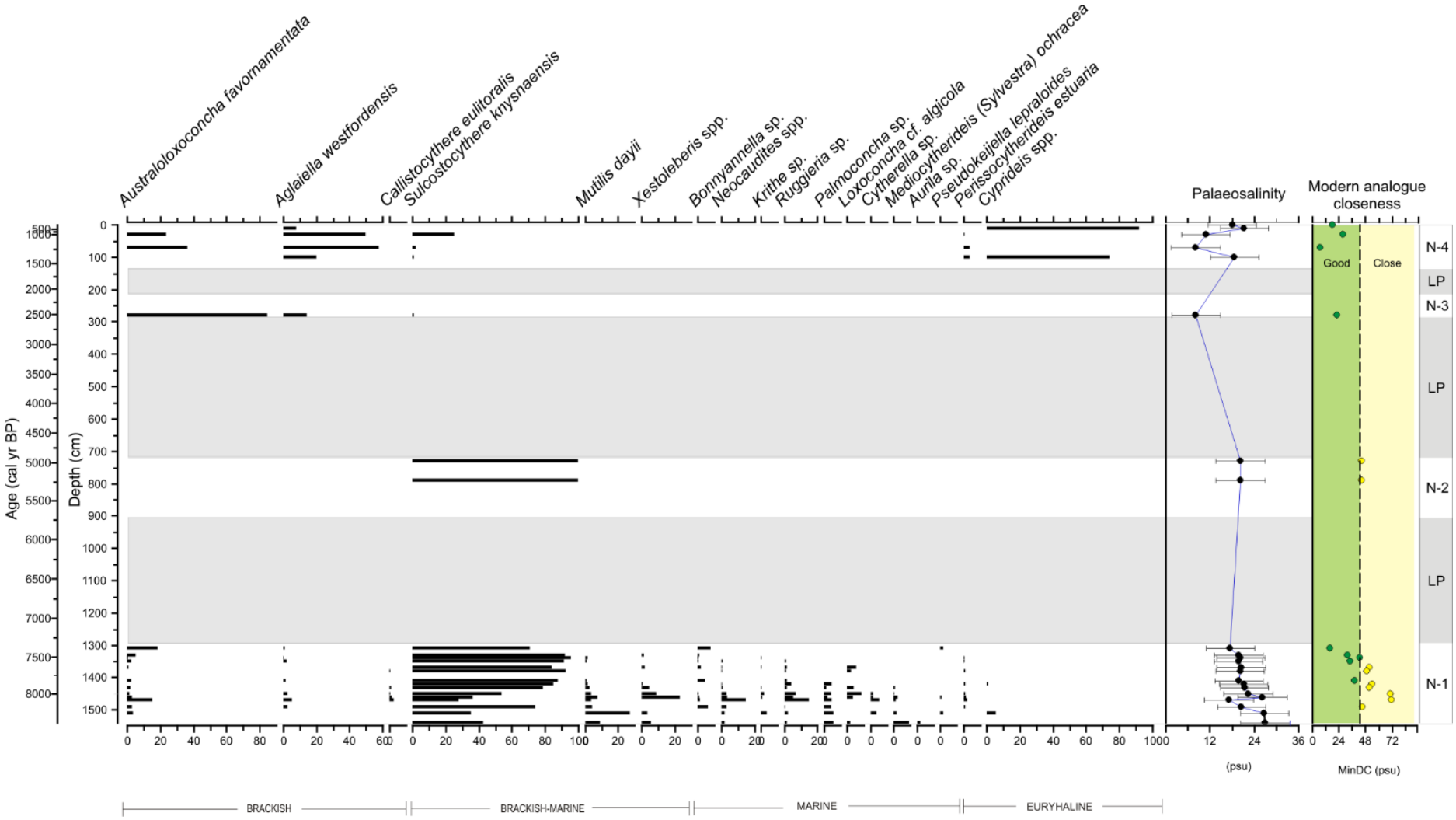

Figure 5.6: Downcore stratigraphic plot of North Lake ostracods plotted alongside palaeosalinity and the modern-analogue closeness.

Table 5.6.1.1: Performance of Weighted Average Partial Least Squares (WAPLS) transfer function for North Lake.

Model Performance				**Bootstrapping**		
Code	RMSE	r^2	Maximum bias	r^2_{boot}	Maximum $bias_{boot}$	RMSEP
WAPLS	5.29	0.71	6.57	0.56	8.58	6.86

Table 5.6.1.2: Results from the transfer function applied to ostracod fossil data for North Lake.

Depth (cm)	Modern analogue fit	Modelled age (cal yr BP)	Modelled error (yr)	Indicative meaning (psu)	Error (psu)	Salinity (psu)
0	Good	0.00	0.00	17.95	0.00	18
10	Poor	399.40	768.40	-	-	-
30	Good	1005.60	176.00	27.70	6.66	10.89
70	Good	1215.70	250.40	7.37	6.63	8.10
100	Poor	1376.20	268.20	-	-	-
280	Good	2518.20	359.80	22.35	6.70	8.19
730	Close	4966.30	402.50	44.4	7.42	20.24
790	Close	5245.30	370.90	44.4	7.42	20.24
1310	Good	7387.40	429.00	15.68	7.11	17.50
1330	Good	7475.30	420.70	31.55	7.31	19.82
1340	Good	7517.80	411.90	43.10	7.37	20.32
1350	Good	7561.00	404.70	34.21	7.32	19.71
1370	Close	7647.10	387.40	51.42	7.36	20.52
1380	Close	7690.40	380.20	49.28	7.41	20.16
1410	Good	7821.00	361.50	38.05	7.32	19.88
1420	Close	7864.00	351.70	54.28	7.29	21.11
1430	Close	7907.20	340.50	51.93	7.25	21.38
1450	Close	7994.20	321.70	70.77	7.06	22.45
1460	Poor	8037.00	313.90	-	-	-
1470	Close	8080.60	303.70	71.33	6.85	17.14
1490	Close	8168.00	295.20	45.49	7.20	20.56
1510	Poor	8257.10	330.40	-	-	-
1540	Poor	8390.40	396.80	-	-	-

5.6 North Lake (NL-1)

North Lake has seven CONISS derived zones, three of which are designated as low preservation zones because of the low ostracod count. Low preservation zones are located at ~7350-5750 cal yr BP (1300-900 cm), ~4900-2550 cal yr BP (720-290 cm) and at ~2100-1650 cal yr BP (220-140 cm).

Zone N-1 (~8180-7350 cal yr BP; 1570-1300 cm)

Ostracod species diversity and abundance appear highest in N-1. Marine species are concentrated within this zone and illustrate a higher diversity over the other ecological groupings. In terms of species abundance, *Sulcostocythere knysnaensis*, a brackish-marine species, is the most dominant ostracod. As evident in the marine taxa, *Callistocythere eulitoralis* (Plate 5.5.1: 7-9) a brackish species, and *Mutilis dayii* and *Xestoleberis* spp. (Plate 5.5.1: 4-6; Plate 5.5.1: 12-15), brackish-marine species, only appear within N-1. Species richness is recorded at 18, of which ten are marine taxa.

Zone N-2 (~5750-4900 cal yr BP; 900-720 cm)

N-2 is dominated by *Sulcostocythere knysnaensis*, a brackish-marine ostracod species. There are no other taxa represented in this zone.

Zone N-3 (~2550-2100 cal yr BP; 290-220 cm)

This is a small zone defined by the presence of ostracods in a single sample at ~2500 cal yr BP (250 cm). *Australoloxoconcha favornamentata* and *Aglaiella westfordensis*, brackish ostracods, are the most dominant ecological grouping. *Sulcostocythere knysnaensis*, a brackish-marine species, is noted in low abundance.

Zone N-4 (~1650-0 cal yr BP; 140-0 cm)

Species diversity and abundance appears to increase in N-4 with brackish species being the most dominant ecological grouping. *Cyprideis* spp., a euryhaline ostracod, is also prominent in this zone. N-4 is the second most species rich zone with 5 recorded species.

North Lake core summary

Overall, brackish-marine and marine species appear to be more concentrated toward the base of the core from ~8180-7350 cal yr BP (~1570-1300 cm). Brackish and euryhaline species appear in higher abundances from ~2500 cal yr BP to the present day (~275-0 cm). *Sulcostocythere knysnaensis*, a brackish-marine ostracod, occurs throughout the length of the core and is the only species to be present in every zone (with the exception of low preservation zones). Marine ostracods illustrate the highest species diversity overall, however, the relative abundance of *Sulcostocythere knysnaensis* makes brackish-marine ostracods the most dominant ecological grouping within North Lake (63.4%, Appendix B1).

5.6.2 Palaeosalinity

Values produced by the WAPLS transfer function have been used to plot downcore palaeosalinity (Figure 5.6). Palaeosalinity in the basal section of North Lake ~8180-7300 cal yr BP (~1570-1300 cm) illustrates elevated levels reaching up to 27 psu (Figure 5.6). From ~7300-4900 cal yr BP (~1300-720 cm) salinity remains fairly stable around 20 psu until it decreases to 10 psu at 2500 cal yr BP (290 cm; Figure 5.6). A sharp increase in salinity is noted by the peak at ~1500 cal yr BP (100 cm) reaching 20 psu before dropping back down to 10 psu at ~1250 cal yr BP (180 cm; Figure 5.6). Salinity continues to increase, peaking at 22 psu at ~500 cal yr BP (25 cm; Figure 5.6). Overall, salinities appear to be within the range of ~10-20 psu for the majority of the length of the core with elevated salinity levels evident in the basal section. The modern analogue closeness (Figure 5.6), produced through the application of the MAT to the transfer function to determine the modern analogue fit (Table 5.6.1.2), has been plotted alongside palaeosalinity. The MinDC are plotted relative to the threshold for a 'close' modern analogue (Figure 5.6).

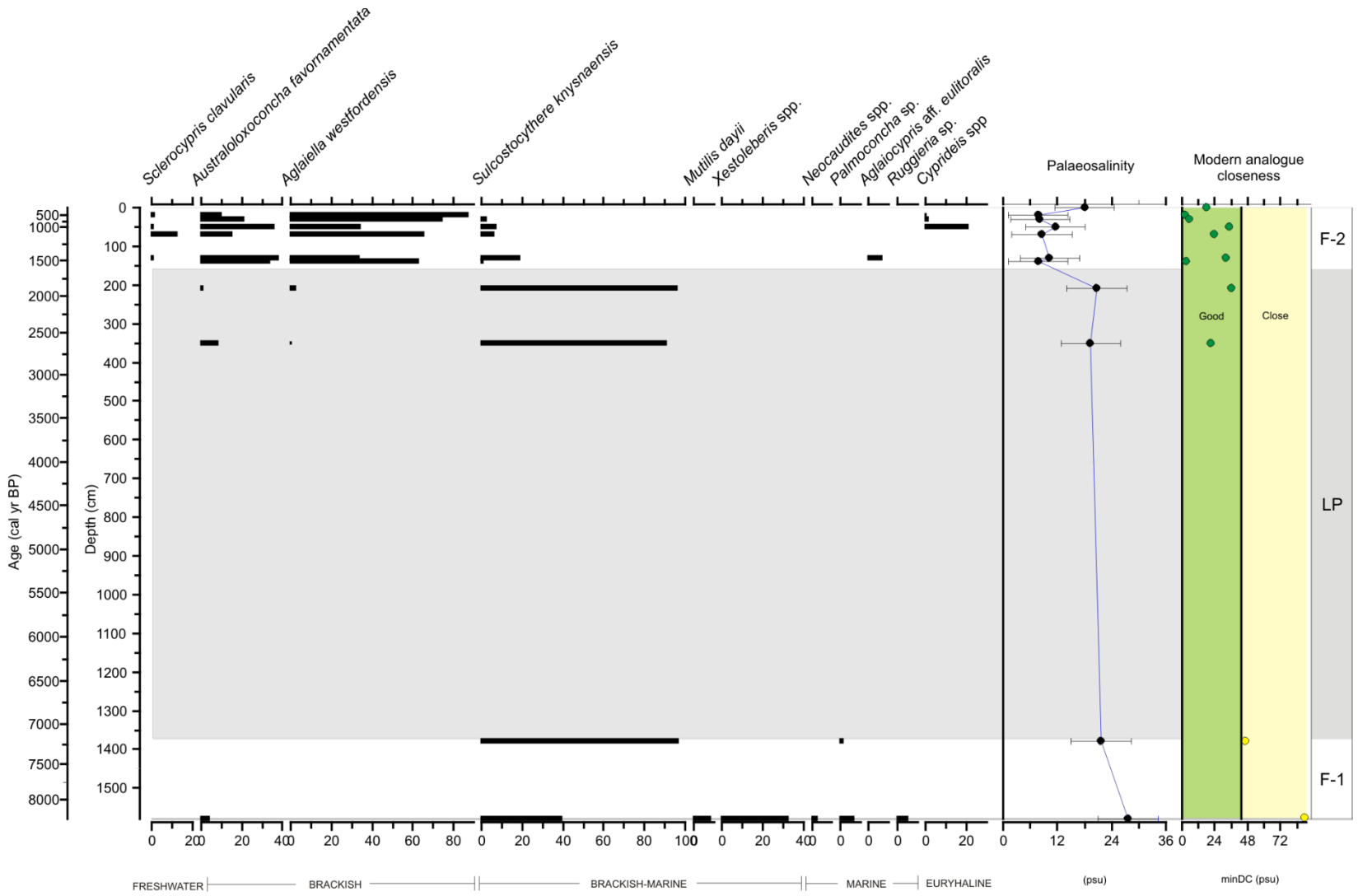

Figure 5.7: Downcore stratigraphic plot of False Bay ostracods plotted alongside palaeosalinity and the modern-analogue closeness.

Table 5.7.1.1: Performance of Weighted Average Partial Least Squares (WAPLS) transfer function for False Bay.

Model Performance				**Bootstrapping**		
Code	RMSE	r^2	Maximum bias	r^2_{boot}	Maximum $bias_{boot}$	RMSEP
WAPLS	5.29	0.71	6.57	0.56	7.91	6.83

Table 5.7.1.2: Results from the transfer function applied to the ostracod fossil data for False Bay.

Depth (cm)	**Modern analogue fit**	**Modelled age (cal yr BP)**	**Modelled error (yr)**	**Indicative meaning (psu)**	**Error (psu)**	**Salinity (psu)**
0	Good	0.00	0.00	17.95	0.00	18.00
20	Good	487.60	582.30	2.49	6.65	7.77
30	Good	766.50	507.80	5.82	6.64	8.20
50	Good	1006.00	349.80	34.59	6.64	11.63
70	Good	1153.50	249.80	23.42	6.64	8.59
130	Good	1470.60	266.90	32.00	6.67	10.35
140	Good	1523.90	262.80	3.45	6.65	7.80
210	Good	1901.90	272.90	36.14	7.28	20.73
350	Good	2642.50	479.10	21.26	7.18	19.37
1380	Close	7199.10	503.80	46.44	7.37	21.67
1580	Close	8261.30	280.00	87.57	6.84	27.64

5.7 False Bay (FB-1)

False Bay has three CONISS derived zones, with one designated as a low preservation zone because of the low ostracod count. This is a large low preservation zone located from ~7200-1650 cal yr BP (1375-160 cm).

Zone F-1 (~8400-7200 cal yr BP; 1580-1375 cm)

Brackish-marine ostracods are the most dominant ecological grouping for F-1, represented by *Sulcostocythere knysnaensis*, *Xestoleberis* spp. and *Mutilis dayii*. Although evident in fairly low abundances, three marine species are noted within F-1; *Neocaudites* spp. (Plate 5.5.3: 25-

27), *Palmoconcha* sp. and *Ruggieria* sp. (Plate 5.5.3: 28-30). *Australoloxoconcha favornamentata*, a brackish species, is evident in a low abundance bringing the total to seven recorded species within F-1

Low preservation zone (~7200-1650 cal yr BP; 1375-160 cm)

This is a large low preservation zone whereby three species are noted from two samples at ~2650 and 1900 cal yr BP (350 and 210 cm). *Sulcostocythere knysnaensis*, a brackish-marine ostracod, is the most dominant species followed by *Australoloxoconcha favornamentata* and *Aglaiella westfordensis*, brackish ostracods, evident in low abundances.

Zone F-2 (~1650-0 cal yr BP; 160-0 cm)

F-2 has the highest recorded ostracod abundances and is dominated by *Aglaiella westfordensis* and *Australoloxoconcha favornamentata*, both falling under brackish taxa. *Cyprideis* spp, a euryhaline ostracod, is also quite prominent followed by *Sulcostocythere knysnaensis*, a brackish-marine species. *Aglaiocypris* aff. *eulitoralis*, a marine ostracod is noted in this zone. *Sclerocypris clavularis*, a freshwater ostracod is evident for the first time in zone F-2 and is the only zone within False Bay that this species occurs. There are six recorded species in F-2.

False Bay core summary

The basal section of False Bay ~8400-7200 cal yr BP (~1580-1375 cm) has a higher presence of brackish-marine and marine species. *Sulcostocythere knysnaensis*, a brackish-marine ostracod¸ is more persistent within False Bay, as evidenced in North Lake. From ~1600 cal yr BP to the present (~150-0 cm), a move toward freshwater and brackish water species is notable. False Bay is the only core to contain a significant abundance of freshwater ostracods. Overall, brackish water species, more specifically *Aglaiella westfordensis*, are the dominant ecological group accounting for 59.3% of the relative abundance (Appendix B2) within False Bay.

5.7.2 Palaeosalinity

Elevated salinity levels are evident at the base of False Bay at 8400 cal yr BP (~1580 cm), peaking at ~28 psu (Figure 5.7). Salinity decreases to 20 psu at 7200 cal yr BP (1370 cm)

where it remains relatively stable at ~20 psu before a slight increase to 24 psu at 1800 cal yr BP (220 cm; Figure 5.7). A decrease is evident from 1500-500 cal yr BP (140-20 cm) where salinities fluctuate between 8 and 12 psu (Figure 5.7). Two small peaks in salinity are illustrated at ~1500 and 1000 cal yr BP (140 and 50 cm) (Figure 5.7). The most recent 500 cal yr BP have seen a rise in salinity to 18 psu (Figure 5.7). Overall, higher salinity levels are noted from the basal section of the core persisting through to 1800 cal yr BP (1580-220 cm), when salinity decreases until 500 cal yr BP (20 cm). The modern analogue closeness (Figure 5.7) reflects a good and close fit to the modern analogues (Table 5.7.1.2). The MinDC is plotted relative to the threshold for a 'close' modern analogue (Figure 5.7).

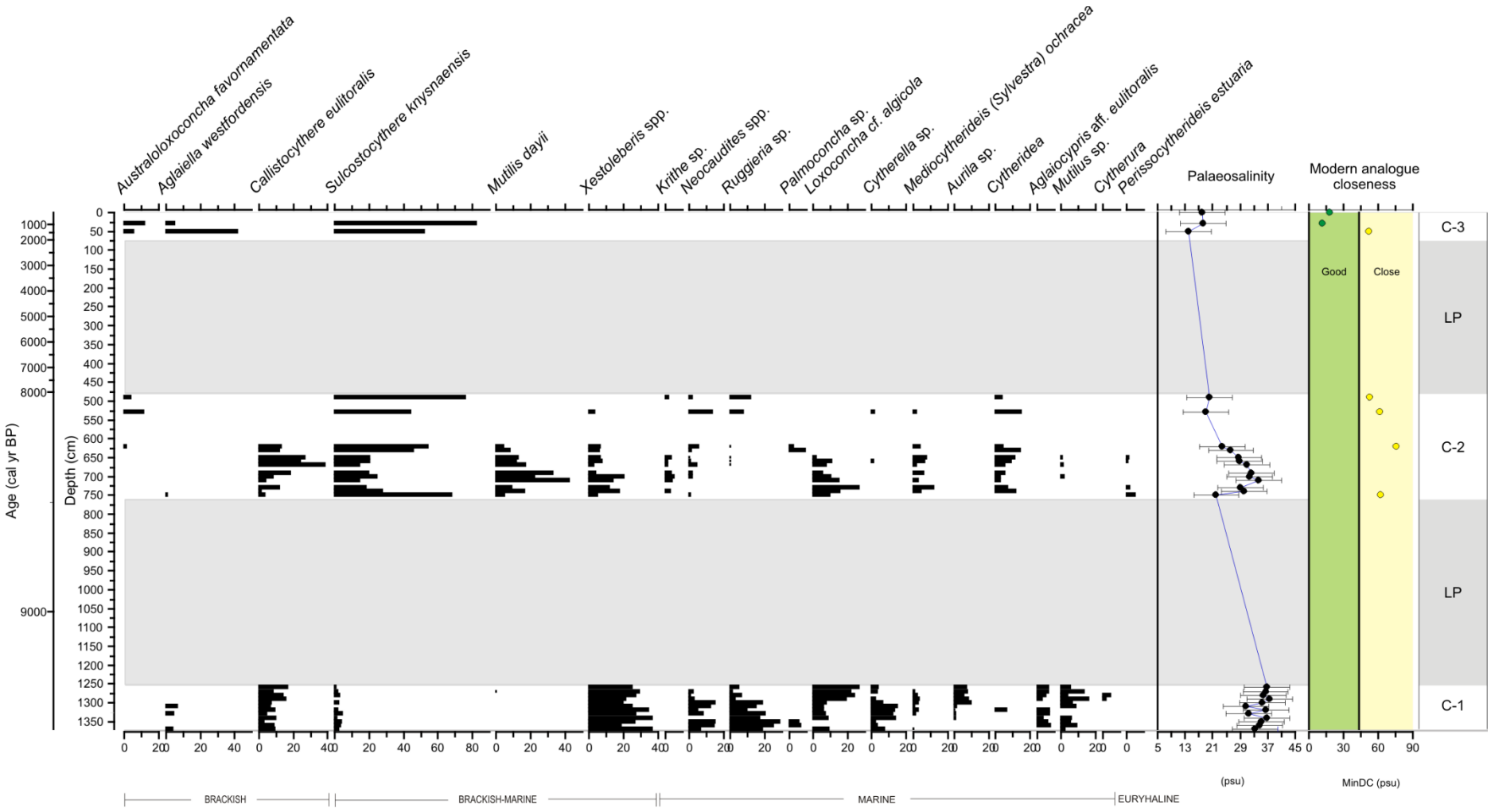

Figure 5.8: Downcore stratigraphic plot of Catalina Bay ostracods plotted alongside palaeosalinity and the modern-analogue closeness.

Table 5.8.1.1: Performance of Weighted Average Partial Least Squares (WAPLS) transfer function for Catalina Bay.

Model Performance				**Bootstrapping**		
Code	RMSE	r^2	Maximum bias	r^2_{boot}	Maximum $bias_{boot}$	RMSEP
WAPLS	4.94	0.75	6.00	0.59	7.70	6.62

Table 5.8.1.2: Results from the transfer function applied to the ostracod fossil data for Catalina Bay.

Depth (cm)	**Modern analogue fit**	**Modelled age (cal yr BP)**	**Modelled error (yr)**	**Indicative meaning (psu)**	**Error (psu)**	**Salinity (psu)**
0	Good	0.00	0.00	17.95	0.00	18.00
30	Good	963.00	84.00	12.13	7.09	18.25
50	Close	1648.00	141.00	51.74	6.65	13.97
490	Close	8196.00	89.00	52.95	7.31	20.01
530	Close	8341.00	87.00	61.54	6.96	19.01
620	Close	8334.00	100.00	75.92	7.05	23.86
630	Poor	8328.00	104.00	-	-	-
650	Poor	8317.00	116.00	-	-	-
660	Poor	8311.00	123.00	-	-	-
670	Poor	8305.00	129.00	-	-	-
690	Poor	8293.00	145.00	-	-	-
700	Poor	8287.00	152.00	-	-	-
710	Poor	8281.00	161.00	-	-	-
730	Poor	8297.00	162.00	-	-	-
740	Poor	8315.00	160.00	-	-	-
750	Close	8332.00	155.00	62.18	7.06	22.07
1260	Poor	9438.00	190.00	-	-	-

5.8 Catalina Bay (CB-2)

Catalina Bay has five CONISS derived zones, two of which are designated as low preservation zones because of the low ostracod count. Low preservation zones are located at ~7400-8500 cal yr BP (1250-760 cm) and ~8000-2000 cal yr BP (480-75 cm).

Zone C-1 (~9520-9400 cal yr BP; 1360-1250 cm)

C-1 has a high diversity and ostracod abundance with brackish, brackish-marine and marine taxa occurring within this zone. Marine species indicate the highest species diversity with 11 recorded species and are the most dominant in terms of species abundance too. *Xestoleberis* spp., a brackish-marine species, is the second most abundant ostracod. *Callistocythere eulitoralis* and *Aglaiella westfordensis*, brackish taxa, appear within C-1. Species richness is high within this zone, reaching 16 recorded species.

Zone C-2 (~8500-8000 cal yr BP; 760-480 cm)

C-2 is similar to C-1 as it has a high ostracod diversity and relatively high ostracod abundances. Marine taxa illustrate the higher species diversity with nine recorded species, whilst *Sulcostocythere knysnaensis*, a brackish-marine ostracod, is more abundant within this zone. *Callistocythere eulitoralis*, a brackish species, is quite a prominent in C-2. *Perissocytheridea estuaria* (Plate 5.5.2: 18-19), a euryhaline ostracod, is present within C-2 and is the only zone where this species occurs. There are 16 recorded species in C-2. In terms of age, C-2 has been found to be between 8500-8000 cal yr BP which would indicate that it is within what would be classified as the basal age range of the core.

Zone C-3 (~2000-0 cal yr BP; 75-0 cm)

The most recent section of the core, C-3, is dominated by the brackish-marine species, *Sulcostocythere knysnaensis*. Brackish species however, illustrate a higher diversity marked by the presence of *Australoloxoconcha favornamentata* and *Aglaiella westfordensis*.

Catalina Bay core summary

Overall, there are two distinct zones (C1 and C2; ~9520-9400 and ~8500-8000 cal yr BP) that are rich in ostracod species and abundance. Species composition changes from a more marine dominated assemblage at the base of the core to a more brackish and brackish-marine dominated assemblage from ~1500 cal yr BP to the present day. As evidenced in North Lake and False Bay, *Sulcostocythere knysnaensis* appears throughout the majority of the core, with the exception of low preservation zones. Marine ostracods are the most dominant ecological group within Catalina Bay and account for 47% of the relative abundance, followed by brackish marine species accounting for 39.9% of the relative abundance (Appendix B3).

5.8.2 Palaeosalinity

At the very basal section of the Catalina Bay core ~9500 cal yr BP (1360-1250 cm) salinity peaks reach 37 psu, the highest salinity level recorded within the core (Figure 5.8). Salinity remains high from 8200-8500 cal yr BP (720-625 cm) with levels reaching 34 psu (Figure 5.8). Salinities steadily decrease from 18 to 21 psu at ~8000 cal yr BP (~500 cm), to 14 psu at 1500 cal yr BP (50 cm). A small peak in salinity occurs at 1000 cal yr BP (25 cm), marking 19 psu (Figure 5.8). Catalina Bay illustrates much higher salinity levels over North Lake and False Bay. The modern analogue closeness reveals that the fossil data recorded in Catalina do have some close modern analogues within the training set data (Table 5.8.1.2). The MinDC is plotted relative to the threshold for a ‘close’ modern analogue (Figure 5.8).

5.9 Statistical analyses

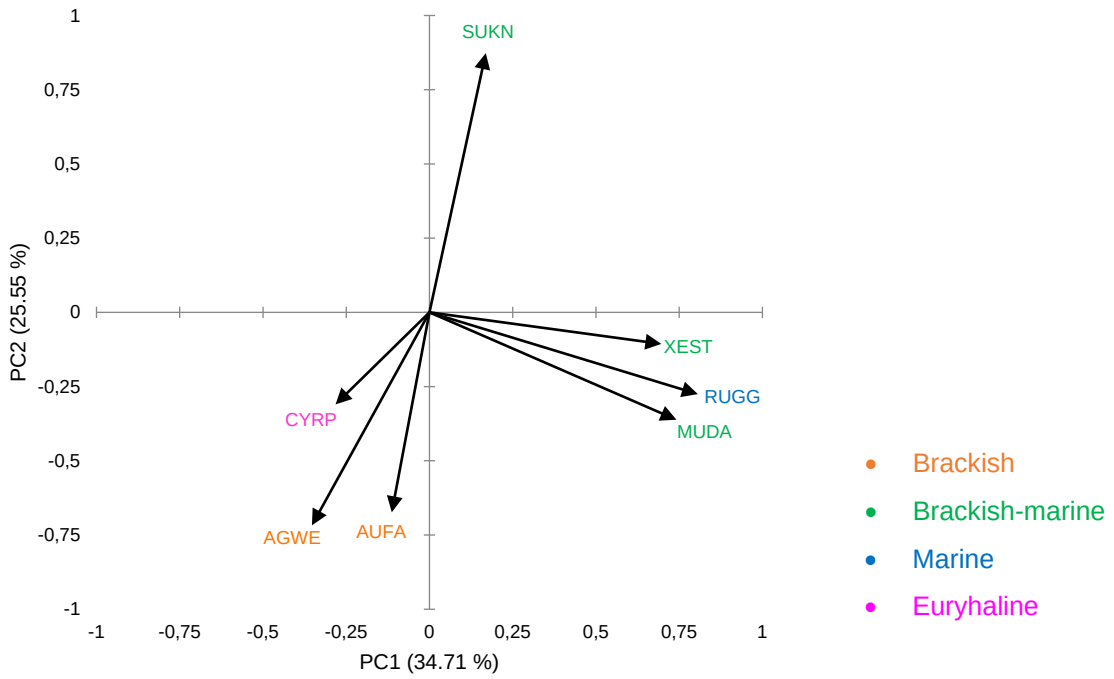

Figure 5.9.1: Principal component analysis for Ostracoda found in North Lake. Taxon codes were used to represent the taxa present; AGWE- *Aglaiella westfordensis*, AUFA- *Australoloxoconcha favornamentata*, SUKN- *Sulcostocythere knysnaensis*, XEST- *Xestoleberis* spp., MUDA- *Mutilus dayii*, RUGG- *Ruggieria* sp., CYPR- *Cyprideis* spp.

Table 5.9.1: Summary of principal component analysis results from North Lake.

Axis	**1**	**2**	**3**	**4**
Eigenvalue	2.78	2.044	1.24	0.76
Variability (%)	34.71	25.55	15.53	9.47

A principal component analysis was performed on 49 samples and seven associated ostracod taxa from the North Lake basin in Lake St Lucia. The first axis (PC1) has a high load of marine and brackish-marine taxa and explains 35% of the variance. The second axis (PC2) explains 26% of the variance. These principal components explain significant percentages of the variance.

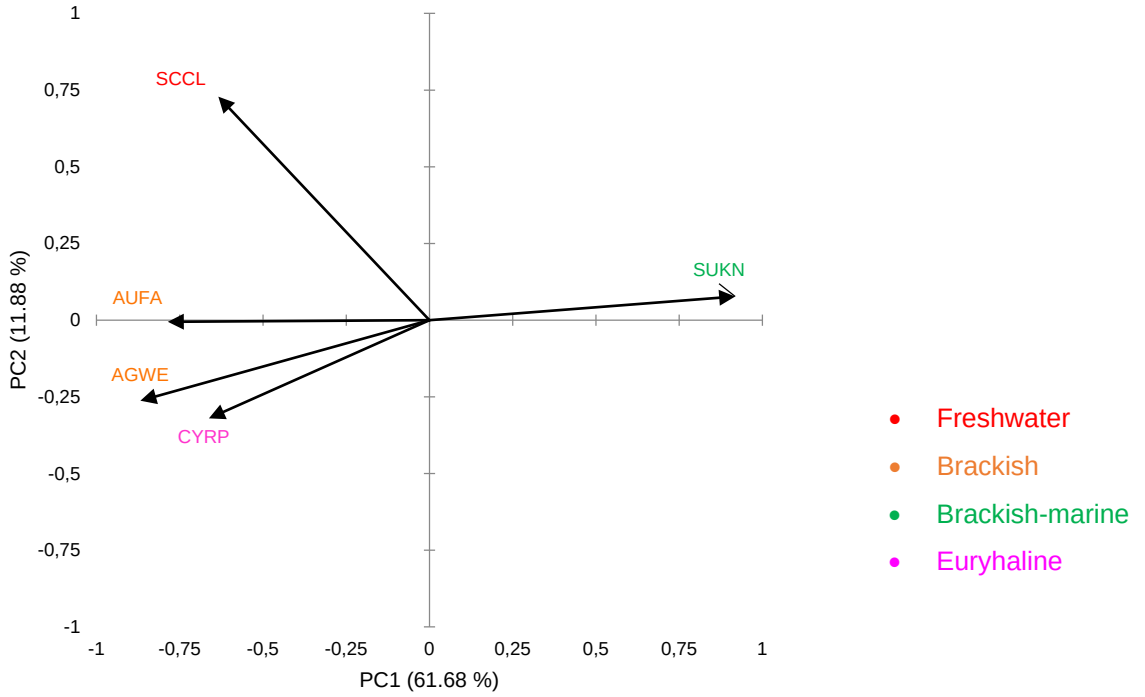

Figure 5.9.2: Principal component analysis for Ostracoda found in False Bay. Taxon codes were used to represent the taxa present; SCCL- *Sclerocypris clavularis*, AUFA- *Australoloxoconcha favornamentata*, AGWE- *Aglaiella westfordensis*, SUKN- *Sulcostocythere knysnaensis*, CYPR- *Cyprideis* spp.

Table 5.9.2: Summary of principal component analysis results from False Bay.

Axis	**1**	**2**	**3**	**4**
Eigenvalue	3.70	0.71	0.63	0.48
Variability (%)	61.68	11.88	10.53	8.07

A principal component analysis was performed using 55 samples and five associated ostracod taxa from Lake St Lucia's False Bay basin. PC1 explains 62% of the variance and PC2 explains 12% of the variance. PC2 illustrates a high loading of freshwater and brackish species.

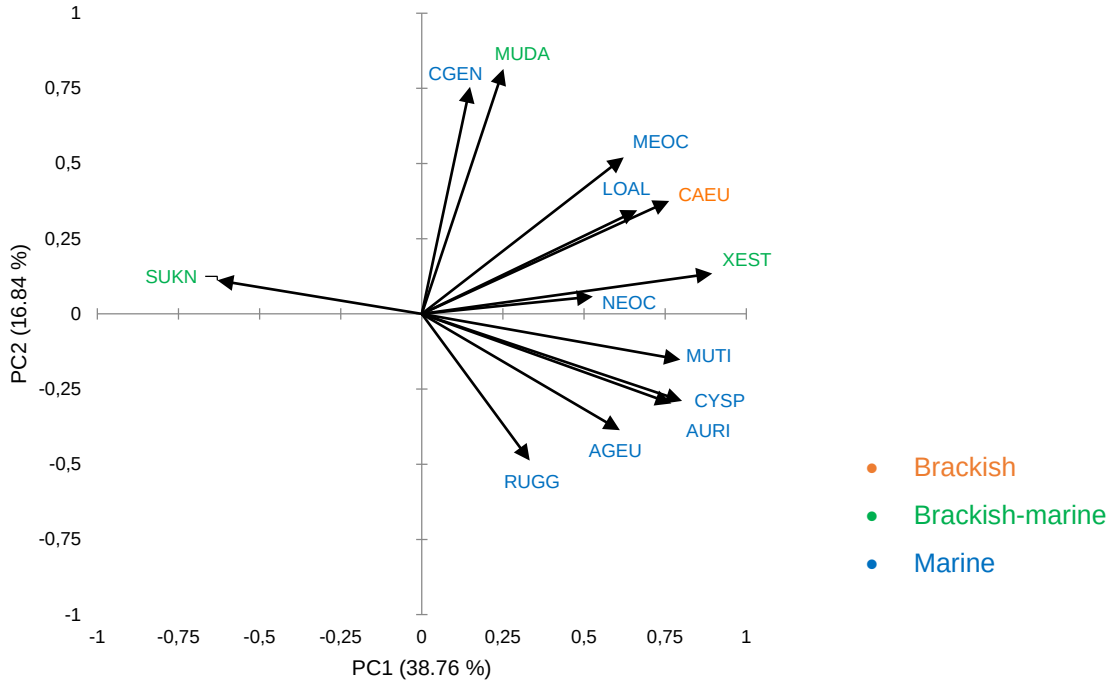

Figure 5.9.3: Principal component analysis for Ostracoda found in Catalina Bay. Taxon codes were used to represent the taxa present; CAEU- *Callistocythere eulitoralis*, MUDA- *Mutilus dayii*, XEST- *Xestoleberis* spp, CGEN- *Cytheridea*, gen. et sp. inc, MEOC-*Mediocytherideis (Sylvestra) ochracea*, LOAL- *Loxoconcha* cf. *algicola*, NEOC- *Neocaudites* spp., MUTI- *Mutilus* sp., CYSP- *Cytherella* sp., AURI- *Aurila* sp, AGEU- *Aglaiocypris* aff. *eulitoralis*, RUGG- *Ruggieria* sp.

Table 5.9.3: Summary of principal component analysis results from Catalina Bay.

Axis	**1**	**2**	**3**	**4**
Eigenvalue	5.81	2.53	1.33	1.03
Variability (%)	38.76	16.84	8.89	6.92

A principal component analysis was performed on 64 samples and 14 associated ostracod taxa from Catalina Bay in Lake St Lucia. The first axis explains 39% of the variance and the second axis explains 17% of the variance. PC1 depicts a high loading of marine taxa with a wide scattering.

Overall, North Lake and Catalina Bay illustrate higher loadings of marine and brackish-marine taxa, with a heavier marine dominance being noted in Catalina Bay. False Bay illustrates minimum marine influence and a higher loading of freshwater and brackish species.

CHAPTER SIX

DISCUSSION

This chapter will review the age models produced for the three St Lucia sediment cores and possible explanations for the age reversals evident. Downcore ostracod stratigraphy will then be examined and with the aid of the principal component analysis results, factors affecting ostracods will be discussed. Reconstructed palaeosalinities will be used to provide an overview of how environmental conditions have changed over time. Results will be compared with other palaeoenvironmental data sources, notably seismics, geochemistry and biological proxies such as diatoms and foraminifera. Finally, implications of the results will be discussed in relation to present day ecology and management.

6.1 Age models

The cores retrieved from North Lake, False Bay and Catalina Bay are dated between 8000-9500 cal yr BP and are thus all of Holocene age. NL-1 and FB-1 have similar sediment accumulation rates and hence produce comparable, linear age-depth profiles. Both of these cores contain age reversals, two within NL-1 and one in FB-1. As Lake St Lucia is home to a vast array of macrobenthos (evidenced by Cyrus *et al*., 2011; Nel *et al*., 2013; Perissinotto *et al*., 2014 and Jones *et al*., 2016 for example) and larger mammals such as hippopotami, it is plausible that these age reversals were caused through bioturbation resulting in sediment reworking. Furthermore, St Lucia is a shallow lacustrine system, leaving it vulnerable to sediment mixing and reworking because of wind-driven waves (Zikhali *et al*., 2014).

Catalina Bay exhibits two distinct sediment accumulation rates and hence depicts a differing age-depth model to those of North Lake and False Bay. The basal region of the core through to ~250 cm has a rapid sediment accumulation rate and hence depicts a steep profile, before levelling out into a more gentle age-depth profile from ~250 cm to the present day, owing to the decline in the sediment accumulation rate. An age reversal at 100 cm has been designated as an outlier as this younger material is likely a result of sediment reworking through bioturbation or wind-driven currents (Benallack *et al*., 2016). A second reversal is evident at 718 cm and has not been excluded as it overlaps with the calibrated error range of the adjacent sample. At a depth of 170 cm, CB-2 illustrates an age of 3570 ^{14}C yr BP (3698-3898 cal yr BP)

and at 242 cm, the age skips to 6400 ^{14}C yr BP (7238-7342 cal yr BP), indicative of a hiatus (Appendix C1). Similar trends have been experienced in surrounding fossil records (Scott *et al*., 2012) and in the nearby Lake Sibaya (Stager *et al*., 2013) which have been attributed to an erosional hiatus under very arid conditions. As evidenced in several studies and reports on St Lucia (e.g. Taylor, 2013; iSimangaliso Wetland Park, 2016a; Benallack *et al*., 2016), the lake bed has been exposed numerous times during periods of drought and deflation, thus it is plausible that an erosional erosion is illustrated at 242 cm.

6.2 Ostracod stratigraphy and palaeosalinity

6.2.1 North Lake (NL-1)

A total of 23 ostracod species were identified from 49 of the 113 samples (43%) taken from NL-1 (Appendix B4; Appendix D1). Both diversity and abundance appear to be highest near the basal section of the core (1570-1300 cm; 8180-7350 cal yr BP), and comprise of brackish, brackish-marine, marine and euryhaline species (Figure 5.5.1). This basal section (early Holocene) is largely dominated by marine species, and is the only section of the record where marine ostracods are present. This finding coincides with Benallack *et al*. (2016) who concluded that the tidal inlet/ palaeomouth at Leven Point was responsible for the marine influence experienced within the northern basin, until its closing around 7123-6325 cal yr BP. Foraminiferal evidence (WRC Report, 2016) further substantiates this interpretation by noting an abundance of well-preserved *Spiroloculina* spp. tests, species commonly found in shallow reefal and lagoonal areas. Furthermore, the low diatom preservation zone, their fragmented frustules, and the reworked shells identified by Gomes *et al*. (2017), prior to ~7700 cal yr BP, can be linked to tidal influences and further validates the inferred marine conditions present in the early part of the record. Personal observations of the ostracod material within this basal area illustrates an increase in crushed fossil valves, alluding to turbulent conditions (Boomer *et al*. 2003) which can be attributed to a marine influence. Ostracod diversity and abundance is greatest within this region, suggestive of more favourable environmental conditions for ostracods. This could be in the deeper, more saline environment, or in the benefits associated with nutrient rich marine inflow.

As North Lake transitioned into a lower energy environment with the closing of the tidal inlet during the early to mid Holocene, evidenced by the shift from coarse marine sand to silt dominated sediment around ~6200 cal yr BP (Benallack *et al*., 2016), there is a change in

ostracod species composition from marine dominated toward brackish-marine and brackish dominated assemblages (Appendix A2). This is indicative of a more estuarine setting. This transition is mirrored in the diatom record which indicates an increase in diatom preservation (Gomes *et al*., 2017). As North Lake is fed by the Mkhuze River, one of the two main sources of freshwater into the system, it is to be expected that the basin would move toward more brackish/estuarine conditions once the marine influence from the Leven Point palaeomouth tapered off. This inference is supported by an increase in brackish ostracod species.

The most recent section of the core/ the late Holocene, sees species diversity and abundance increase again. Euryhaline taxa (*Cyprideis* spp. and *Perissocytheridea estuaria*) depict an increased dominance within the recent section of the core, in comparison to their presence throughout the rest of the core. As euryhaline taxa are more generalist species, they are capable of tolerating a vast salinity range and are thus not as sensitive as freshwater or brackish species to fluctuations within the environment (Frenzel and Boomer, 2005). This may be indicative of unfavourable or unstable environmental conditions experienced within North Lake over the late Holocene. This may be attributed to the severity of drought conditions experienced within St Lucia in the recent past, exasperated by anthropogenic interferences, and the resulting hypersaline conditions evidenced by Wright *et al*. 2000; Whitfield *et al*. 2006 and Whitfield and Taylor, 2009.

Low preservation zones are evident amongst N-1, N-2, N-3 and N-4. Although these zones are poor in terms of ostracod perseveration, several samples are still abundant in calcareous foraminifera tests. Species such as *Spiroloculina* sp., *Quinqueloculina* sp. and *Ammonia tepida* are noted within these low preservation zones. As calcareous foraminifera are considered facultative anaerobes, they are capable of surviving under anoxic conditions (Bernhard and Sen Gupta, 2003). Ostracods however, do not survive when oxygen levels fall below a critical value (Frenzel and Boomer, 2005). As zones N-2, N-3 and N-4 are dominated by few ostracod species, this is generally indicative of unfavourable conditions (Dügel *et al*., 2008). It is likely that ostracods do not have sufficient time to recover their populations before unfavourable, anoxic conditions return to the basin.

PC1 (Figure 5.9.1) of North Lake has a high loading of marine taxa and thus indicates marine influence. Marine influence is strongest at the base of the core between ~8180-7350 cal yr BP (1570-1300 cm; Appendix A2), further corresponding with the palaeomouth described by Benallack *et al*. (2016) during the early Holocene. PC2 is indicative of salinity and is elevated in the basal section of the core from ~8180-7350 cal yr BP (1570-1300 cm), and at ~5750-7900 cal yr BP (905-720 cm). This coincides with the increased marine and brackish-marine species (Appendix A2). PC2 (salinity) decreases significantly from 2550 cal yr BP and the present day (290-0 cm), corresponding with the increase in brackish water ostracods (Appendix A2).

A WAPLS transfer function was applied to a modern and fossil ostracod dataset to produce a reconstruction of palaeosalinity within North Lake. The average error was ±7 with a r^2_{boot} = 0.56, indicating a fairly strong relationship. The basal section on the core (~8180-7200 cal yr BP) reflects a period of increased salinity levels that fluctuate between 18 and 27 psu, coinciding with the marine influence from Leven Point (Benallack *et al*., 2016). These levels are likely driven by the heavy presence of marine species. Elevated palaeosalinity levels within the basal region is also reflected in the transfer function performed on foraminifera (WRC Report, 2016). A peak in salinity at 1500 cal yr BP appears to be driven by the presence of *Cyprideis* spp. as it is mirrored at ~500 cal yr BP. The results from a study compiled by Humphries *et al*. (2016) noted distinct peaks in salinity at 1100 and 1750 cal yr BP in North Lake and False Bay as a result of maximum El Niño events. An increase in the euryhaline species *Cyprideis* spp. corresponds with the timing event of El Niño at 1500 cal yr BP. Increased salinity levels, associated with desiccation caused by El Niño, would cause various ostracod taxa to die off and allow for *Cyprideis* spp. to colonise an empty niche.

As a means of testing the suitability of the transfer function, the MinDC was used to determine ‘good’ and ‘close’ modern analogues (Birks 1995). The majority of the fossil samples fell within the 20th percentile and thus rendering the model suitable. Findings from the regression analysis performed on the observed sample salinities vs the modelled sample salinities indicate a fair relationship (r^2= 0.44; Figure 5.5.1).

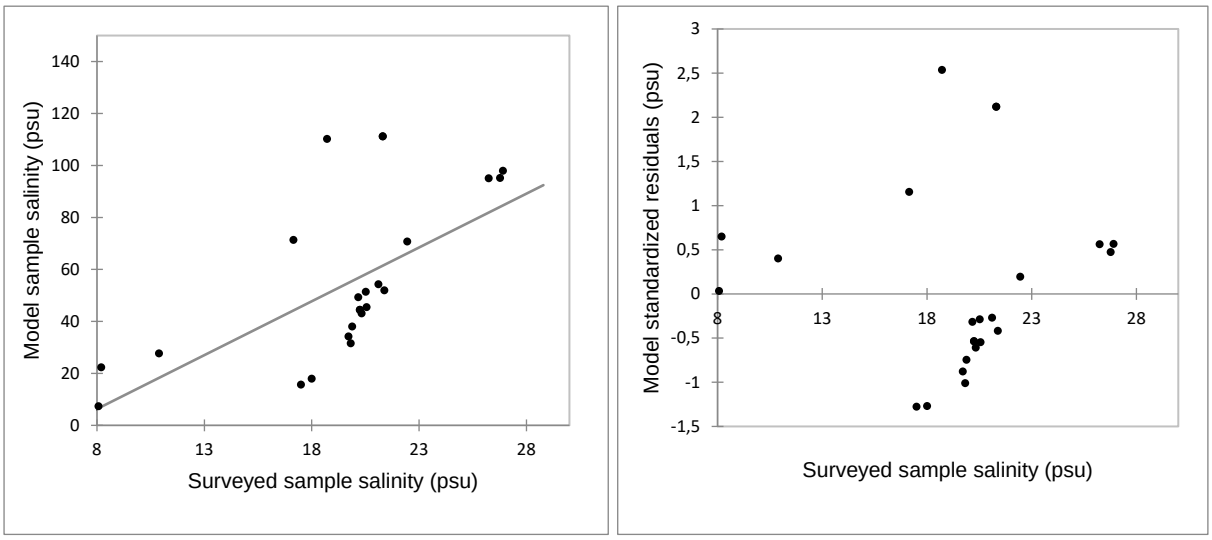

Figure 6.2.1: Modelled sample salinities regressed with observed samples salinities and residual plots for North Lake.

6.2.2 False Bay (FB-1)

False Bay has the lowest ostracod richness and abundance of the three sites, with 17 identified species totalling 2791 individuals present in 56 of the 117 of the samples (48%) (Appendix B4; Appendix D2). At the base of FB-1 (8400-7200 cal yr BP; 1580-1375 cm) marine ostracods are most dominant, aligning with foraminiferal data (WRC Report, 2016), signifying a greater marine influence in the early Holocene. Based on the diatom record of False Bay, Gomes *et al*. (2017) noted a transition toward a low energy system occurred prior to 8300 cal yr BP. This coincides with the ostracod data as the majority of marine species are evident at the base of the core (8400 cal yr BP; 1580 cm). The reasoning behind these effects occurring earlier in FB-1 can be attributed to its landward position and the sheltering effect provided by the Nibela Peninsula (Benallack *et al*., 2016).

A large low preservation zone is evident from 7200-1650 cal yr BP whereby *Sulcostocythere knysnaensis* is still evident. As described in North Lake, calcareous foraminifera tests are still evident within this low preservation zone thus indicating this zone is likely a result of anoxic conditions. *Aglaiella westfordensis* makes a small appearance at ~4300 cal yr BP (700 cm; Appendix A3), corresponding with the foraminifera record (WRC Report, 2016) which illustrates a peak in *Cribroelphidium articulatum* at a similar age that has been attributed to a freshwater influence. Brackish and freshwater species become more dominant from this point

up to the present day, perhaps indicative of the increase in freshwater influence and thus corresponding with the foraminifera data (WRC Report, 2016).

Over the late Holocene (~1700 cal yr BP to the present day; 150-0 cm), ostracod species richness and abundance tend to increase again, and brackish species dominate (Appendix B2). The presence of *Sclerocypris clavularis*, a freshwater ostracod, is noteworthy as it only occurs within False Bay. Because of the landward, sheltered positioning of False Bay, the lack of marine influence, and the freshwater input from three rivers, a fresher ostracod community is anticipated. The bulk of the fossilized double valves are evident in the more recent section of the core (~2300-0 cal yr BP; Appendix A1), indicating that the fossil material found within these samples is autochthonous and perhaps suggesting environmental conditions that are more favourable to ostracod preservation (Boomer *et al*., 2003). Favourable environmental conditions in False Bay would thus differ from North Lake as these conditions are low energy environments with a fresh to estuarine salinity preference.

PC1 of False Bay reflects salinity and indicates a lack of marine influence (Figure 5.9.2). Values are higher in the basal section of the core from ~8400-7200 cal yr BP (1580-1375cm) where brackish-marine and marine species are evident (Appendix A3), and decrease in the recent section of the core where there is an influx of freshwater and brackish taxa (~1650-0 cal yr BP; 160-0 cm). PC2 illustrates a high loading of freshwater taxa, indicative of freshwater inflow (Figure 5.9.2). The peak in freshwater inflow at ~1000 cal yr BP (Appendix A3) coincides with the increase in freshwater and brackish ostracod species.

A WAPLS transfer function was applied to ostracod data to yield a reconstruction of palaeosalinity within False Bay, with an average error of ±7. Salinity ranged from 8 to 28 psu throughout the core. The early Holocene (~8400-7200 cal yr BP; 1580-1375 cm) illustrated the highest salinity values of 28 psu, mirrored by the foraminifera-based reconstruction (WRC Report, 2016). Palaeosalinity remains fairly stable at 20 psu over most of the mid Holocene (7200-2550 cal yr BP; 1375-340 cm). A peak of 23 psu is noted at 1800 cal yr BP (200 cm) which could be the effects of an El Niño occurring around the time, identified by Humphries *et al*. (2016). The lowest salinity levels ranging between 6 and 12 psu are evident in the late Holocene (~1600-500 cal yr BP; 140-20cm), coinciding with the increase in freshwater and

brackish water species. The MAT was applied to the transfer function data to determine the suitability of the model (Birks, 1995). The MinDC values illustrated that the majority of the samples fell within the 20th percentile, and hence most samples had a good or close fit with the modern analogues. A regression analysis furthers these interpretations with the r^2= 0.64 indicating a relatively strong relationship between the observed and modelled salinities (Figure 6.6.2).

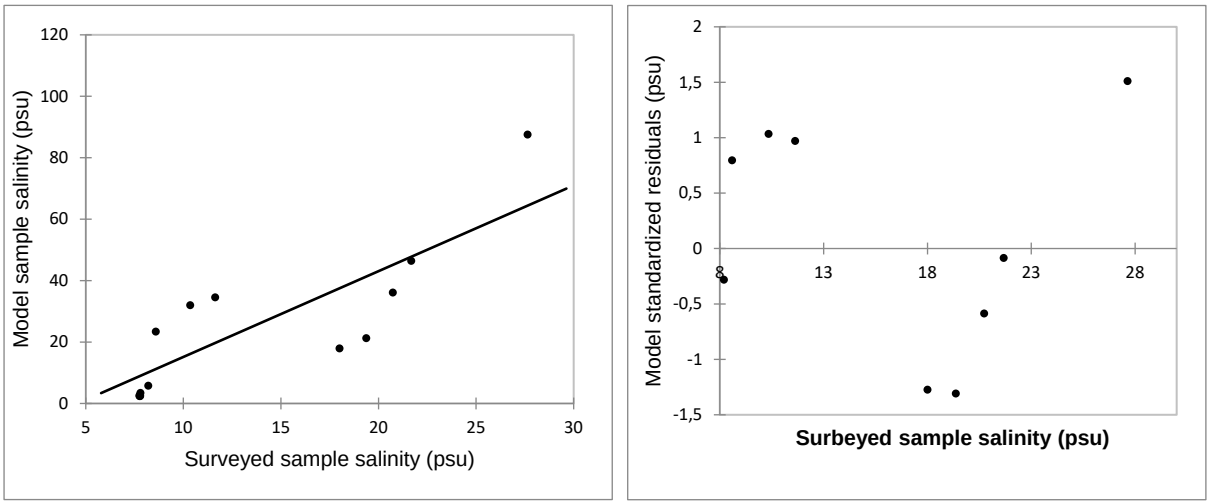

Figure 6.6.2: Modelled sample salinities regressed with observed samples salinities and residual plots for False Bay.

Overall, there appears to be a significant change in environmental conditions experienced within False Bay. The early Holocene (~8400-7200 cal yr BP; 1580-1375 cm) illustrates a marine-dominated ostracod assemblage with higher salinities, indicative of a palaeoenvironment with a higher marine influence. The late Holocene (~2700 cal yr BP to the present day; 360- 0 cm) depicts a much fresher and less saline environment, with an estuarine dominated ostracod assemblage. The closing of the tidal inlet and the landward, sheltered positioning of False Bay (Benallack *et al.*, 2016) may explain the low presence of marine species. These factors, in conjunction with the freshwater inputs received from the Mzinene, Hluhluwe and Nyalazi rivers, could be driving force in the shift in basin conditions and associated ostracod assemblages evident within FB-1. Marine influence was strongest in North Lake and Catalina Bay over the early Holocene and is illustrated in the ostracod fossil record (Figures 5.6 and 5.8). False Bay however, was not largely influenced by the marine intrusions because of its sheltered positioning, and hence does not reflect ostracod assemblages dependent on marine influence and may explain why ostracod richness increases in the recent section of the core. These recent, late Holocene environmental conditions of a sheltered basin with an

increase in freshwater inputs evident from ~4300 cal yr BP appear more favourable to ostracods.

6.2.3 Catalina Bay (CB-2)

A total of 23 species were identified from 65 of the 105 samples (62%) (Appendix B4). Catalina Bay illustrates the highest ostracod diversity and abundance. Ostracods are highly concentrated within the basal area of the core from 9520-9400 cal yr BP and 8500-8000 cal yr BP (1360-1250 cm and 760-480 cm), with these two zones accounting for 97% of the total ostracod abundance. Marine ostracod species are dominant (47%, Appendix B3) within the basal section displaying a high diversity, followed by brackish-marine species (40%, Appendix B3). This illustrates a high marine influence over the early Holocene. Brackish species are also represented within this basal section. As the locality of the core is relatively close to the St Lucia mouth, it would have been subjected to a strong tidal influence and one could expect to see a heavily marine dominated assemblage. Furthermore, the Mfolozi River, a large contributor of freshwater, feeds into the southern reaches of the lake, providing favourable environmental conditions for brackish species.

Two low preservation zones evident from 9400-8500 cal yr BP and 8000-2000 cal yr BP (1250-760 cm and 480-75 cm). The first low preservation zone (9400-8500 cal yr BP) still illustrates ostracod presence, albeit in low abundances (Appendix B4). This areas of the core was noted as having an increased portion of crushed valves and perhaps infers largely turbulent environmental conditions unfavourable to ostracods, perhaps associated with a strong marine influence. The latter low preservation zone (8000-2000 cal yr BP) did indicate the presence of foraminifera tests, however, some samples had very few foraminifera fossils (in comparison to foraminifera abundance in samples further down the core) which substantiates the interpretation of an erosional hiatus, as sediment material has been eroded away together with the fossil record (Appendix C1).

Over the late Holocene (~1700-0 cal yr BP; 70-0 cm), *Sulcostocythere knysnaensis* is evident in addition to two brackish species with low abundances. A low species diversity may be attributed to unfavourable or unstable environmental conditions (Boomer *et al.*, 2003). These environmental instabilities could perhaps be attributed to the hypersaline events noted in the

recent literature. Catalina Bay is the deepest of the three basins with a steadier inflow of both fresh and marine water, and thus should theoretically provide more favourable conditions for all species of ostracods. The excellent fossil preservation in the basal region, and the drastically reduced record presented in the remainder of the core, makes interpretations for the mid to late Holocene quite challenging.

There are high loadings of marine taxa on PC1 (Figure 5.9.3), indicating a strong marine influence. As the site is situated near the present day mouth, the marine influence is likely to be the strongest. Furthermore, the majority of the samples taken from Catalina Bay are composed of beach sand and contain shell fragments indicating a significant marine influence. Marine influence is strongest over the early Holocene (~9520-9400 cal yr BP and 8500-8000 cal yr BP; 1360-1250 cm and 760-480 cm) coinciding with high marine abundances (Appendix A4). Marine influence appears weaker over the late Holocene (~2000 cal yr BP to the present day; 75-0 cm). A possible explanation could be the declining marine influence in the transition to the shallower estuarine system, or perhaps even due to prolonged periods of mouth closure. As documented records within St Lucia indicate that anthropogenic alterations to the mouth and surrounding freshwater systems have resulted in prolonged mouth closures, it could be a contributing factor to the overall decline in ostracod species as taxa illustrate a preference for environments with a higher marine influence.

Palaeosalinity was determined by a WAPLS transfer function and yielded an error of ±7 with a r^2_{boot} = 0.59, thus being significant for reconstruction. The early Holocene (~9500-8300 cal yr BP; 1360-625 cm) depicts the highest salinity values, reaching 37 psu. This is likely driven by the heavy presence of marine species and can be attributed to the core site located near the estuary mouth. At 8050 cal yr BP (490 cm), salinity is reconstructed at 21 psu. Salinity decreases to 14 psu at 1500 cal yr BP (50 cm). A smaller salinity peak, reaching 19 psu, is evident at 1000 cal yr BP (25 cm) may be attributed to the drought conditions associated with an El Niño event identified by Humphries *et al*. (2016). The MinDC used to assess the suitability of the transfer function illustrated that just under half of the samples had a good or close fit as they fell within the 20th percentile. Samples that fell outside of the 20th percentile were rendered a ‘poor’ fit however, the values are just outside of the ‘close’ range and hence

the regression analysis (Figure 6.2.3; r^2= 0.80) illustrates a relatively strong relationship between the observed sample salinities and the modelled sample salinities.

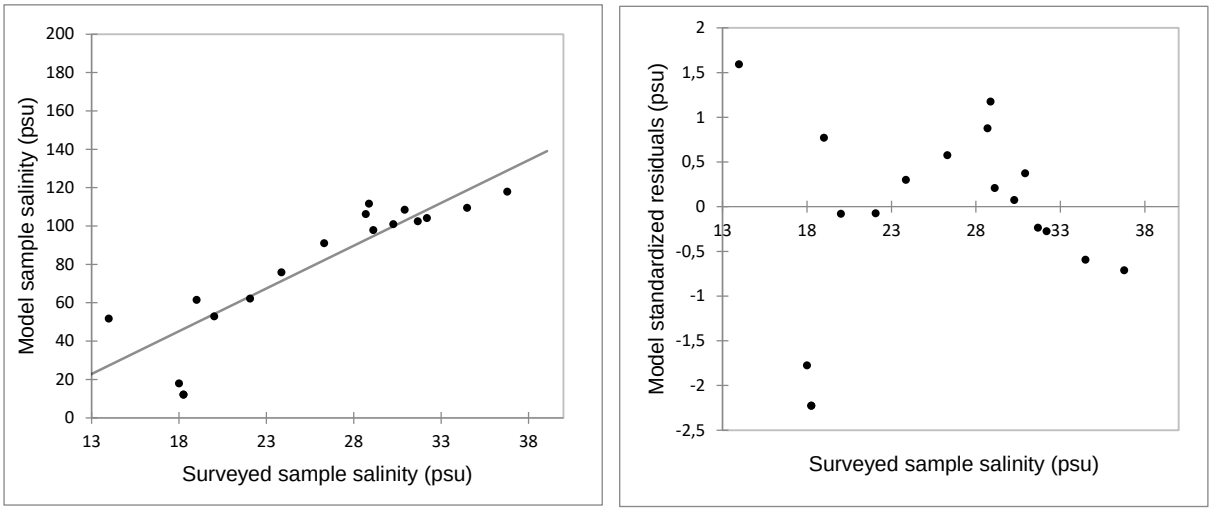

Figure 6.2.3: Modelled sample salinities regressed with observed samples salinities and residual plots for Catalina Bay.

Between core comparisons:

NL-1 and CB-2 have good fossil preservation in the basal sections of their cores (Figures 5.6 and 5.8). These basal sections are the only areas in which marine ostracods occur, indicating a stronger marine influence over the early Holocene than that of contemporary environments (Figures 6.2.4). Furthermore, the basal areas also have the highest portion of double valves (Appendix A1), indicating autochthonous material and environmental conditions were favourable to ostracod preservation (Boomer *et al*., 2003). It is likely that these deeper-water conditions allowed for a much higher degree of mixing between the basins (Perissinotto *et al*., 2013), facilitating ostracod movement and thus facilitating species dispersal and enabling them to thrive within their optimum environmental range. Deep water conditions would have reduced the risk of desiccation, and any consequent erosion or deflation, as well as reducing the impact of wind-driven waves on sediment reworking (Zikhali *et al*., 2014; Benallack *et al*., 2016). These factors would contribute to increased fossil preservation. NL-1 and CB-2 illustrate reduced ostracod diversity and abundance over the late Holocene (Figures 6.2.4; Appendix A2; Appendix A4), a finding for NL-1 that is mirrored in the diatom (Gomes *et al*., 2017) and foraminifera records (WRC Report, 2016). NL-1 and CB-2 yield a higher species diversity and abundance over FB-1, likely attributed to their stronger link to tidal influences from the palaeomouth at Leven Point in North Lake, and the locality of CB-2 near the present day mouth. There are however, no marine species evident in North Lake or Catalina Bay from

~6300 cal yr BP to the present, indicating a reduction in marine influence and corresponding with the closure of the palaeomouth. False Bay is similar to the other two basins in that marine ostracods are evident in the early Holocene, albeit in low abundances (Figure 5.7). However, False Bay differs from NL-1 and CB-2 as ostracod assemblages indicate fresher environmental conditions, and abundances appears much stronger in late Holocene (2650-0 cal yr BP; 350-0 cm). As False Bay is largely sheltered, an increase in marine influence (largely beneficial to ostracod success in North Lake and Catalina Bay) is not likely to negatively affect the current ostracod assemblages found within the basin, but rather add to the diversity. *Sulcostocythere knysnaensis* is well represented throughout all the zones within the cores, and is also present in some of the low preservation zones (Appendix A2; Appendix A3; Appendix A4). This denotes the estuarine environment of St Lucia and perhaps conditions better suited to this species. From personal observation, carinae present on *Sulcostocythere knysnaensis* valves may make them more mechanically resistant.

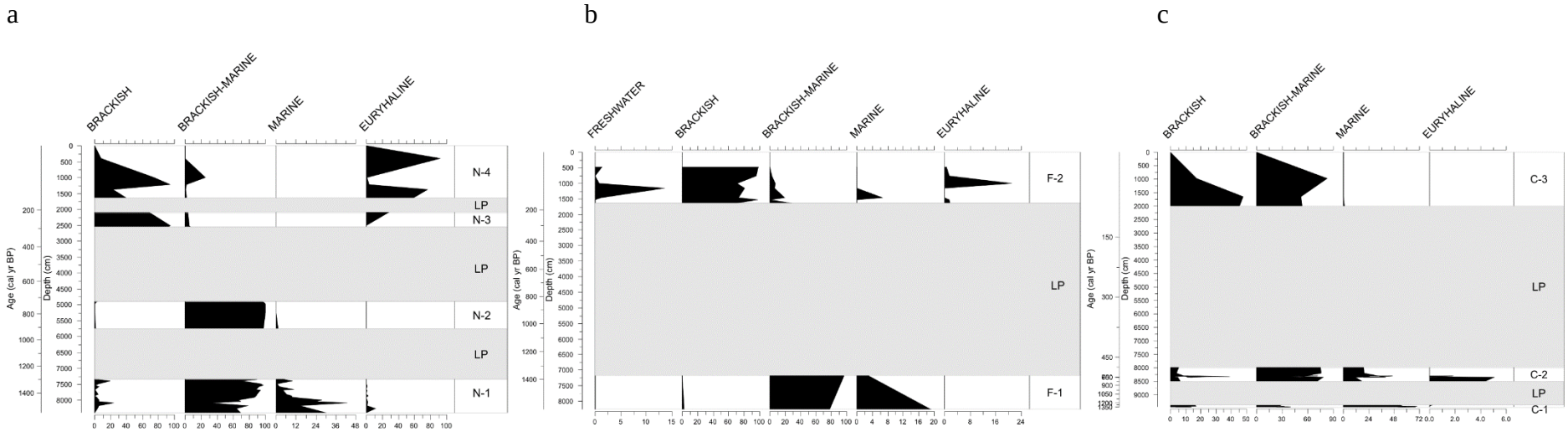

Figure 6.2.4: Ecological groupings evident within a) North Lake, b) False Bay and c) Catalina Bay.

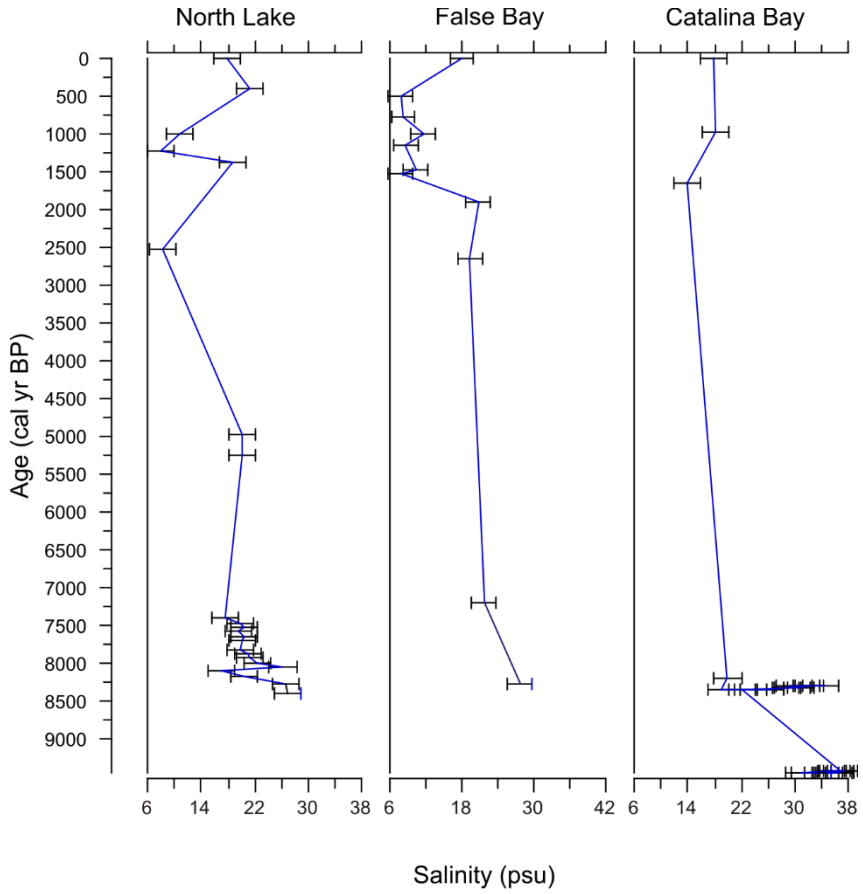

Figure 6.2.5: Downcore palaeosalinities for North Lake, False Bay and Catalina Bay.

NL-1, FB-1 and CB-2 all illustrate increased salinities over the early Holocene (~9500-7250 cal yr BP; Figure 6.2.5). Catalina Bay yields the highest salinity readings reaching 37 psu, likely the result of its close proximity to the St Lucia mouth. North Lake depicts another small peak in salinity in the mid Holocene (5300-5000 cal yr BP) which is likely due to an overwash event as this coincides with foraminifera data (WRC Report, 2016), which has been linked to episodic overwashing. Salinity within False Bay seems to remain relatively stable at 20 psu throughout much of the mid Holocene, until it declines to 10 psu from 1500 cal yr BP. Salinity levels are also lower over the late Holocene for North Lake and Catalina Bay, in comparison to early Holocene values.

Recent studies in St Lucia have revealed hypersaline (>90 psu) events occurring within the system, with North Lake generally exhibiting the highest salinity recordings (e.g: Wright *et al*., 2000; Whitfield *et al*., 2006 and Whitfield and Taylor, 2009; Carrasco and Perissinotto, 2012; Perissinotto *et al*., 2013). These hypersaline events are not reflected in ostracod fossil data however. The reasoning for this is likely due to the fact that these studies involve direct salinity

measures that were taken at the time of sampling, whereas this study is subject to time averaging with brief hypersaline events likely being lost with sediment mixing. Furthermore, very few taxa within this study are capable of withstanding such salinity extremes and are likely to die out. *Cyprideis* spp. are one such generalist taxon that has the ability to withstand increased salinites, and will colonise an empty niche as other species die out (Dügel *et al*. 2008). The increased prevalence of *Cyprideis* spp. in contemporary environments in North Lake may be indicative of some sort of hypersaline event. A recent study in Verlorenvlei focussed on ostracods within the top 0-2 cm of sediment, and was able to identify hypersaline events by the presence of living *Sarscypridopsis glabrata* (Fürstenberg *et al*., 2017). However, only empty valves of *Cyprideis* spp. are found with living *S. glabrata* (Fürstenberg *et al*., 2017), indicating that even this euryhaline taxon of *Cyprideis* spp. does not cope well under extreme salinities, and further explains why such hypersaline events are not evident in contemporary environments of the North Lake, False Bay and Catalina Bay.

6.3 Limitations

A number of limitations were experienced in this study relating to ostracod preservation and identification, and chronological control. Low preservation zones were encountered in each of the three cores, where less than 50 preserved valves were recorded. This renders large sections of the records statistically insignificant and creates gaps within the records.

The Catalina Bay core chronology poses some complications due to a possible erosional hiatus. The first 242 cm of the core represents 6400 ^{14}C yrs BP (7238-7342 cal yr BP), and remaining metre of sediment profile only accounts for a further 2000 years (8460 ^{14}C yrs BP; 9401-9523 cal yr BP). This hiatus is likely due to a desiccation event, and deflation has taken place. Fossil preservation is good in the basal areas of CB-2 however, the recent section of the core illustrates low abundances and because of the possibility of the hiatus and missing fossil record, interpretation is difficult for inferring late Holocene environmental conditions. As St Lucia is home to a large population of hippopotami and other bioturbators, there is an increased risk of valve fragmentation and crushing. The presence of macrobenthos increases the risk of sediment reworking and could be responsible for the age reversals.

Access to a SEM was limited, making ostracod identification, in some instances, unattainable. Although a Leica stereomicroscope was used to take several photographs of the ostracod valve as possible, identification was not always achievable. An example of this is evident in Sp. E, whose abundance was high enough to be included in the reportable fossil data.

The use of ostracods as environmental proxies is still a relatively new technique for southern Africa and hence information is fairly scarce and patchy. Although this study aims to provide insight into palaeo- and contemporary environmental changes within St Lucia, achieved through the identification of changes in ostracod assemblages, available ecological information on ostracods in the southern hemisphere is limited and thus only broad inferences can be made. Hypersaline events, noted in the recent literature on St Lucia, are not evident in the ostracod fossil record as these are generally short lived events that will often be averaged out with sediment deposition or reworking. Furthermore, very few taxon have the ability to withstand salinities above 90 psu, adding to the inability to detect hypersaline events.

6.4 Conclusion

NL-1, FB-1 and CB-2 yield cores that are of Holocene age with NL-1 and FB-1 illustrating fairly straightforward linear age models. Some complexities are evident in CB-2 due to the likelihood of a hiatus, possibly attributed to erosion within the basin during times of drought. Ostracod-salinity transfer functions revealed elevated salinity values over the early Holocene for the three basins, indicating a stronger marine influence was experienced from ~9500-7500 cal yr BP. This is likely a result of the deep water system having a much stronger link to the ocean via the inlet at Leven Point as well as the mouth of the estuary. As the system transitioned (early to mid Holocene) into the shallow estuarine system we see today, there is a general decrease in ostracod diversity and abundance in North Lake and Catalina Bay. This indicates an increased ostracod preference toward deeper water environments with increased marine influence. A shallower system is more at risk during times of environmental instability, evidenced in studies that have identified exposed areas of the lake bed during droughts (e.g: Whitfield and Taylor, 2009; Perissinotto *et al*., 2013), and sediment reworking due to wind-driven waves (Zikhali *et al*., 2014; Benallack *et al*., 2016). False Bay records indicate increased marine influence at the base, corresponding with the open tidal inlet at Leven Point. The transition to the estuarine environment sees fresher conditions persisting within this basin and the establishment of a strong freshwater and brackish assemblage. This indicates an ostracod

preference toward a sheltered, low energy estuarine environment within this basin. All three basins encompass low preservation zones which render gaps in the fossil record and serve as a limitation within this study. Other limitations are evident in ostracod identification and chronological constraints and in the scarcity of available ecological information within southern Africa.

CHAPTER SEVEN

CONCLUSION

7.1 Summary of palaeoenvironmental conditions at Lake St Lucia

The early Holocene saw St Lucia as a deep lagoonal system with a direct link to the sea through palaeomouths and the tidal inlet at Leven Point. The marine influence from the palaeomouth is evident in the North Lake core by the dominance of marine ostracod taxa in the basal region (early Holocene). Dune accretion and stabilization resulted in the restricting and, ultimately, closing of this inlet around 7123-6325 cal yr BP which consequently saw the transitioning of St Lucia into the shallow, low-energy estuarine system seen today. The closing of the inlet and consequent transition results in less saline conditions within the basin, and sees a reduction in marine ostracod diversity. Estuarine conditions persist, noted by the dominance of *Sulcostocythere knysnaensis, Aglaiella westfordensis* and *Australoloxoconcha favornamentata*. Decreased ostracod diversity and abundance evident in the contemporary fossil record indicate that late Holocene environmental conditions are less favourable than those of the early Holocene environments, consisting of a deeper system with a marine influence. *Cyprideis* spp., a euryhaline ostracod is found in surface samples in North Lake and is likely indicative of environmental instability, associated with hypersaline events.

The landward positioning of False Bay coupled with the sheltering effect offered by the Nibela Peninsula resulted in very little marine influence over False Bay. This is evident in the early Holocene fossil record as marine species account for less than 2% relative abundance. Because of the lack of marine influence and the three freshwater inputs into the basin, ostracod assemblages appear to have developed fresher, estuarine communities.

Catalina Bay has the highest fossil preservation and illustrates a much more saline environment over the Holocene in comparison to the other two basins. Core chronology indicates a possible erosional hiatus in the recent section with minimal fossil preservation, therefore making interpretations difficult for late Holocene environmental conditions. Marine taxa are most dominant in Catalina Bay, which can be attributed to the coring site located near the estuary mouth. As Catalina Bay is the deepest of the three basins, water coverage is likely to have been more constant, reducing the risk of desiccation and leaving it less at risk of sediment

disturbance from wind-generated waves. These factors may explain higher ostracod abundances and the better preservation potential. Early Holocene environmental conditions of a deeper system with increased marine influence appear more favourable to ostracods, as evident in North Lake.

The transition to a low-energy estuarine environment, occurring in the early to mid Holocene, is indicated by the shift in species composition form marine dominated assemblages in the early Holocene records, to brackish and marine-brackish dominated assemblages in the late Holocene records. *Aglaiella westfordensis*, *Australoloxoconcha favornamentata* and *Sulcostocythere knysnaensis* are the dominating species in the late Holocene and are thus indicative of estuarine conditions in contemporary environments. As marine influence tapered off following the transition, ostracod diversity and abundance decrease in North Lake and Catalina Bay indicating an ostracod preference toward early Holocene palaeoenvironmental conditions of increased, stable salinities that likely benefitted from the input of a fresh marine inflow. All three cores illustrate gaps within the fossil records due to anoxic conditions experienced within the system.

Recent anthropogenic alterations to the system and surrounding catchments have had detrimental impacts on St Lucia, seeing prolonged periods of desiccation and mass mortalities. This is the result of an overall reduction in water supply to the system leading to extended periods of mouth closure, the only contemporary connection to the sea. Ostracods, as with many other species, benefit from an increased marine influence.

7.2 Review of objectives

I. Quantify downcore fossil ostracod assemblages from sediment cores collected in the three main basins of Lake St Lucia.

Fossil ostracods were extracted from each sediment core microscopically, and identified with the aid of relevant literature and a SEM. Using the statistical software of C2 v 1.7.7 (Juggins, 2007) and Psimpoll v 4.263 (Bennet, 1994), downcore stratigraphic plots of fossil data for North Lake, False Bay and Catalina Bay were produced.

II. Infer past environmental conditions experienced at Lake St Lucia based on the findings from the fossil assemblages.

Ostracods were classified according to five ecological groups: freshwater, brackish, brackish-marine and marine to give a broad inference of their ecological tolerances. These inferences revealed early Holocene environments of a deeper system with a higher marine influence, marked by the dominance in marine taxa. A transition toward an estuarine system, occurring in the early to mid Holocene, is evident in the changing assemblage composition from marine dominated toward a more brackish-marine and brackish dominated assemblage. False Bay illustrates a fresher system over the late Holocene, noted by the increased dominance in freshwater and brackish taxa.

III. Reconstruct past salinity fluctuations within the lake using a transfer function based on modern distribution data

A WAPLS transfer function was applied to modern and fossil ostracod datasets to produce downcore palaeosalinity records for each basin. Elevated salinity records are evident in the early Holocene, when St Lucia had multiple tidal inlets. Salinity has gradually decreased over the Holocene, a result of the tapering marine influence associated with the closing of the inlets and subsequent system transition.

IV. Understand long term natural fluctuations in water chemistry and habitat structure to inform current management practices.

The early Holocene saw St Lucia as a deep water system with a significant marine influence through various palaeomouths, evidenced in the fossil record. The closing of these inlets led to the transition toward a shallow, low energy estuarine environment (noted by the dominance in brackish-marine and brackish taxa) and an increase in anoxic conditions. Recent anthropogenic alterations to the system have further reduced the water supply into and out of the system, resulting the overall degradation of the system and reduction in ostracod diversity. This study encourages management to allow the natural diversion and relinking of the Mfolozi back into the St Lucia estuary, increasing the resilience and maintaining the successful functioning of the system.

Conclusion

St Lucia is a highly managed ecosystem, with a significant portion of the system manipulation and changing land use patterns within the catchments resulting in the degradation of the system. Inhibiting the natural diversion of the Mfolozi River into the estuary has led to hypersalinity and dry, exposed lake beds during times of drought and subsequent mass mortalities. This highlights the importance of a palaeoenvironmental understanding of natural system functioning, if restoration is to be possible. Reconstructed palaeosalinity produced by an ostracod-salinity transfer function indicates higher palaeosalinities during the early Holocene, a likely result of an increased marine influence. Salinities have decreased over the Holocene as marine influence tapered off after the closing of the palaeomouths. These interpretations coincide with findings by Benallack *et al*. (2016). Records indicate ostracod populations flourish under times of deeper system conditions with greater marine influence. There are significant similarities between the ostracod record and the diatom and foraminifera records (Gomes *et al*., 2017; WRC Report, 2016). Although brief hypersaline events are not evident within the fossil record because of time averaging through sediment mixing, large scale system events (such as drought conditions associated with El Niño) and natural fluctuations are still reflected within the fossil record. Similarities between the ostracod record and other studies within St Lucia indicate a strong confidence in the ability of ostracods as biological indicators for salinity reconstruction.

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APPENDIX A: Ostracod stratigraphy

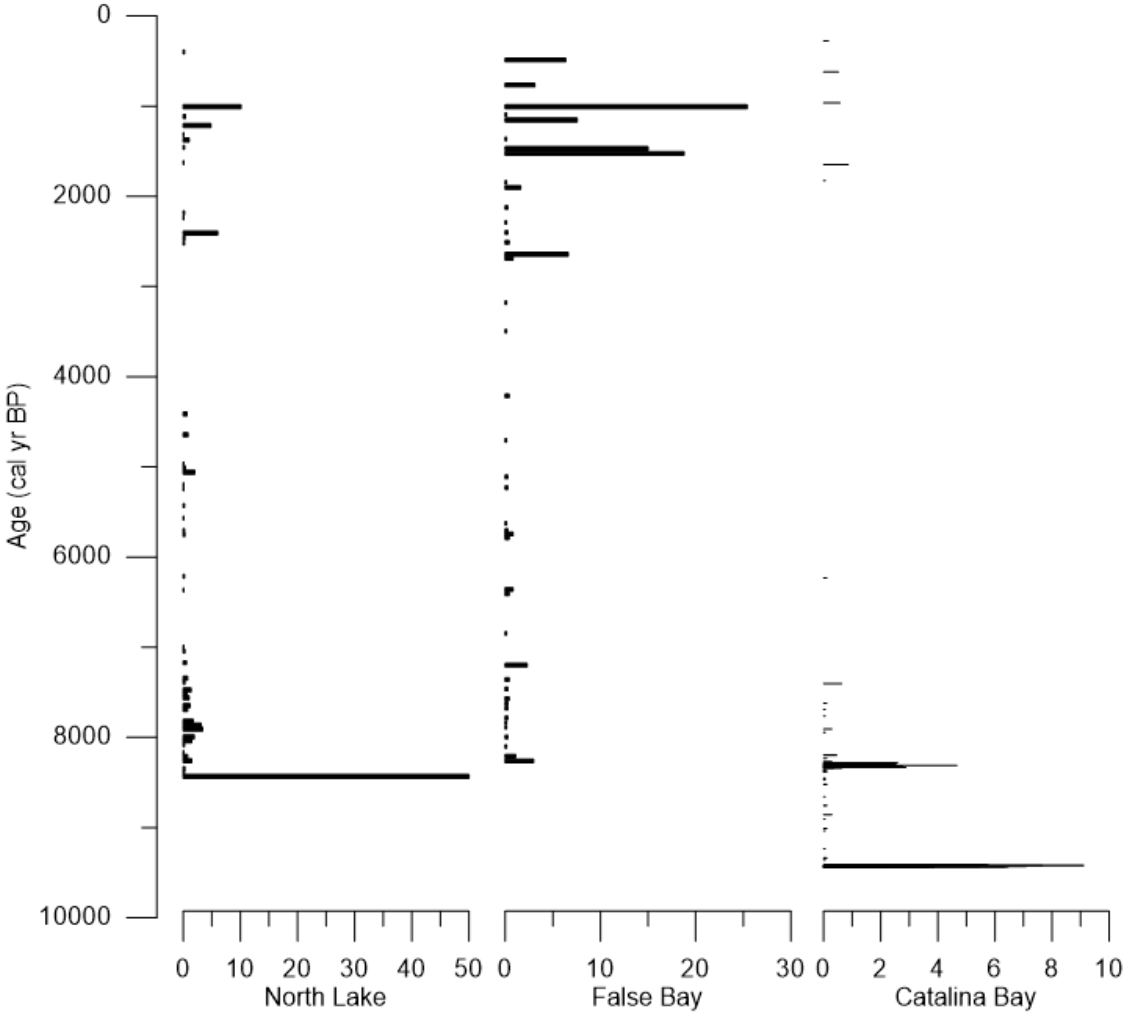

Figure A1: Downcore double valve fossil percentage distribution plotted for North Lake, False Bay and Catalina Bay.

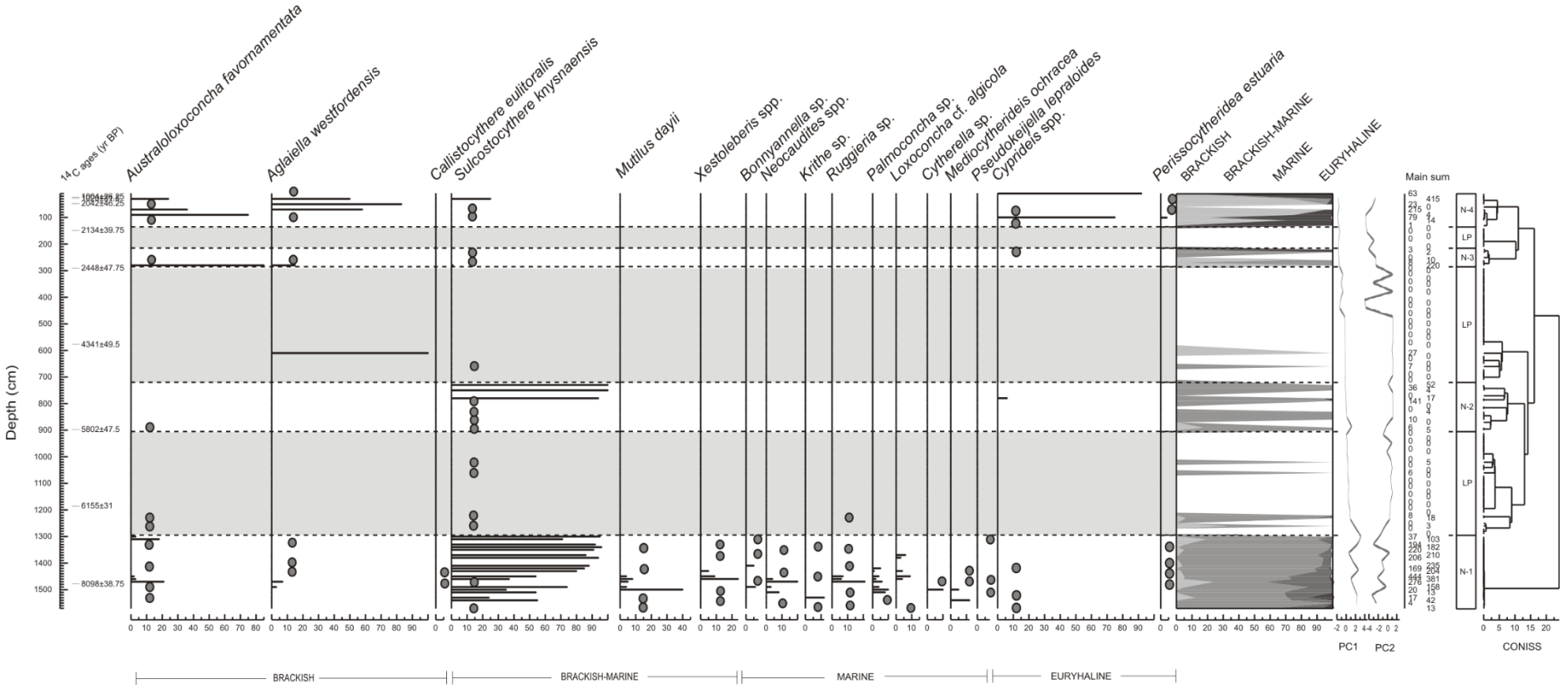

Figure A2: Downcore stratigraphic plot of all fossil ostracods in North Lake with seven CONISS derived zones.

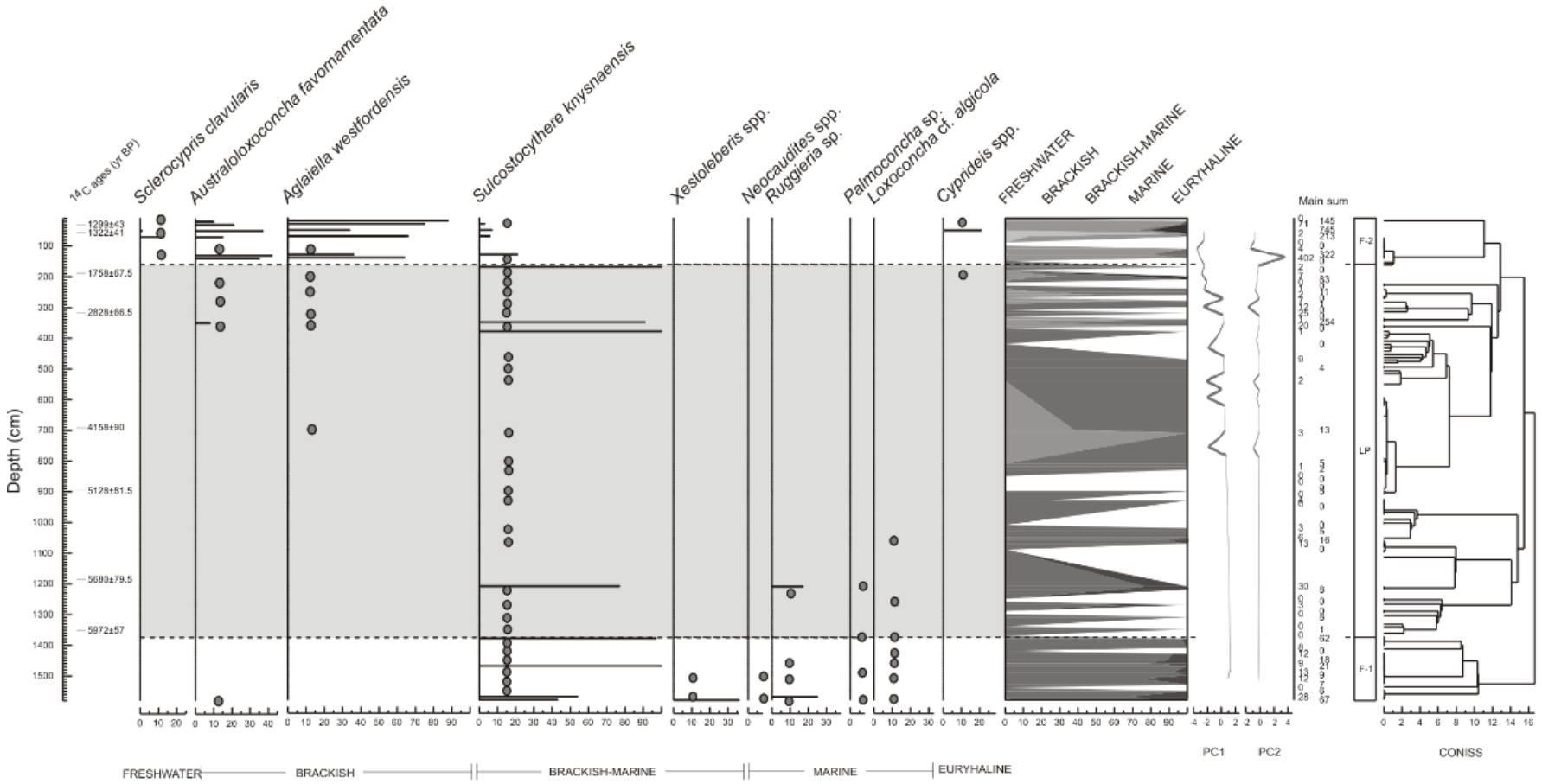

Figure A3: Downcore stratigraphic plot of all fossil ostracods in False Bay with three CONISS derived zones.

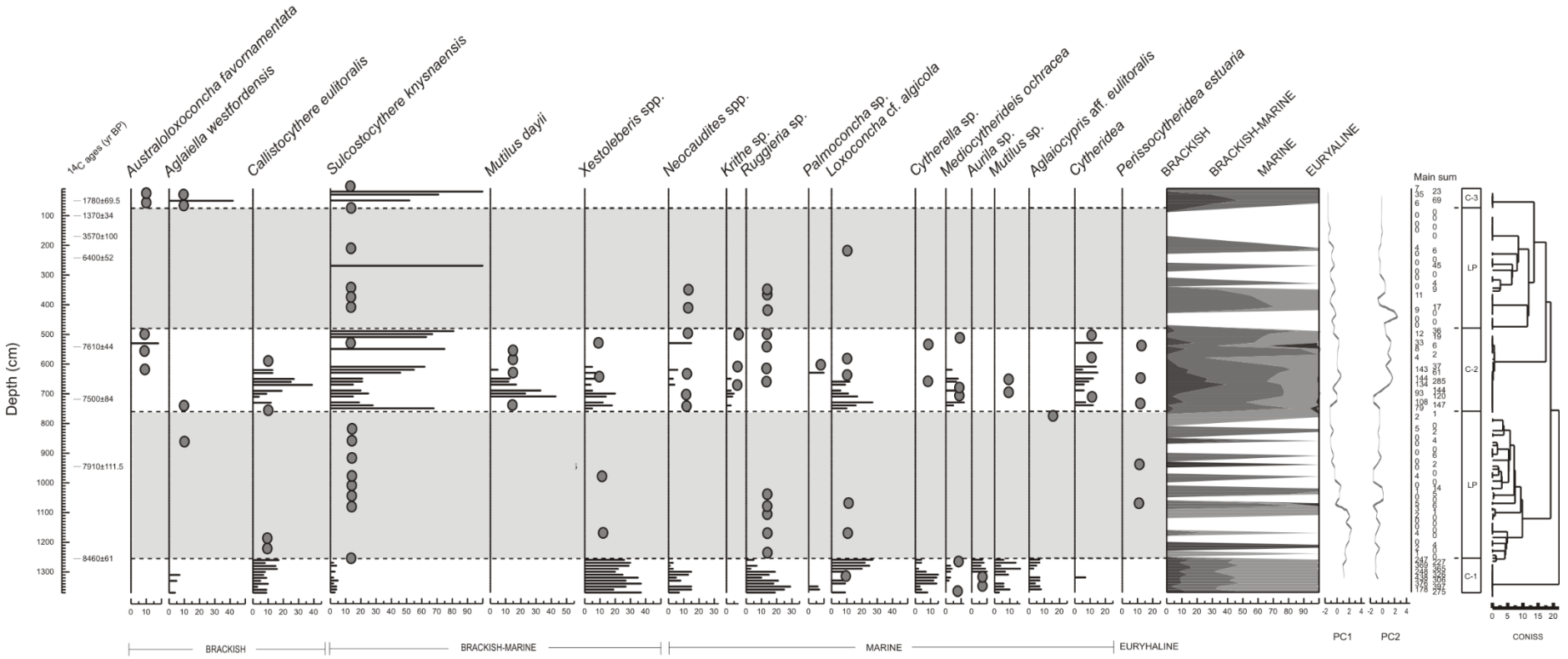

Figure A4: Downcore stratigraphic plot of all fossil ostracods in Catalina Bay with five CONISS derived zones.

APPENDIX B: Ostracod assemblage composition

Table B1: Ostracod percentage composition for North Lake.

Ostracod species	**Percentage (%)**
Australoloxoconcha favornamentata	11.0
Aglaiella westfordensis	10.7
Callistocythere eulitoralis	0.4
Total brackish	22.1
Sulcostocythere knysnaensis	57.6
Mutilus dayii	2.4
Xestoleberis spp.	3.4
Total brackish-marine	63.4
Bonnyannella sp.	1.1
Neocaudites spp.	1.9
Krithe sp.	0.4
Ruggieria sp.	2.7
Palmoconcha sp.	1.4
Loxoconcha cf. *algicola*	1.9
Cytherella sp.	0.6
Mediocytherideis (Sylvestra) ochracea	0.6
Pseudokeijella lepraloides	0.2
Total marine	10.7
Cyprideis spp.	2.9
Perissocytheridea estuaria	0.9
Total euryhaline	3.8

Table B2: Ostracod percentage composition for False Bay.

Ostracod species	**Percentage (%)**
Sclerocypris clavularis	1.5
Total freshwater	1.5
Australoloxoconcha favornamentata	23.8
Aglaiella westfordensis	35.6
Total brackish	59.3
Sulcostocythere knysnaensis	30.6
Xestoleberis spp.	1.1
Total brackish-marine	31.7
Neocaudites spp.	0.2
Ruggieria sp.	0.8
Palmoconcha sp.	0.3
Loxoconcha cf. *algicola*	0.4
Total marine	1.6
Cyprideis spp.	5.9
Total euryhaline	5.9

Table B3: Ostracod percentage composition for Catalina Bay.

Ostracod species	**Percentage (%)**
Australoloxoconcha favornamentata	0.4
Aglaiella westfordensis	1.5
Callistocythere eulitoralis	10.9
Total brackish	12.8
Sulcostocythere knysnaensis	14.1
Mutilus dayii	4.5
Xestoleberis spp.	21.9
Total brackish-marine	39.9
Neocaudites spp.	5.4
Krithe sp.	0.6
Ruggieria sp.	10.1
Palmoconcha sp.	0.8
Loxoconcha cf. *algicola*	10.3
Cytherella sp.	5,1
Mediocytherideis (Sylvestra) ochracea	2,3
Aurila sp.	2,3
Mutilus sp.	4,3
Aglaiocypris aff. *eulitoralis*	3,1
Cytheridea	2,7
Total marine	47
Perissocytheridea estuaria	0,3
Total euryhaline	0,3

Table B4: Summary of ostracod richness and abundance, the number of samples within each core as well as the length for each site.

	Ostracod richness	**Ostracod abundance**	**Samples counted (samples with ostracods present)**	**Core length (cm)**
North Lake	23	4580	113 (49)	1570
False Bay	17	2791	117 (56)	1580
Catalina Bay	23	5939	105 (65)	1370

APPENDIX C: Age-depth models

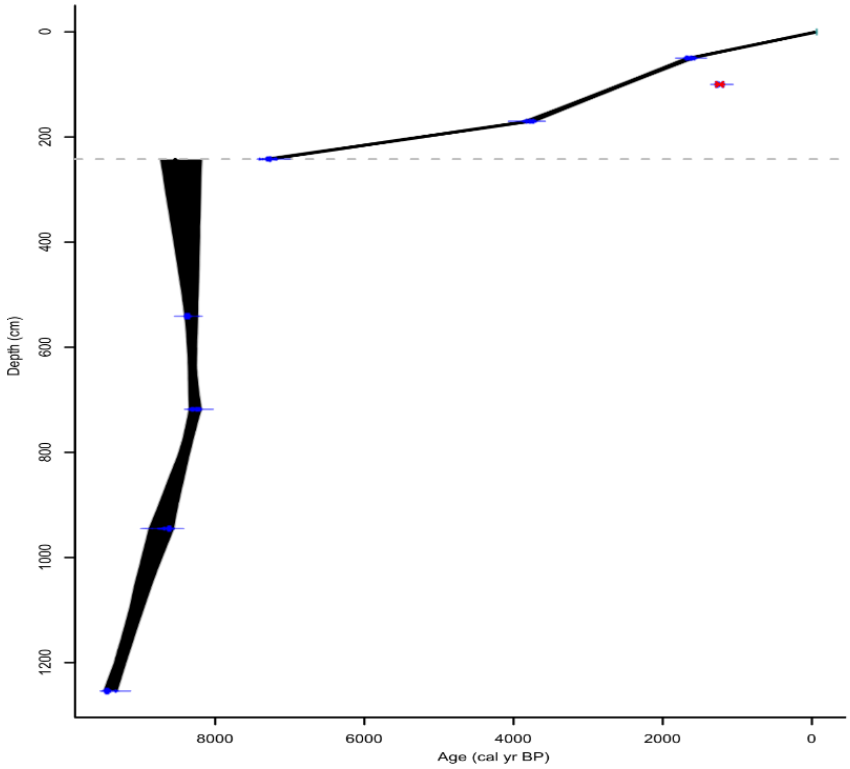

Figure C1: Hiatus break in the linear interpolation age-depth model of Catalina Bay.

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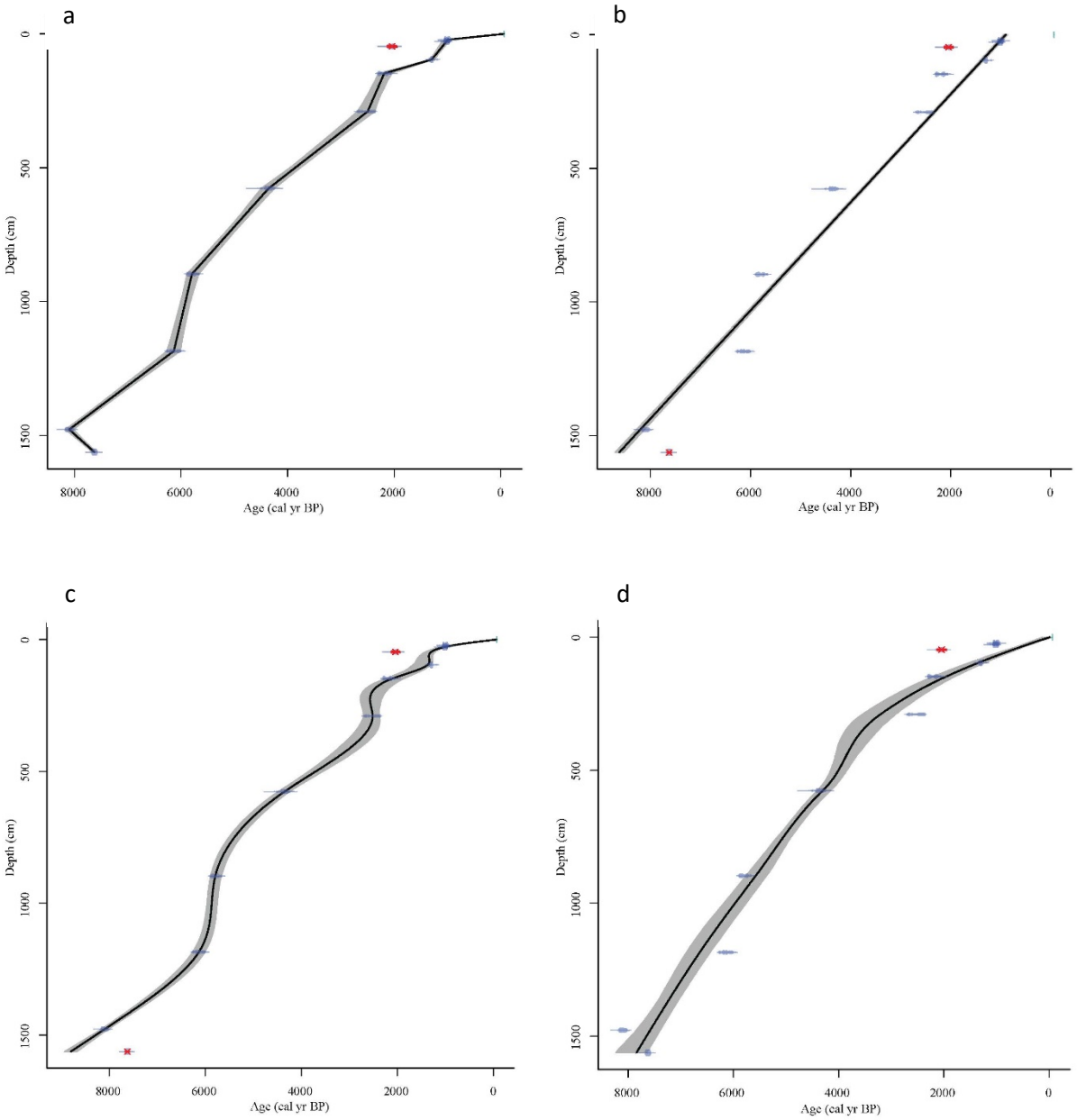


Figure C2: Age-depth models for North Lake illustrating a) linear interpolation, b) linear regression, c) smooth spline and d) loess models.

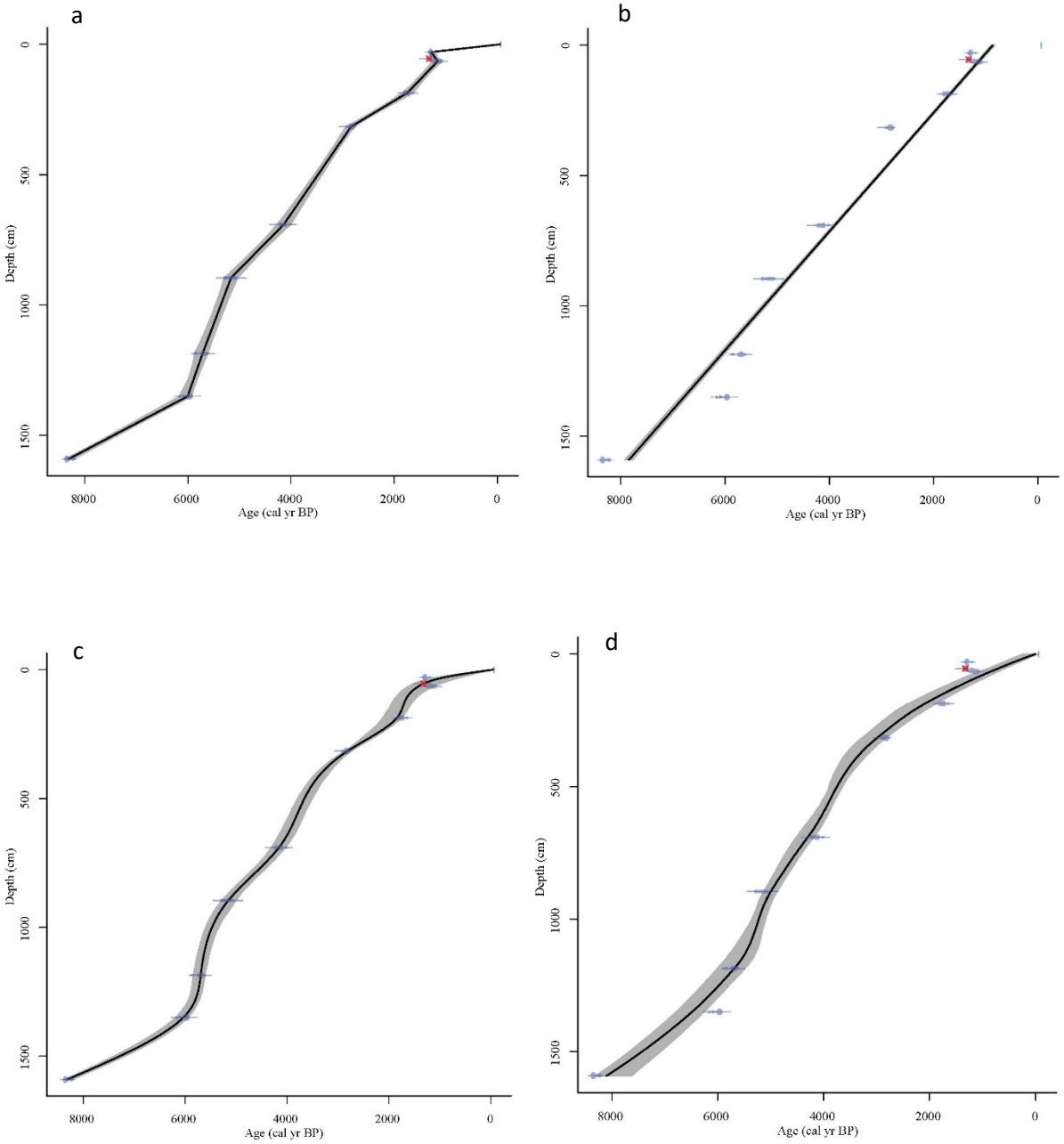
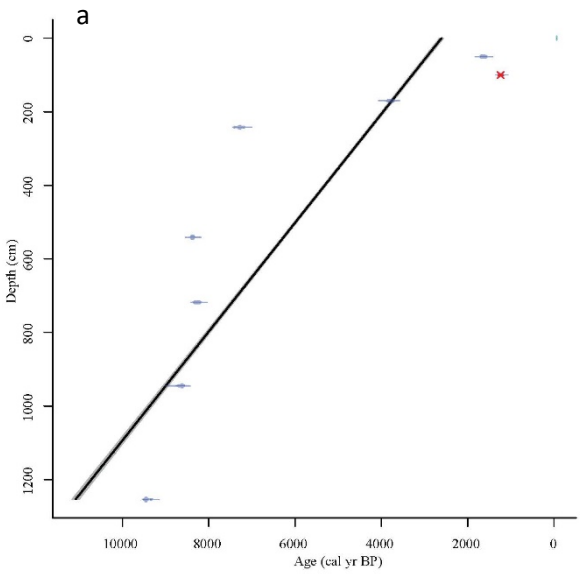
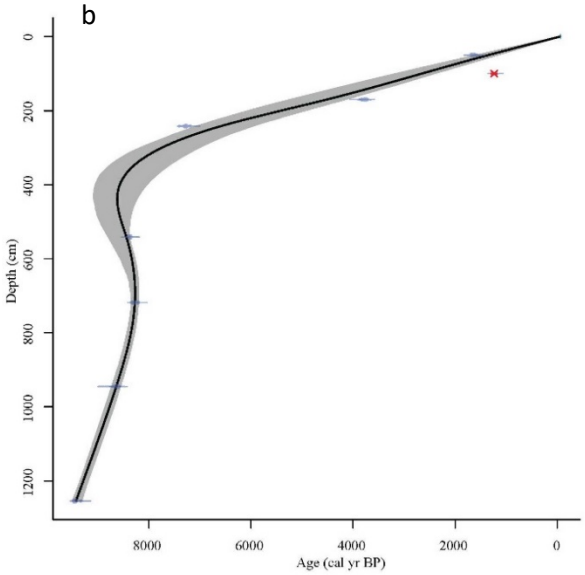
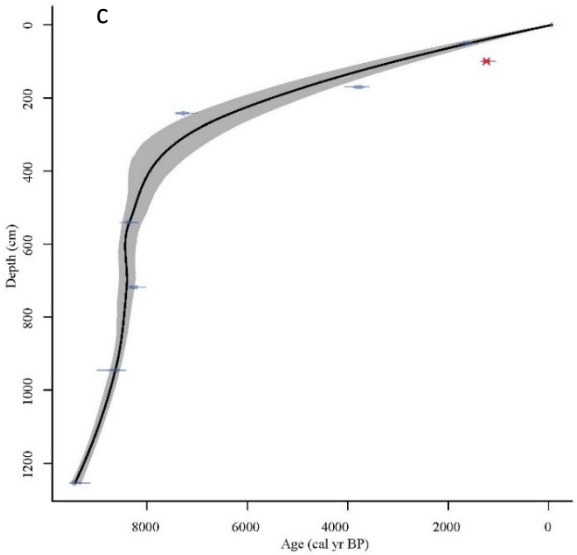


Figure C3: Age-depth models for False Bay illustrating a) linear interpolation, b) linear regression, c) smooth spline and d) loess models.


a
Depth (cm)
0
200
400
600
800
1000
1200
10000
8000
6000
4000
2000
0
Age (cal yr BP)


b
Depth (cm)
0
200
400
600
800
1000
1200
8000
6000
4000
2000
0
Age (cal yr BP)


c
Depth (cm)
0
200
400
600
800
1000
1200
8000
6000
4000
2000
0
Age (cal yr BP)

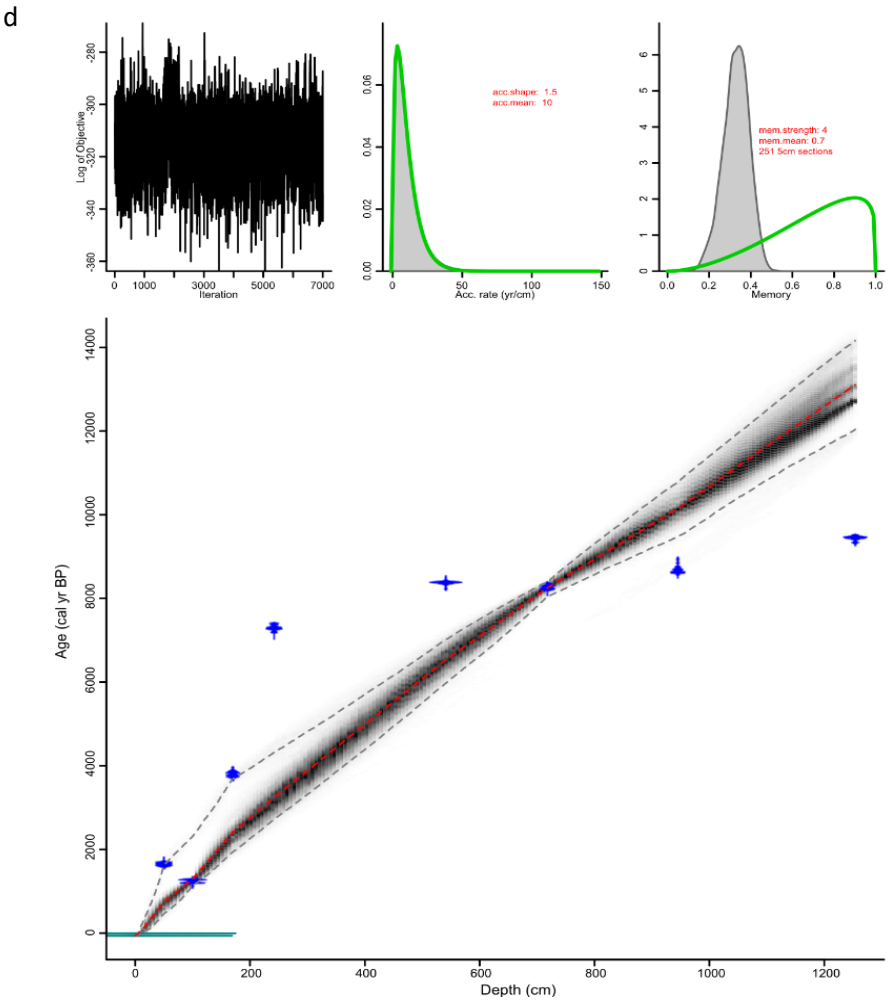


Figure C4: Age-depth models for Catalina Bay illustrating a) linear regression, b) smooth spline, c) loess models and d) the Bayesian model.

APPENDIX D: Raw fossil ostracod datasets

Table D1: Raw fossil ostracod dataset for North Lake.

Depth (cm)	70	90	220	230	260	270	610	660	730	740	750
A. favornamentata single valve	32	1	0	0	4	0	0	0	0	0	0
A. favornamentata double valve	23	1	0	0	1	0	0	0	0	0	0
S. knysnaensis single valve	4	0	0	0	1	6	0	3	38	18	2
S. knysnaensis double valve	0	0	0	1	1	1	0	2	7	9	1
A. westfordensis single valve	65	0	0	0	1	0	21	0	0	0	0
A. westfordensis double valve	30	0	0	0	0	0	3	0	0	0	0
Cyprideis spp. single valve	0	1	3	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	0	0	0	0	0	0	0	0	0
C. limbocostata single valve	0	0	0	0	0	0	0	0	0	0	0
C. limbocostata double valve	0	0	0	0	0	0	0	0	0	0	0
Bonnyannella sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Bonnyannella sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. B single valve	0	0	0	0	0	0	0	0	0	0	0
M. dayii single valve	0	0	0	0	0	0	0	0	0	0	0
M. dayii double valve	0	0	0	0	0	0	0	0	0	0	0
P, estuaria single valve	8	0	0	0	0	0	0	0	0	0	0
P. estuaria double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis aff. *Crenulata* single valve	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* single valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* double valve	0	0	0	0	0	0	0	0	0	0	0
C. eulitoralis single valve	0	0	0	0	0	0	0	0	0	0	0
Cyterella sp. single valve	0	0	0	0	0	0	0	0	0	0	0
M. ochracea single valve	0	0	0	0	0	0	0	0	0	0	0
M. ochracea double valve	0	0	0	0	0	0	0	0	0	0	0
Sp. E single valve	0	0	0	0	0	0	0	0	0	0	0
Sp. E double valve	0	0	0	0	0	0	0	0	0	0	0
Aurila sp. single valve	0	0	0	0	0	0	0	0	0	0	0
S. clavularis single valve	0	0	0	0	0	0	0	0	0	0	0
P. lepraloides single valve	0	0	0	0	0	0	0	0	0	0	0
Undetermined	0	0	0	0	0	0	0	0	0	0	0

Depth (cm)	780	790	830	860	890	900	1020	1060	1220	1230	1260
A. favornamentata single valve	0	0	0	0	1	0	0	0	0	1	1
A. favornamentata double valve	0	0	0	0	0	0	0	0	0	0	0
S. knysnaensis single valve	8	97	2	8	1	3	1	0	4	13	0
S. knysnaensis double valve	4	22	1	1	2	1	2	3	2	1	1
A. westfordensis single valve	0	0	0	0	0	0	0	0	0	0	0
A. westfordensis double valve	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. single valve	1	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	0	0	0	0	0	0	0	0	0
C. limbocostata single valve	0	0	0	0	0	0	0	0	0	0	0
C. limbocostata double valve	0	0	0	0	0	0	0	0	0	0	0
Bonnyannella sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Bonnyannella sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. B single valve	0	0	0	0	0	0	0	0	0	0	0
M. dayii single valve	0	0	0	0	0	0	0	0	0	0	0
M. dayii double valve	0	0	0	0	0	0	0	0	0	0	0
P, estuaria single valve	0	0	0	0	0	0	0	0	0	0	0
P. estuaria double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis aff. *Crenulata* single valve	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. single valve	0	0	0	0	0	0	0	0	0	2	0
Ruggieria sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* single valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* double valve	0	0	0	0	0	0	0	0	0	0	0
C. eulitoralis single valve	0	0	0	0	0	0	0	0	0	0	0
Cyterella sp. single valve	0	0	0	0	0	0	0	0	0	0	0
M. ochracea single valve	0	0	0	0	0	0	0	0	0	0	0
M. ochracea double valve	0	0	0	0	0	0	0	0	0	0	0
Sp. E single valve	0	0	0	0	0	0	0	0	0	0	0
Sp. E double valve	0	0	0	0	0	0	0	0	0	0	0
Aurila sp. single valve	0	0	0	0	0	0	0	0	0	0	0
S. clavularis single valve	0	0	0	0	0	0	0	0	0	0	0
P. lepraloides single valve	0	0	0	0	0	0	0	0	0	0	0
Undetermined	0	0	0	0	0	0	0	0	0	0	0

Depth (cm)	1300	1310	1330	1340	1350	1370	1380	1410	1420	1430	1450
A. favornamentata single valve	1	19	10	1	6	2	0	6	0	4	7
A. favornamentata double valve	0	0	0	0	0	0	0	0	0	0	0
S. knysnaensis single valve	29	65	163	168	173	169	176	187	132	125	198
S. knysnaensis double valve	3	4	8	3	14	6	9	10	6	19	21
A. westfordensis single valve	0	1	0	1	5	0	0	4	0	0	12
A. westfordensis double valve	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. single valve	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	0	0	0	0	0	0	1	0	0
C. limbocostata single valve	0	0	0	0	0	0	0	0	0	0	0
C. limbocostata double valve	0	0	0	0	0	0	0	0	0	0	0
Bonnyannella sp. single valve	1	4	2	1	1	5	0	7	0	0	2
Bonnyannella sp. double valve	0	2	0	0	0	0	0	2	0	0	0
Neocaudites sp. single valve	0	0	0	0	1	1	1	0	1	2	15
Neocaudites sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. B single valve	0	0	0	0	1	0	0	0	0	0	0
M. dayii single valve	0	0	0	3	0	0	0	3	1	5	14
M. dayii double valve	0	0	0	0	1	0	0	0	1	0	1
P, estuaria single valve	0	0	0	1	1	0	2	0	2	0	5
P. estuaria double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. single valve	0	0	3	0	0	3	0	0	1	10	21
Xestoleberis sp. double valve	0	0	0	0	0	1	0	0	0	0	9
Xestoleberis aff. *Crenulata* single valve	0	0	0	0	0	0	0	0	1	0	0
Krithe sp. single valve	0	0	0	1	0	1	0	0	0	1	9
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. single valve	0	0	0	0	2	3	0	2	7	3	30
Ruggieria sp. double valve	0	0	0	0	0	0	1	1	0	0	0
Palmoconcha sp. single valve	0	0	0	0	0	0	0	0	8	3	18
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* single valve	0	0	0	0	0	12	6	0	0	9	33
Loxoconcha cf. *algicola* double valve	0	0	0	0	0	0	0	0	0	0	3
C. eulitoralis single valve	0	0	0	0	0	0	1	0	0	2	3
Cyterella sp. single valve	0	0	0	0	0	0	0	0	0	0	6
M. ochracea single valve	0	0	0	0	0	0	0	0	0	2	3
M. ochracea double valve	0	0	0	0	0	0	0	0	0	0	0
Sp. E single valve	0	0	0	0	0	5	2	0	0	3	0
Sp. E double valve	0	0	0	0	0	0	1	0	0	0	0
Aurila sp. single valve	0	0	0	0	0	0	0	0	0	0	0
S. clavularis single valve	0	0	0	0	0	0	0	0	0	0	0
P. lepraloides single valve	0	2	0	0	0	0	0	0	0	0	0
Undetermined	0	0	0	0	0	0	0	0	0	0	0

Depth (cm)	1460	1470	1490	1530	1540	1550	1570
A. favornamentata single valve	9	27	3	0	0	0	0
A. favornamentata double valve	2	8	1	1	0	0	0
S. knysnaensis single valve	122	73	101	0	11	0	1
S. knysnaensis double valve	10	2	8	2	6	0	1
A. westfordensis single valve	0	9	4	0	0	0	0
A. westfordensis double valve	0	3	0	0	0	0	0
Cyprideis spp. single valve	0	0	0	0	0	0	1
Cyprideis spp. double valve	0	0	0	0	0	0	0
C. limbocostata single valve	0	0	0	1	0	0	0
C. limbocostata double valve	0	0	0	1	0	0	0
Bonnyannella sp. single valve	1	4	8	0	0	0	0
Bonnyannella sp. double valve	2	0	1	0	0	0	0
Neocaudites sp. single valve	15	34	5	0	1	0	0
Neocaudites sp. double valve	0	3	0	0	0	0	0
Neocaudites sp. B single valve	0	0	0	0	0	0	0
M. dayii single valve	18	8	1	0	1	0	3
M. dayii double valve	6	1	3	3	2	2	1
P, estuaria single valve	7	6	0	0	0	0	0
P. estuaria double valve	0	0	1	0	0	0	0
Xestoleberis sp. single valve	63	0	0	0	1	0	0
Xestoleberis sp. double valve	14	2	1	0	1	0	0
Xestoleberis aff. *Crenulata* single valve	0	0	0	0	0	0	0
Krithe sp. single valve	5	0	0	0	0	0	1
Krithe sp. double valve	0	0	0	1	0	0	0
Ruggieria sp. single valve	20	38	1	0	1	0	1
Ruggieria sp. double valve	1	2	0	0	0	0	0
Palmoconcha sp. single valve	9	13	5	0	1	0	0
Palmoconcha sp. double valve	0	0	1	0	1	0	0
Loxoconcha cf. *algicola* single valve	13	0	0	0	1	0	2
Loxoconcha cf. *algicola* double valve	1	0	0	0	0	0	0
C. eulitoralis single valve	6	7	0	0	0	0	0
Cyterella sp. single valve	6	14	0	0	0	0	0
M. ochracea single valve	9	5	0	0	1	0	0
M. ochracea double valve	1	0	0	0	2	0	0
Sp. E single valve	8	0	0	0	2	3	6
Sp. E double valve	0	0	0	0	4	1	0
Aurila sp. single valve	0	0	0	0	1	0	0
S. clavularis single valve	0	0	0	0	1	0	0
P. lepraloides single valve	4	0	0	0	0	0	0
Undetermined	0	0	0	0	0	0	2

Table D2: Raw fossil ostracod dataset for False Bay.

Depth (cm)	20	30	50	60	70	110	130	140	170	200	210
A. favornamentata single valve	5	3	114	0	13	1	30	42	0	0	1
A. favornamentata double valve	5	6	79	0	10	1	52	49	0	0	0
S. knysnaensis single valve	0	0	32	0	7	0	31	3	2	3	56
S. knysnaensis double valve	0	1	11	0	3	0	18	1	0	0	12
A. westfordensis single valve	43	21	85	0	62	1	55	82	0	0	2
A. westfordensis double valve	42	16	86	0	39	0	31	87	0	1	0
Cyprideis spp. single valve	1	1	134	0	0	0	0	1	0	2	0
Cyprideis spp. double valve	0	0	11	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. double valve	0	0	0	0	0	0	0	0	0	0	0
M.dayii single valve	0	0	0	0	0	0	0	0	0	0	0
M. dayii double valve	0	0	0	0	0	0	0	0	0	0	0
P. estuaria single valve	0	0	0	0	0	0	0	1	0	0	0
P. estuaria double valve	0	0	0	0	0	0	0	2	0	0	0
Xestoleberis sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis aff. *Crenulata* single valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis aff. *Crenulata* double valve	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* single valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* double valve	0	0	0	0	0	0	0	0	0	0	0
P. lepraloides single valve	0	0	0	0	0	0	0	0	0	0	0
P. lepraloides double valve	0	0	0	0	0	0	0	0	0	0	0
H. salina single valve	0	0	4	0	1	0	0	0	0	0	0
H. salina double valve	0	0	1	0	0	0	2	0	0	0	0
S. clavularis single valve	2	0	0	0	18	0	0	0	0	0	0
S. clavularis double valve	0	0	0	1	4	0	0	0	0	0	0
Aglaiocypris aff. *Eulitoralis* single valve	0	0	0	0	0	0	7	0	0	0	0
Aglaiocypris aff. *eulitoralis* double valve	0	0	0	0	0	0	8	0	0	0	0
Undetermined	0	0	0	0	0	0	3	0	0	0	0

Depth (cm)	240	250	260	280	290	300	320	340	350	360	380
A. favornamentata single valve	0	0	0	5	0	0	0	0	11	2	0
A. favornamentata double valve	0	0	0	0	0	0	0	0	5	4	0
S. knysnaensis single valve	1	5	1	0	1	8	19	0	145	1	1
S. knysnaensis double valve	0	2	0	1	0	2	3	0	43	1	0
A. westfordensis single valve	0	2	1	0	0	0	0	1	0	5	0
A. westfordensis double valve	0	0	0	0	0	0	0	0	1	1	0
Cyprideis spp. single valve	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. double valve	0	0	0	0	0	0	0	0	0	0	0
M.dayii single valve	0	0	0	0	0	0	0	0	0	0	0
M. dayii double valve	0	0	0	0	0	0	0	0	0	0	0
P. estuaria single valve	0	0	0	0	0	0	0	0	0	0	0
P. estuaria double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis aff. *Crenulata* single valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis aff. *Crenulata* double valve	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* single valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* double valve	0	0	0	0	0	0	0	0	0	0	0
P. lepraloides single valve	0	0	0	0	0	0	0	0	0	0	0
P. lepraloides double valve	0	0	0	0	0	0	0	0	0	0	0
H. salina single valve	0	0	0	0	0	0	0	0	0	0	0
H. salina double valve	0	0	0	0	0	0	0	0	0	0	0
S. clavularis single valve	0	0	0	0	0	0	0	0	0	0	0
S. clavularis double valve	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *Eulitoralis* single valve	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *eulitoralis* double valve	0	0	0	0	0	0	0	0	0	0	0
Undetermined	0	0	0	0	0	0	0	0	0	0	0

Depth (cm)	470	500	540	700	710	810	820	830	900	930	1020
A. favornamentata single valve	0	0	0	0	0	0	0	0	0	0	0
A. favornamentata double valve	0	0	0	0	0	0	0	0	0	0	0
S. knysnaensis single valve	7	4	0	6	0	3	1	2	1	0	3
S. knysnaensis double valve	1	0	1	1	0	1	0	0	2	2	0
A. westfordensis single valve	0	0	0	1	3	0	0	0	0	0	0
A. westfordensis double valve	0	0	0	2	0	0	0	0	0	0	0
Cyprideis spp. single valve	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. double valve	0	0	0	0	0	0	0	0	0	0	0
M.dayii single valve	0	0	0	0	0	0	0	0	0	0	0
M. dayii double valve	0	0	0	0	0	0	0	0	0	0	0
P. estuaria single valve	0	0	0	0	0	0	0	0	0	0	0
P. estuaria double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis aff. *Crenulata* single valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis aff. *Crenulata* double valve	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* single valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* double valve	0	0	0	0	0	0	0	0	0	0	0
P. lepraloides single valve	0	0	0	0	0	0	0	0	0	0	0
P. lepraloides double valve	0	0	0	0	0	0	0	0	0	0	0
H. salina single valve	0	0	0	0	0	0	0	0	0	0	0
H. salina double valve	0	0	0	0	0	0	0	0	0	0	0
S. clavularis single valve	0	0	0	0	0	0	0	0	0	0	0
S. clavularis double valve	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *Eulitoralis* single valve	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *eulitoralis* double valve	0	0	0	0	0	0	0	0	0	0	0
Undetermined	0	0	0	0	0	0	0	0	0	0	0

Depth (cm)	1030	1050	1060	1070	1210	1220	1230	1270	1310	1350	1380
A. favornamentata single valve	0	0	0	0	0	0	0	0	0	0	0
A. favornamentata double valve	0	0	0	0	0	0	0	0	0	0	0
S. knysnaensis single valve	3	2	4	7	15	1	0	2	6	1	26
S. knysnaensis double valve	1	2	5	3	4	2	0	0	1	0	17
A. westfordensis single valve	0	0	0	0	0	0	0	0	0	0	0
A. westfordensis double valve	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. single valve	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. double valve	0	0	0	0	0	0	0	0	0	0	0
M.dayii single valve	0	0	0	0	0	0	0	0	0	0	0
M. dayii double valve	0	0	0	0	0	0	0	0	0	0	0
P. estuaria single valve	0	0	0	0	0	0	0	0	0	0	0
P. estuaria double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. single valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis aff. *Crenulata* single valve	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis aff. *Crenulata* double valve	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. single valve	0	0	0	0	0	4	1	0	0	0	0
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. single valve	0	0	0	0	1	1	0	0	0	0	0
Ruggieria sp. double valve	0	0	0	0	2	1	0	0	0	0	0
Palmoconcha sp. single valve	0	0	0	0	2	0	0	0	0	0	1
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* single valve	0	0	0	0	0	0	0	1	0	0	1
Loxoconcha cf. *algicola* double valve	0	0	1	0	0	0	0	0	0	0	0
P. lepraloides single valve	0	0	0	0	0	0	0	0	0	0	0
P. lepraloides double valve	0	0	0	0	0	0	0	0	0	0	0
H. salina single valve	0	0	0	0	0	0	0	0	0	0	0
H. salina double valve	0	0	0	0	0	0	0	0	0	0	0
S. clavularis single valve	0	0	0	0	0	0	0	0	0	0	0
S. clavularis double valve	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *Eulitoralis* single valve	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *eulitoralis* double valve	0	0	0	0	0	0	0	0	0	0	0
Undetermined	0	0	0	0	0	0	0	0	0	0	0

Depth (cm)	1410	1430	1450	1460	1470	1490	1500	1510	1530	1550	1570	1580
A. favornamentata single valve	0	0	0	0	0	0	0	0	0	0	0	1
A. favornamentata double valve	0	0	0	0	0	0	0	0	0	0	0	1
S. knysnaensis single valve	2	7	10	3	17	8	7	7	3	4	11	15
S. knysnaensis double valve	3	2	3	2	2	2	1	0	2	1	2	7
A. westfordensis single valve	0	0	0	0	0	0	0	0	0	0	0	0
A. westfordensis double valve	0	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. single valve	0	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	0	0	0	0	0	0	0	1	0	0	1	2
Neocaudites sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0
M.dayii single valve	0	0	0	0	0	0	0	0	0	0	0	2
M. dayii double valve	0	0	0	0	0	0	0	0	0	0	2	2
P. estuaria single valve	0	0	0	0	0	0	0	0	0	0	0	0
P. estuaria double valve	0	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. single valve	0	0	0	0	0	0	0	0	0	0	0	4
Xestoleberis sp. double valve	0	0	0	0	0	0	0	0	0	0	2	10
Xestoleberis aff. *Crenulata* single valve	0	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis aff. *Crenulata* double valve	0	0	0	0	0	0	0	1	0	0	0	0
Krithe sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. single valve	0	0	0	1	0	0	0	1	0	0	3	2
Ruggieria sp. double valve	0	0	0	0	0	0	0	0	0	0	2	1
Palmoconcha sp. single valve	0	0	0	0	0	1	0	0	0	0	0	3
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0	1
Loxoconcha cf. *algicola* single valve	0	1	2	1	0	0	0	1	0	0	1	0
Loxoconcha cf. *algicola* double valve	0	0	0	0	0	0	0	0	0	0	0	0
P. lepraloides single valve	0	0	0	0	0	0	0	1	0	0	0	0
P. lepraloides double valve	0	0	0	0	0	0	0	0	0	0	0	0
H. salina single valve	0	0	0	0	0	0	0	0	0	0	0	0
H. salina double valve	0	0	0	0	0	0	0	0	0	0	0	0
S. clavularis single valve	0	0	0	0	0	0	0	0	0	0	0	0
S. clavularis double valve	0	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *Eulitoralis* single valve	0	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *eulitoralis* double valve	0	0	0	0	0	0	0	0	0	0	0	0
Undetermined	0	0	0	0	0	0	0	0	0	0	0	0

Table D3: Raw fossil ostracod dataset Catalina Bay

Depth (cm)	10	20	30	50	60	210	220	230	270	330	350	370	410
A. favornamentata single valve	0	0	1	0	0	0	0	0	0	0	0	0	0
A. favornamentata double valve	0	0	3	2	0	0	0	0	0	0	0	0	0
S. knysnaensis single valve	1	5	13	18	2	4	1	0	23	0	3	6	4
S. knysnaensis double valve	3	9	6	9	1	0	2	0	11	2	0	0	4
A. westfordensis single valve	0	0	1	21	2	0	0	0	0	0	0	0	0
A. westfordensis double valve	0	0	1	4	0	0	0	0	0	0	0	0	0
Cyprideis spp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	0	0	0	0	0	0	0	0	0	0	2	1	3
Neocaudites sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. B single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. B double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M. dayii single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M. dayii double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
P. estuaria single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
P. estuaria double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. single valve	0	0	0	0	0	0	0	0	0	0	2	2	0
*Ruggieria s*p. double valve	0	0	0	0	0	0	0	0	0	0	1	1	1
Palmoconcha sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* single valve	0	0	0	0	0	0	1	0	0	0	0	0	0
Loxoconcha cf. *algicola* double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
C. eulitoralis single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
C. eulitoralis double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyterella sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyterella sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M.ochracea single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M. ochracea double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytherura sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytherura sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Sp. E single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Sp. E double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aurila sp.single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aurila sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
S. clavularis single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Mutilus sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Mutilus sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *eulitoralis* single valve	0	0	0	0	0	0	0	0	0	0	0	1	0
Aglaiocypris aff. e*ulitoralis* double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytheridea sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytheridea sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Undeteremined	0	0	0	0	0	0	0	0	0	0	0	0	0

Depth (cm)	420	490	500	510	530	540	550	570	580	610	620	630	650
A. favornamentata single valve	0	2	0	0	0	0	1	0	0	1	0	0	0
A. favornamentata double valve	0	0	0	0	3	0	0	0	0	0	1	0	0
S. knysnaensis single valve	4	15	4	8	7	0	2	0	0	11	27	16	16
S. knysnaensis double valve	0	7	2	2	2	1	2	0	0	6	26	6	7
A. westfordensis single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
A. westfordensis double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	1	1	0	0	5	0	0	0	0	0	4	1	5
Neocaudites sp. double valve	1	0	0	1	0	0	0	0	0	0	2	0	0
Neocaudites sp. B single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. B double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M. dayii single valve	0	0	0	0	0	0	0	0	1	0	5	3	5
M. dayii double valve	0	0	0	0	0	0	0	1	0	0	1	1	7
P. estuaria single valve	0	0	0	0	0	2	0	0	0	0	0	0	0
P. estuaria double valve	0	0	0	0	0	0	0	0	0	0	0	0	1
Xestoleberis sp. single valve	0	0	0	0	2	0	0	0	0	0	0	0	6
Xestoleberis sp. double valve	0	0	0	0	0	0	0	0	0	1	5	2	2
Krithe sp. single valve	0	0	1	0	0	0	0	0	0	0	0	0	3
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	1	0	0	1
Ruggieria sp. single valve	2	2	1	0	0	0	1	0	0	1	1	0	1
*Ruggieria s*p. double valve	0	1	0	1	1	1	0	0	0	0	0	0	0
Palmoconcha sp. single valve	0	0	0	0	0	0	0	0	0	1	4	2	0
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0	2	0
Loxoconcha cf. *algicola* single valve	0	0	0	0	0	0	0	0	1	0	0	0	3
Loxoconcha cf. *algicola* double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
C. eulitoralis single valve	0	0	0	0	0	0	0	0	0	0	1	0	17
C. eulitoralis double valve	0	0	0	0	0	0	0	0	0	1	9	4	11
Cyterella sp. single valve	0	0	0	0	1	0	0	0	0	0	0	0	0
Cyterella sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M.ochracea single valve	0	0	0	1	0	0	0	0	0	0	0	0	7
M. ochracea double valve	0	0	0	0	0	0	0	0	0	0	3	0	2
Cytherura sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytherura sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Sp. E single valve	0	0	0	0	0	0	0	0	0	0	0	2	7
Sp. E double valve	0	0	0	0	0	0	0	0	0	1	1	1	6
Aurila sp.single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aurila sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
S. clavularis single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Mutilus sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	2
Mutilus sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *eulitoralis* single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. e*ulitoralis* double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytheridea sp. single valve	0	0	2	0	6	0	0	0	0	3	3	3	13
Cytheridea sp. double valve	0	0	0	1	0	0	0	0	1	1	2	3	2
Undeteremined	0	2	0	0	0	0	0	0	0	2	2	0	3

Depth (cm)	660	670	690	700	710	730	740	750	770	780	820	830	860
A. favornamentata single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
A. favornamentata double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
S. knysnaensis single valve	23	12	15	7	8	6	21	26	0	0	3	0	0
S. knysnaensis double valve	18	4	7	8	5	7	10	14	0	0	1	1	1
A. westfordensis single valve	0	0	0	0	0	0	0	1	0	0	0	0	0
A. westfordensis double valve	0	0	0	0	0	0	0	0	0	0	0	0	1
Cyprideis spp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	1	6	1	0	0	0	0	1	0	0	0	0	0
Neocaudites sp. double valve	1	0	1	1	0	0	0	0	0	0	0	0	0
Neocaudites sp. B single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. B double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M. dayii single valve	17	13	22	3	9	6	7	0	0	0	0	0	0
M. dayii double valve	9	5	13	9	21	2	9	2	0	0	0	0	0
P. estuaria single valve	3	0	0	0	0	2	0	0	0	0	0	0	0
P. estuaria double valve	0	0	0	0	0	0	0	2	0	0	0	0	0
Xestoleberis sp. single valve	13	1	7	11	7	3	8	0	0	0	0	0	0
Xestoleberis sp. double valve	5	2	0	4	5	5	9	2	0	0	0	0	0
Krithe sp. single valve	0	0	1	3	1	0	3	0	0	0	0	0	0
Krithe sp. double valve	2	1	2	1	2	0	1	0	0	0	0	0	0
Ruggieria sp. single valve	2	1	0	0	0	0	0	0	0	0	0	0	0
*Ruggieria s*p. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* single valve	24	8	8	8	8	17	17	4	0	0	0	0	0
Loxoconcha cf. *algicola* double valve	5	2	0	1	6	6	3	2	0	0	0	0	0
C. eulitoralis single valve	22	20	17	4	1	3	2	1	0	0	0	0	0
C. eulitoralis double valve	24	16	5	2	2	5	0	1	0	0	0	0	0
Cyterella sp. single valve	5	0	0	0	0	0	0	0	0	0	0	0	0
Cyterella sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M.ochracea single valve	6	3	9	0	2	3	3	0	0	0	0	0	0
M. ochracea double valve	7	0	0	0	1	5	2	0	0	0	0	0	0
Cytherura sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytherura sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Sp. E single valve	9	10	9	6	5	5	12	0	0	0	0	0	0
Sp. E double valve	5	2	7	4	3	11	9	3	0	0	0	0	0
Aurila sp.single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aurila sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
S. clavularis single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Mutilus sp. single valve	0	2	0	2	0	0	0	0	0	0	0	0	0
Mutilus sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *eulitoralis* single valve	0	0	0	0	0	0	0	0	1	0	0	0	0
Aglaiocypris aff. e*ulitoralis* double valve	0	0	0	0	0	0	0	0	0	1	0	0	0
Cytheridea sp. single valve	17	8	6	1	0	2	8	0	0	0	0	0	0
Cytheridea sp. double valve	5	0	1	1	0	3	5	0	0	0	0	0	0
Undeteremined	0	0	0	0	3	4	3	0	0	2	0	0	0

Depth (cm)	910	940	980	1020	1030	1040	1070	1080	1090	1100	1110	1170	1210
A. favornamentata single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
A. favornamentata double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
S. knysnaensis single valve	6	0	2	4	1	2	3	1	0	0	0	0	0
S. knysnaensis double valve	0	0	0	5	0	1	0	2	0	0	0	0	0
A. westfordensis single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
A. westfordensis double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. single valve	0	0	5	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	2	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. B single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. B double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M. dayii single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M. dayii double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
P. estuaria single valve	0	0	0	0	0	0	1	0	0	0	0	0	0
P. estuaria double valve	0	1	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. single valve	0	0	2	0	0	0	0	0	0	0	0	1	0
Xestoleberis sp. double valve	0	0	,	0	0	0	0	0	0	0	0	0	0
Krithe sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. single valve	0	0	0	0	0	1	0	1	1	1	2	1	0
*Ruggieria s*p. double valve	0	0	0	0	0	0	0	0	1	0	0	0	0
Palmoconcha sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cf. *algicola* single valve	0	0	0	0	0	0	1	0	0	0	0	0	0
Loxoconcha cf. *algicola* double valve	0	0	0	0	0	0	0	0	0	0	0	1	0
C. eulitoralis single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
C. eulitoralis double valve	0	0	0	0	0	0	0	0	0	0	0	0	2
Cyterella sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyterella sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M.ochracea single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
M. ochracea double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytherura sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytherura sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Sp. E single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Sp. E double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aurila sp.single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aurila sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
S. clavularis single valve	0	0	8	0	0	0	0	0	0	0	0	0	0
Mutilus sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Mutilus sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. *eulitoralis* single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Aglaiocypris aff. e*ulitoralis* double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytheridea sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytheridea sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0
Undeteremined	0	0	0	0	0	0	0	0	0	0	0	0	0

Depth (cm)	1220	1240	1260	1270	1280	1290	1300	1310	1320	1330	1340	1350	1360	1370
A. favornamentata single valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A. favornamentata double valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S. knysnaensis single valve	0	0	3	1	7	0	3	0	4	6	0	3	7	2
S. knysnaensis double valve	0	0	0	2	3	0	2	0	3	4	3	7	0	3
A. westfordensis single valve	0	0	0	0	0	0	0	15	0	8	0	0	0	10
A. westfordensis double valve	0	0	0	0	0	0	0	4	0	3	0	0	0	1
Cyprideis spp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyprideis spp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Neocaudites sp. single valve	0	0	0	4	1	4	18	12	0	16	0	33	12	0
Neocaudites sp. double valve	0	0	0	1	2	4	10	15	0	5	0	14	7	0
Neocaudites sp. B single valve	0	0	0	0	0	0	0	0	12	0	0	0	0	15
Neocaudites sp. B double valve	0	0	0	0	0	0	0	0	6	0	0	0	0	2
M. dayii single valve	0	0	0	1	0	0	0	0	0	0	0	1	0	0
M. dayii double valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P. estuaria single valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P. estuaria double valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. single valve	0	0	15	15	23	23	32	52	86	61	72	62	28	72
Xestoleberis sp. double valve	0	0	24	26	42	29	9	15	33	11	33	22	3	15
Krithe sp. single valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Krithe sp. double valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ruggieria sp. single valve	0	1	3	0	8	5	25	15	19	25	28	37	21	18
*Ruggieria s*p. double valve	0	0	5	2	9	3	11	17	14	19	19	39	12	17
Palmoconcha sp. single valve	0	0	0	0	0	0	0	0	0	0	0	6	6	0
Palmoconcha sp. double valve	0	0	0	0	0	0	0	0	0	0	0	8	3	0
Loxoconcha cf. *algicola* single valve	0	0	4	2	11	17	4	5	10	13	6	0	0	12
Loxoconcha cf. *algicola* double valve	0	0	31	24	41	28	8	8	9	5	14	0	0	7
C. eulitoralis single valve	0	0	8	1	2	8	1	0	7	2	2	1	0	4
C. eulitoralis double valve	1	0	17	9	27	26	9	11	17	6	18	6	8	11
Cyterella sp. single valve	0	0	1	0	0	5	7	11	14	26	15	2	1	3
Cyterella sp. double valve	0	0	5	4	0	2	5	19	23	6	19	4	3	9
M.ochracea single valve	0	0	0	0	2	8	4	4	4	3	0	0	0	2
M. ochracea double valve	0	0	0	1	4	3	2	0	5	1	0	0	0	0
Cytherura sp. single valve	0	0	0	0	3	0	0	0	0	0	0	0	0	0
Cytherura sp. double valve	0	0	0	0	8	4	0	0	0	0	0	0	0	0
Sp. E single valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sp. E double valve	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Aurila sp.single valve	0	0	2	0	5	10	11	3	3	4	4	0	0	0
Aurila sp. double valve	0	0	8	9	9	11	7	1	0	0	0	0	0	0
S. clavularis single valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mutilus sp. single valve	0	0	8	5	4	28	11	19	0	0	15	16	11	3
Mutilus sp. double valve	0	0	3	13	6	17	3	5	0	0	4	4	3	2
Aglaiocypris aff. *eulitoralis* single valve	0	0	3	2	6	3	0	0	12	18	10	14	12	0
Aglaiocypris aff. *eulitoralis* double valve	0	0	7	7	7	4	0	0	10	2	2	6	1	0
Cytheridea sp. single valve	0	0	0	0	0	0	0	0	24	0	0	0	0	0
Cytheridea sp. double valve	0	0	0	0	0	0	0	0	3	0	0	0	0	0
Undeteremined	0	0	0	0	2	6	0	0	0	0	0	0	4	0

APPENDIX E: Training dataset

Table E1: Modern ostracod training dataset

Sample	ZA 14/48	ZA 14/50	ZA 14/52	ZA 14/54	ZA 14/55	ZA 14/56	ZA 14/57	ZA 14/58	ZA 14/60	ZA 14/61	ZA 14/62
Locality	Kosi Bay	Kosi Bay	Kosi Bay	Kosi Bay mouth	Kosi Bay mouth	Kosi Bay mouth	Kosi Bay mouth	Kosi Bay mouth	Kosi Bay	Kosi Bay	Kosi Bay
Salinity (psu)	2,1	2,1	7,4	7,4	3,3	2,1	2,1	2,1	34,6	32,3	32,3
P. estuaria	27	10	72	12	25	19	62	428	42	82	136
S. knysnaensis	0	0	0	0	0	0	0	0	0	0	0
C. milleri	294	0	0	192	110	2	0	0	47	98	0
C. limbocostata	186	2	0	25	73	332	78	25	0	0	0
A. favornamentata	0	28	320	0	0	0	0	8	0	0	0
Paradoxostoma spp.	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. 1	0	0	0	0	1	0	0	0	0	0	0
Xestoleberis sp. 2	0	0	0	0	4	0	0	0	0	0	0
Hemicythere? sp.	0	0	0	0	0	0	0	0	0	0	0
A. westfordensis	0	23	0	5	13	9	30	0	4	0	0
S. aculeata	0	0	0	0	0	0	0	0	0	0	0
Physocypria sp.	0	0	0	0	0	0	0	0	0	0	0
Leucocythere?	0	0	0	0	0	0	0	0	0	0	0
Candoninae	0	0	0	0	0	0	0	0	0	0	0
cf. *Neocythereis*	0	0	0	0	0	0	0	0	0	0	0
Bairdia sp.	0	0	0	0	2	0	0	0	0	0	0
Cytherella spp.	0	0	0	0	2	0	0	0	0	0	0
Cytheridea	0	0	0	0	2	0	0	0	0	0	0
M. bensonmaddocksorum	0	0	0	0	8	0	0	0	0	0	0
Loxoconcha sp. 1	0	0	0	0	3	3	0	0	0	0	0
Loxoconcha sp. 2	0	0	0	0	1	0	0	0	0	0	0

Sample	ZA 14/66	ZA 14/67	ZA 14/68	ZA 14/69	ZA 14/70	ZA 14/71	ZA 14/72	ZA 14/73	ZA 14/75	ZA 14/76
Locality	False Bay, Lake St Lucia	False Bay, Lake St Lucia	False Bay, Lake St Lucia	False Bay, Lake St Lucia	False Bay, Lake St Lucia	False Bay, Lake St Lucia	False Bay, Lake St Lucia	South Lake, Lake St Lucia	South Lake, Lake St Lucia	South Lake, Lake St Lucia
Salinity (psu)	18,9	18,9	18,9	18,9	17,4	17,4	19,2	12,5	12,5	12,5
P. estuaria	0	0	6	0	0	2	1	0	88	32
S. knysnaensis	56	47	63	8	80	80	18	84	14	33
C. milleri	0	0	0	0	0	0	0	0	0	0
C. limbocostata	633	293	162	58	246	249	260	0	1	11
A. favornamentata	16	8	4	14	2	0	4	43	11	50
Paradoxostoma spp.	0	0	0	0	0	0	1	0	0	0
Xestoleberis sp. 1	0	0	0	0	0	0	0	0	0	0
Xestoleberis sp. 2	0	0	0	0	0	0	0	0	0	0
Hemicythere? sp.	0	0	0	0	0	0	0	0	0	0
A. westfordensis	46	47	19	10	4	32	10	5	6	2
S. aculeata	3	1	0	0	0	0	1	0	0	0
Physocypria sp.	0	0	1	0	0	0	0	0	0	0
Leucocythere?	0	0	0	0	0	0	0	0	2	0
Candoninae	0	1	0	0	0	0	0	0	0	0
cf. *Neocythereis*	0	0	0	0	0	1	0	0	0	2
Bairdia sp.	0	0	0	0	0	0	0	0	0	0
Cytherella spp.	0	0	0	0	0	0	0	0	0	0
Cytheridea	0	0	1	0	0	0	0	0	0	0
M. bensonmaddocksorum	0	0	0	0	0	0	0	0	0	0
Loxoconcha sp. 1	0	0	0	0	0	0	0	0	0	0
Loxoconcha sp. 2	0	0	0	0	0	0	0	0	0	0

APPENDIX F: Salinity range

Table F1: Ostracod salinity ranges

Ostracod taxa	Salinity (psu)		Reference
	Living	Valves	
S. clavularis	Freshwater		Karanovic, 2012
H. salina	0.4-8.6		Frenzel *et al*. 2010
A. favornamentata	0-10	35	Meschner *et al.* unpublished (living); Fürstenberg *et al*. 2017 (valves)
A. westfordensis	0-10	0-36	Meschner *et al.* unpublished (living); Fürstenberg *et al*. 2017 (valves)
C. eulitoralis			No published data
S. knysnaensis	10-35	1-35	Meschner *et al.* unpublished
	28	28-35	Fürstenberg *et al*. 2017
M.dayii	11-35	10-35	Meschner *et al.* unpublished
Cytherura			No published data
Xestoleberis spp.	18-35	1-37	Meschner *et al.* unpublished
		0-180	Fürstenberg *et al.* 2017
M. ochracea			No published data
Mutilus sp.			No published data
P. lepraloides		34-35	Dingle *et al*. 1996
Cytherella sp.	33-35	33	Meschner *et al*. unpublished
Palmoconcha sp.	25-35	25-35	Meschner *et al.* unpublished
Aurila sp.			No published data
Aglaiocypris sp.	33-34	33-34	Meschner *et al.* unpublished
Cytheridea			No published data
Neocaudites spp.	Marine		Dingle *et al*. 1996
Ruggieria sp.	Marine		Dingle *et al*. 1996
Krithe sp.	Marine		Dingle *et al*. 1993
Bonnyannella sp.			No published data
Loxoconcha cf. algicola			No published data
Cyprideis spp.		32-180	Fürstenberg *et al.* 2017
P. estuaria	0-37	0-37	Meschner *et al.* unpublished