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Holocene relative sea-level changes in Cleveland Bay, North Queensland, Australia

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Thesis submitted for the degree of Doctor of Philosophy

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Sarah Woodroffe, Durham, April 2006.

PHD THESIS ABSTRACT

Sarah Alice Woodroffe

Holocene relative sea-level changes in Cleveland Bay, North Queensland, Australia

Durham University, April 2006

Full understanding of sea level, ice sheet and earth interactions during the Holocene, and the impact of current and future global sea-level rise requires observations of Holocene relative sea-level change from both near- and far-field locations. North Queensland is an ideal far-field location for testing models of mid/late Holocene global meltwater discharge and the viscosity structure of the solid earth, despite problems with indicators and gaps in its Holocene sea-level record.

This thesis addresses inadequacies in the record of Holocene sea-level changes in North Queensland using for the first time a foraminifera-based transfer function, which employs vertically zoned modern intertidal and shallow subtidal calcareous foraminifera to reconstruct past water-level changes from fossil foraminiferal assemblages. This technique provides reconstructions which are of equal or greater vertical precision than reconstructions using mangrove mud or coral indicators on this coastline. AMS ^{14}C dated calcareous foraminifera provide intra-site correlation of environmental and sea-level changes over the past 6000 calibrated years.

This thesis also highlights problems which limit the applicability of the transfer function technique in this environment, including poor preservation of agglutinated foraminifera in fossil sediments and reworking of Holocene intertidal and shallow subtidal sediments which is not obvious from visual, bio- or litho-stratigraphical analysis.

By creating new sea-level index points and re-calibrating existing ones from other indicators I infer the general form of the mid/late Holocene sea-level record in central North Queensland as sea level rising above its present value prior to 6700 cal years BP, with relatively stable sea level 1-2.3 m above present between 6700-5000 cal years BP, and between 1-2.8 m above present between 5000-3000 cal years BP. This is followed by sea-level fall to between 0.4-0.8 m above present until 1200 cal years BP and subsequent slow fall to present. This sea-level data supports theories suggested by geophysical models of a gradual end to global ice sheet melt, with melting ending after 5000 cal years BP.

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John Whittaker at the Natural History Museum provided invaluable advice on foraminifera taxonomy and amazing SEM photographs of my species, Steve Juggins at Newcastle helped hugely with transfer-function development and Glenn Milne at Durham kindly gave his geophysical model predictions of Holocene sea-level change in Cleveland Bay.

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Finally I want to thank my partner, Jim, and my family for being incredibly supportive throughout, and for reminding me when things were difficult that there is life outside of your PhD.

CHAPTER ONE - CONTEXT

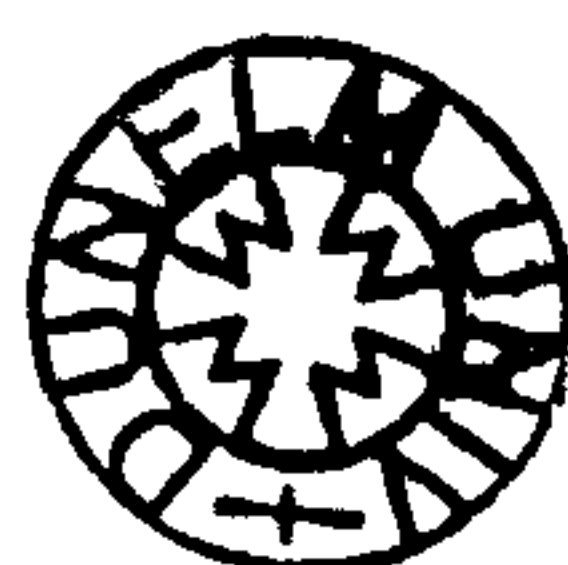
1.1 INTRODUCTION

Transfer of immense volumes of water between ice sheets and oceans characterises fluctuations between glacial and interglacial conditions during the Quaternary (Broecker and Denton, 1989; Alley and Clark, 1999; Lambeck *et al.*, 2002). Since the latest of these glacial fluctuations, the Last Glacial Maximum (LGM), approximately $50 \times 10^6 \text{ km}^3$ of ice has melted from land-based ice sheets, raising global sea level in regions distant from the major glaciation centres (far-field locations) by about 130 metres (Lambeck *et al.*, 2002). In contrast, the position of the sea relative to the land (Relative Sea Level, RSL) has dropped by hundreds of metres in regions once covered by major ice sheets (near-field locations) due to isostatic rebound of the solid Earth following melting of land-based ice (e.g. Belknap, 1987; Shennan and Horton, 2002). Full understanding of sea level, ice sheet and earth interactions requires observations of relative sea-level change from both near- and far-field locations.

The coastline of Northern Queensland in Australia is a particularly important far-field location as relative sea-level reconstructions give information on the nature and response of materials of the crust (Nakada and Lambeck, 1989; Lambeck and Nakada, 1990). Reconstructions through the mid to late Holocene allow modellers to quantify lithospheric thickness and mantle viscosity and establish lateral variations in mantle structure across the continental/oceanic margin, aims not achieved using long records from other far-field locations (Nakada and Lambeck, 1989; Lambeck and Nakada, 1990; Lambeck, 2002). These variables are important to modelling the earth's response to future climate and sea-level change and can be applied to locations where Holocene relative sea-level reconstructions are hard to obtain.

Change in relative sea level ($\Delta\xi_{\text{RSL}}$) at time τ and location φ can be expressed schematically as:

$$\Delta\xi_{\text{RSL}}(\tau, \varphi) = \Delta\xi_{\text{eust}}(\tau) + \Delta\xi_{\text{iso}}(\tau, \varphi) + \Delta\xi_{\text{tect}}(\tau, \varphi) + \Delta\xi_{\text{local}}(\tau, \varphi)$$



Where $\Delta\xi_{\text{eust}}(\tau)$ is the time-dependent eustatic function, $\Delta\xi_{\text{iso}}(\tau, \varphi)$ is the total isostatic effect of the glacial rebound process including both ice (glacio-isostatic) and water (hydro-isostatic) load contributions, $\Delta\xi_{\text{tect}}(\tau, \varphi)$ is any tectonic effect, usually considered negligible on the Holocene time-scale in most studies of Australia (Chappell *et al.*, 1983; Lambeck, 2002), and $\Delta\xi_{\text{local}}(\tau, \varphi)$ is the total effect of local processes at the site involved (Shennan and Horton, 2002).

This thesis analyses and interprets evidence of Holocene sea-level changes in Cleveland Bay, North Queensland, Australia. Section 1.2 defines broad research aims and objectives, sections 1.3 to 1.6 outline major controls on relative sea level in far-field locations, in particular Australia, section 1.7 discusses existing research in this area and section 1.8 defines hypotheses tested in this thesis.

1.2 RESEARCH AIMS

This thesis investigates Holocene relative sea-level changes in Cleveland Bay, North Queensland, Australia. The main aims are:

1. To understand the nature of mid-late Holocene relative sea-level change in Cleveland Bay.
2. To develop quantitative estimates of sea-level change from fossil evidence to help achieve this aim.

Broad research questions arising from these aims are:

1. What indicators can be used in reconstructing Holocene relative sea-level change in North Queensland?
2. What is the pattern of Holocene relative sea-level change in North Queensland?
3. Does application of sea-level index point analysis in sediments help define the mid Holocene high stand?
4. Is the resolution of sea-level data sufficient to differentiate between models of mid Holocene sea level high stand duration and amplitude?

1.3 RECONSTRUCTING SEA LEVEL

1.3.1 Definitions

Sea level refers to a calculated value which in theory is the Mean Sea Level of the ocean if no tidal forces operated. Mean Tide Level is the average of low and high

water over time, varying from place to place, and is normally used in the construction of sea level curves. It is common practice to assume that Mean Sea Level and Mean Tide Level are the same, given the resolution possible in past sea level research (Long, 1991).

Transgression and regression have been used in a wide variety of contexts, with inconsistencies causing confusion in the past (Shennan *et al.*, 1983). Accordingly they are used in a purely descriptive manner to describe a change in lithology up core from a semi-terrestrial to shallow marine deposit (transgression), and the replacement of a shallow marine deposit by a semi-terrestrial deposit (regression). Their usage does not imply any vertical movement of sea level.

Sea-level index point is a point plotted on a graph of relative sea level over time which has an age, elevation, location and tendency. These variables fix the former position of relative sea level at one point in time. Sea-level index points should have both age and elevation errors, so each index point should sit within an error box.

Proxy sea-level indicators including sediments and microfossils provide indirect evidence of former sea-level position.

Indicative meaning is the relationship of a proxy indicator to the environment in which it accumulated and its reference water level. The indicative meaning is made up of the reference water level, the tide level at which the indicator would have accumulated at, and the indicative range, the error term associated with estimating reference water level.

Radiocarbon and calibrated age - all ages derived from radiocarbon analysis used in this thesis are calibrated using Oxcal v.3.10 (Bronk Ramsey, 1995; Hughen *et al.*, 2004) using 95% confidence limits. Error bars indicate maximum and minimum ages defined by this method, with vertical bars depicting median age.

Elevation refers to measurements made to Australian Height Datum (AHD). This is the Australian elevation datum to which all vertical control for mapping is referred. Elevation is quoted in metres AHD (see table 2.1 for the relationship between AHD and mean sea level).

1.3.2 Sea-level indicators and Techniques

Indicators used for relative sea-level reconstruction in northern Queensland

A review of sea-level data from the Indo-Pacific region as a whole (Woodroffe and Horton, 2005) shows that criteria to produce accurate sea-level reconstructions are frequently not met (e.g., relative sea level estimates with large error bands $\pm >1$ m, dating of material which may not be in situ).

Microfossils such as pollen, diatoms, foraminifera or testate amoebae are often preserved in sediments from coastal environments and are widely used in temperate locations to reconstruct sea level because they live at specific heights within the tidal frame (e.g. Gehrels, 1994; Horton *et al.*, 2000; Shennan *et al.*, 2000b). Quantifying their indicative meaning allows better estimation of altitude error used in age/altitude analysis. However, microfossils are infrequently used to reconstruct Holocene sea level on the North Queensland coastline. Other proxy indicators more frequently used are coral, encrusting shells and sediments (e.g. Hopley, 1983; Beaman *et al.*, 1994; Larcombe and Carter, 1998). The main sea-level indicator used to date is coral, which is restricted to offshore islands and reefs of the Great Barrier Reef. Two commonly used approaches to defining relative sea level on coral reefs are to use reef top micro-atolls and in situ core materials.

Carefully measured reef top micro-atolls from single or closely spaced sites provide sea-level index points with error terms of a few centimetres (Mclean *et al.*, 1978; Hopley, 1986; Smithers and Woodroffe, 2000). Micro-atolls usually grow up to the level of Mean Low Water of Neap Tides (MLWNT) unless they are moated in reefal lagoons where they can grow up to Mean High Water of Neap Tides (MHWNT). Open water (un-moated) micro-atolls are the most precise sea-level indicators on coral reef systems. However it is sometimes difficult to establish whether fossil micro-atolls are moated or unmoated (Smithers 2005, pers. comm.). More commonly used in studies of sea-level change in North Queensland is in situ coral core material. Use of this material is associated with much greater uncertainty, especially in the Indo-Pacific where, unlike the Caribbean, common species clearly limited to shallow water do not exist (Davies and Montaggioni, 1985; Hopley, 1986)

Radiocarbon dated coral cores from the Great Barrier Reef form a large part of a database of sea-level reconstructions through the Holocene. Much of the evidence has been re-evaluated since large-scale coring programs occurred in the 1960s and 1970s

(Hopley, 1983; Hopley, 1986), and today sea-level reconstructions with applications to geophysical modelling only use evidence from coral micro-atolls (Nakada and Lambeck, 1989; Lambeck and Nakada, 1990; Lambeck, 2002).

Sedimentary environments along the North Queensland coast consist mainly of mangroves, chenier plains and beaches. Low gradient and macrotidal tropical coasts with abundant sediment supply provide good environments for mangrove growth. They occur between ~Mid Tide Level to Mean High Water of Spring Tides in the seasonally arid tropics and Highest Astronomical Tide level in the wet tropics (Grindrod, 1988). Mangrove muds are preserved in fossil cores, complete with macrofossils such as mangrove wood and seeds and microfossils such as mangrove pollen (Grindrod and Rhodes, 1984; Pye and Rhodes, 1985; Grindrod, 1988). Mangrove muds comprise mainly of silt and clay (<20 % organic material) therefore should not compact as easily as temperate salt-marsh peat (>50 % organic material). They should therefore be more useful sea-level indicators than organic-rich deposits found in temperate latitudes. Some scientists narrow the lower boundary between mangrove and mud flat using microfossils and observations to within 5 cm, and use this transition as a sea-level indicator in North Queensland (Harvey *et al.*, 2001).

Encrusting shells, such as barnacles and oysters preserved in growth position are used as sea-level indicators on the rocky shore of Magnetic Island (Figure 1.1). Species with the narrowest growth ranges provide the best reconstructions. Beaman *et al.* (1994) use the upper boundary of a fossil encrustation of *Saccostrea cucculata* within a cave as a sea-level indicator, which today forms shell beds between Mean High Water of Neap Tides and Mid Tide Level in other sheltered caves on Magnetic Island. Modern encrustations grow 'ramped up' cave walls as vertical wave splash is increased in a confined space, which means the upper boundary of the encrustation is not a horizontal marker. This increases the error estimate from +/- 15 cm in exposed cliff locations (Baker *et al.*, 2001) to an unknown error, in excess of 30 cm.

Each proxy indicator above is useful in reconstructing sea level if it can be assigned an indicative meaning. If age and elevation terms can be defined, all sea-level index points give at least a gross indication of sea-level behaviour through the Holocene. Sea-level reconstructions are improved if we take a multi-proxy approach, which uses all available information whilst appreciating precision variances in existing data. Collection of new sea-level data from this region focuses on where there are gaps in the existing data set and where indicators have large error terms.

Techniques for reconstructing sea-level changes

Sea-level index points are used extensively in the UK to produce local records of Holocene sea-level change (e.g. Shennan and Horton, 2002). Transitions between terrestrial/brackish peats and marine silts and clays usually provide index points. Foraminifera, diatoms or pollen pinpoint the onset or removal of marine conditions, but commonly an indicative meaning comes from the position of dated material in a lithological sequence.

Applying a transfer function technique to extended inter- and sub-tidal sampling potentially expands the range of environments which can be assigned an indicative meaning (e.g. Horton and Edwards, 2006), by quantifying the relationship between an environmental variable of interest (elevation), and an environmental proxy (microfossil assemblages) so elevation can be expressed as a function of microfossil assemblages. This potentially broadens the number of index points possible from each fossil sequence by giving environments below the onset of marine conditions indicative meanings, assuming there is suitable in situ material available for direct dating or through a sediment accumulation curve. Therefore transfer functions using microscopic organisms which live in marine environments (e.g., diatoms and foraminifera) can potentially calibrate fossil sediments from intertidal and some shallow subtidal environments. The transfer-function approach is used in this thesis to help reconstruct Holocene sea levels.

1.4 RELATIVE SEA-LEVEL PROCESSES

Relative sea-level changes are a product of changes in oceanic and crustal variables (see section 1.1). A change in relative sea level at any time or location is dependent upon a combination of changes eustatic sea level, isostatic changes and local processes occurring at the site.

Geographical variability in Holocene sea-level change is well illustrated by Pirazzoli's (1991) atlas of sea-level curves and by geophysical model predictions (e.g. Clark *et al.*, 1978; Peltier, 2002; Shennan *et al.*, 2002; Lambeck *et al.*, 2003; Mitrovica, 2003). Clark *et al.* (1978) identify six different sea-level patterns which reflect a range of relative sea-level histories recorded at coasts which have emerged, submerged, or which record a combination of uplift and subsidence (Figure 1.2).

1.4.1 Eustasy

Eustasy is defined as the rise and fall of sea level on a worldwide scale (Thomas and Goudie, 2000) produced primarily by direct mass exchange between ice sheets and oceans. Ocean level is influenced by three main groups of factors: water volume in the oceans, the distribution of water and volume of ocean basins. Water in the ocean and glacial ice on land are in balance; when one increases the other decreases. This is *glacial eustasy* (Suess, 1885). Small scale changes in ocean volume are also due to other factors, such as the addition of juvenile water, storage of water in sediments, variations in the main hydrologic cycle changing continental lake volumes, cloudiness, and the evaporation/precipitation balance. Steric expansion or contraction of the water column is particularly important on short timescales and sea-level rise over the next century will be driven predominantly by changes in temperature and, to a lesser degree, salinity (Church *et al.*, 2001). The volume of ocean basins changes so slowly it is considered negligible on Holocene time scales (Shennan and Horton, 2002).

1.4.2 Isostasy

Glaciation and deglaciation causes changes to the Earth's shape and gravitational field due to large-scale changes in surface mass load. Ice sheet development causes the crust to subside beneath the ice mass (*glacio isostasy*). Deeper material flows away and a peripheral bulge builds around the ice margin. When the ice sheet melts, unloading occurs, resulting in uplift beneath the melted ice at rates which may reach 50 to 100 mm/yr. (Tarasov and Peltier, 2002). The marginal rim subsides and moves towards the centre of vanishing load. During deglaciation meltwater from ice sheets produces a considerable load (of the order of 100 t/m² for a sea-level rise of 100 m (Lambeck *et al.*, 2003) on ocean floors so the sea floor subsides (*hydro-isostasy*).

1.4.3 Ocean-surface deformation

Sea level also changes as the result of the global distribution of oceanic water. The earth is not spherical, but broadly flattened at the poles and bulging at the equator. Ocean surface is not even and does not parallel the Earth surface. Present geodetic sea level may vary with respect to the Earth's centre by as much as 180 m (Pirazzoli, 1996). Geoid relief is not stable through time; it deforms vertically as well as horizontally. During the LGM, the weight of continental ice sheets caused downward deformation of the crust, forcing sublithospheric flow away from the centres of load. A low latitude gravitational anomaly developed creating a high in the oceanic geoid. During deglaciation, continents viscoelastically rebounded causing the gravity anomaly to decay and the oceanic geoid to migrate from lower to higher latitudes.

Coupled with this is migration of meltwater from far-field into near-field regions vacated by collapsing peripheral forebulges. Zones of sea-level rise surround glaciated areas as water moves into these spaces. This is *equatorial ocean siphoning* (Mitrovica and Peltier, 1991).

1.4.4 Local factors

Although the interaction of eustatic and isostatic factors produces the general pattern of relative sea-level changes (Figure 1.2), various processes operate at the coast and within estuaries that influence how relative sea-level changes are registered in the fossil record. Local scale factors include modified tidal regime due to coastal configuration and when looking at sedimentary deposits the relationship between the freshwater table and tide levels is important. Shennan and Horton (2002) observe a change in the elevation of Mean High Water of Spring Tide (MHWST) in relation to Mean Tide Level (MTL) through the mid to late Holocene in the Humber estuary, UK. Also important is changes in elevation of sediment since deposition. This can be a major limiting factor on sedimentary deposits as sea-level indicators as organic-rich deposits can be compressed to up to 10% of their former volume. Accumulation of overlying sediments and land drainage are the main factors causing consolidation over time (Allen, 2000).

1.5 FAR-FIELD LOCATIONS

Although much research (e.g. Shennan and Horton, 2002) to test theoretically derived geophysical models has focused on data sets from near- and intermediate-field locations (Zones I-II in Figure 1.2), it is widely recognised that 'far-field locations' (Zones IV-VI in Figure 1.2) provide the best constraints on the eustatic signal. Glacio-isostatic effects are smaller away from former ice sheets, allowing better estimation of eustatic change from far-field locations (Clark *et al.*, 1978; Yokoyama *et al.*, 2001; Peltier, 2002). Thus far-field data provide the most direct measure of the total mass exchanged between grounded ice and oceans during the last glacial cycle (Clark and Mix, 2002).

Factors affecting far-field sea-level records

Characteristic sea-level change in far-field locations is rapid rise from a low around 120 m at 18,000 cal BP culminating in a small high stand of up to 4 m 6000 cal years BP, and small scale changes (usually sea-level fall) from about 6000 cal BP to present (Clark *et al.*, 1978) (Figure 1.2). There is a complex relationship between site-specific sea-level records and the generalised eustatic sea-level curve in the far-field. The

eustatic signal helps to quantify ice parameters such as period of maximum ice and rate of ice-sheet disintegration (Fleming *et al.*, 1998; Milne *et al.*, 2002). However, local sea-level change can vary significantly from the eustatic function because of tectonic and glacio-isostatic effects. Estimating meltwater volumes and ice parameters based on far-field sea level records relies on the accuracy to which the non-meltwater signal can be predicted.

Despite the range of factors influencing relative sea-level change in far-field locations, a small number of relative sea-level records are considered sufficiently dominated by eustasy to approximate the eustatic signal since the LGM (e.g. Fairbanks, 1989; Chappell and Polach, 1991; Blanchon and Shaw, 1995; Bard *et al.*, 1996; Hanebuth *et al.*, 2000; Yokoyama *et al.*, 2000). Despite potential influence of other factors these records are used in geophysical models to estimate ice mass at the LGM and to tune models of earth rheology (e.g. Peltier, 2002; Bassett *et al.*, 2005). Fairbanks (1989) developed a sea-level curve from dated cored coral (*Acropora palmata*) in Barbados. This record, dominated by eustatic change concentrates on the late glacial and early Holocene period from 17,100 to 7800 BP. Peltier (2002) believes this record, along with a sea-level history from sediments on the Sunda Shelf in SE Asia (Hanebuth *et al.*, 2000), are dominated by the eustatic signal and he uses the Barbados data to tune his ICE-5G model of global glacio-isostatic adjustment (Peltier, 2004). Peltier argues that late glacial eustatic records from the Huon Peninsula, Papua New Guinea (Chappell and Polach, 1991), Tahiti (Bard *et al.*, 1996) and Joseph Bonaparte Gulf, NW Australia (Yokoyama *et al.*, 2000) are contaminated by other processes and are useful only as relative sea-level records which are predicted by the model.

Processes affecting the pattern of Holocene relative sea-level change in different far-field locations are summarised below (Table 1.1):

Table 1.1: Processes affecting Holocene relative sea-level change in far-field locations

Eustasy	Continental margin or ocean basin records?
1. Before ~6000 cal BP far-field sea-level curves show the average rate of ice sheet melt and variations in melt-rate (Fleming <i>et al.</i>, 1998). 2. After ~6000 cal BP continued melting is contentious. Peltier (2002) argues adding significant late Holocene melting (0.5 mm/yr after 4000 cal BP) to his glacio-isostatic model means it no longer predicts mid Holocene high stands in equatorial oceans. Others argue for no melting past 4000 cal BP (Milne <i>et al.</i>, 2005), a small eustatic signal between 7000-3000 cal BP (Lambeck, 2002) and continued Antarctic melting until 1000 cal BP (Fleming <i>et al.</i>, 1998).	1. During the early Holocene all locations experience relative sea-level rise. 2. During the mid Holocene timing of high stand differs between continental and ocean basin locations depending on timing of meltwater cut off, due to loading of the ocean floor with continued late Holocene melting: • No meltwater added to the oceans after 6000 cal BP = high stand is within 1000 years at continental margin and ocean basin locations. • Meltwater added after 6000 cal BP difference in high stand timing with distance from a coastline significant (Lambeck and Nakada, 1990; Lambeck, 2002)

Hydro-Isostasy	Continental margin or ocean basin records?
Sea-floor subsidence under weight of meltwater.	• Ocean basins and small islands within them subside (e.g.,Tahiti ~12m of relative sea-level rise due to sea-floor subsidence) (Peltier, 2002). • Continental margins are affected less (e.g.,Joseph Bonaparte Gulf, Australia because of migration of the coastline during sea-level rise (Milne <i>et al.</i>, 2002)).
Continental levering/warping – continents are flexed up at their margin and down offshore due to changing water load. This constrains upper mantle viscosity and lithospheric thickness (Nakada and Lambeck, 1989; Lambeck and Nakada, 1990; Lambeck, 2002; Kendall <i>et al.</i>, 2003).	• Ocean basin locations with small shelves are not affected. • At continental margins changes in width of shelf affects high stand amplitude over short distances (e.g.,amplitude varies between +4 and +2 m over 100 km in the upper Spencer Gulf, South Australia (Barnett <i>et al.</i>, 1997; Cann <i>et al.</i>, 2000a)).

Ocean surface deformation	Continental margin or ocean basin records?
Equatorial ocean siphoning is due to 2 different processes: 1. Water migrates away from far-field equatorial ocean basins to fill space vacated by collapsing forebulges at the periphery of formerly glaciated regions. 2. Ocean loading at continental margins induces levering of continents and subsidence of offshore regions causing influx of water and sea-level fall in locations distant to these margins (Mitrovica and Peltier, 1991; Mitrovica and Milne, 2002).	• Ocean basin locations experience relative sea-level fall in the late Holocene as water migrates to near-field locations (e.g., Cocos Keeling Islands (Woodroffe and Mclean, 1990; Woodroffe <i>et al.</i>, 1999), but this is counteracted by sea-floor subsidence and sea-level rise in offshore regions closer to continental margins. • Continental margins may experience relative sea-level fall in the late Holocene due to upward levering of the margin, e.g., NE Australia (Harvey <i>et al.</i>, 2001).

There are differences in the way far-field processes act on equatorial oceans and continental margins such as North Queensland. Eustasy and hydro-isostasy affect both places, while equatorial ocean siphoning causes relative sea-level fall at the centre of ocean basins and relative sea-level rise at their margins. Continental levering and crustal warping only occur where there is a shallow continental shelf offshore of the continental margin.

1.6 SEA-LEVEL CHANGE IN THE AUSTRALIAN REGION

Australia is relatively seismically stable with little evidence of tectonic deformation since the Mesozoic. It is situated at the centre of the Australian-Indian plate and has passive continental margins (Chappell, 1987). This makes Australia an important far-field location for relative sea-level study. It has a large coastline (59,630 km, Hopley and Thom, 1983) spanning a range from 10° to 43° south (Figure 1.3), with many different coastal environments from rocky shorelines, salt-marshes and mangrove swamps to coral reefs. Because of difficulties with collecting material from offshore locations, most work focuses on the present coastline during the mid-late Holocene period, when sea levels were close to or slightly above present.

Australia has a long history of sea-level research, ranging from the first widely proposed eustatic sea-level curve (Fairbridge, 1961), which used sites in Western Australia, to some of the earliest debates on hydro-isostasy (Bloom, 1967; Walcott, 1972; Clark *et al.*, 1978). Hydro-isostasy is now recognised as a major factor in producing regional variation in Holocene shorelines around Australia (Figure 1.3).

Improving ocean loading and continental levering terms drives continued development of mid-late Holocene sea-level records around the Australian coastline (Figure 1.3). For example, recent studies around the Spencer Gulf and Gulf St. Vincent in South Australia test models of continental levering (Burne, 1982; Belperio *et al.*, 1984; Cann *et al.*, 1993; Cann *et al.*, 2000a; Cann *et al.*, 2000b; Cann *et al.*, 2002). Studies along the coast of New South Wales investigate sea-level change where there is a narrow continental shelf (Baker and Haworth, 1997; Baker and Haworth, 2000b; Baker and Haworth, 2000a; Baker *et al.*, 2001), and at Joseph Bonaparte Gulf, Northern Territory a recent study attempts to approximate the eustatic function back to the LGM (Yokoyama *et al.*, 2000; Yokoyama *et al.*, 2001).

1.7 HOLOCENE SEA-LEVEL CHANGES IN NORTHERN QUEENSLAND

Studies over the past 30 years reconstruct Holocene sea levels along this coastline, focusing on late glacial and early Holocene sea-level rise, the timing and magnitude of the mid Holocene high stand and the subsequent regression to present (e.g. reviews by Flood, 1983; Hopley, 1983; Larcombe *et al.*, 1995). It was initially studied because of the presence of the Great Barrier Reef, the largest complex of coral reefs and islands in the world stretching 1200 miles from Cape York to Bundaberg (Figure 1.1). It is now recognised that few areas in the world have the advantage of North Queensland for study of hydro-isostasy, as the Great Barrier Reef region provides a range of information on reef and continental islands extending across the continental shelf (Hopley, 1983).

The coastline between Townsville and the mouth of the Burdekin river, especially Cleveland Bay is dominated by well developed broad intertidal mud flats. This results from a combination of high fluvial sediment transport delivery to the area and tidal transport mechanisms which move muds back onto the coast (Belperio, 1979; Harvey *et al.*, 2001). This provides the ideal environment of low energy, shallow intercalated muds for a microfossil-based sedimentary study of mid-late Holocene sea-level change. The following points show the range of geophysical information available from study of relative sea-level change on the North Queensland coast:

1.7.1 Information on eustasy

The timing of the end of meltwater input has a dramatic effect on the shape of predicted late Holocene sea-level curves for North Queensland. If the Laurentide ice sheet disappeared by 6000 cal BP, but Antarctic melting continued through the late Holocene, North Queensland sea-level curves should show a pronounced high stand

after 6800 cal BP followed by rapid fall to present levels (Nakada and Lambeck, 1989; Lambeck and Nakada, 1990; Lambeck, 2002). However if Antarctic melting continued until or after 4000 cal BP, the sea-level curve should show a rounded high stand with a significant period after 6000 cal BP with sea levels above present (Lambeck, 2002; Peltier, 2002).

1.7.2 Information on crustal variables

Sea-level data from different distances offshore heightens understanding of the influence of the continental shelf in modifying ocean loading and continental levering. Chappell *et al.* (1982) present a theoretical isobase map of hydro-isostatic warping for North Queensland since 5500 ^{14}C years BP (~6300 cal years). They use a viscoelastic earth model and field data from coral spanning from Britomart Reef to the Gulf of Carpentaria (Figure 1.4 b). The +1 m contour at 5500 ^{14}C years BP lies roughly parallel to the coastline between Cape York and just south of Cairns, where the continental shelf is constantly less than 50 km wide. Further isobase maps developed by Nakada and Lambeck (1989) predict Holocene sea levels along the GBR coastline at 6800 cal years BP (Figure 1.4 c, d). They predict 4 different types of sea-level curve found at different distances from the coastline (Figure 1.4 d). Modelled sea level is calibrated using sea-level index points from the region. Many studies along small sections of coastline give a better understanding of regional crustal warping, and the range of evidence used allows an independent assessment of any resultant models of sea-level change.

1.7.3 Existing sea-level reconstructions

Cored coral provide the majority of evidence for relative sea-level change in Queensland, although coral has wide error terms (~ $\pm$ 5 m at best) (e.g. Mclean *et al.*, 1978; Hopley, 1983; Johnson and Carter, 1987). There is a concentration of sea-level index points around the rising limb of sea level between 8000-6000 cal BP, with fewer reconstructions during the late Holocene apart from in the central area (Figure 1.5).

Cored coral or coral micro atolls close to the mainland provide the only reconstructions from the northern area, from Torres Strait to Cairns (Mclean *et al.*, 1978; Chappell *et al.*, 1982; Chappell *et al.*, 1983; Hopley, 1983; Johnson and Carter, 1987). Sea level rose above present prior to 7000 cal BP, with the peak elevation of the high stand poorly defined (Figure 1.5 a). Cored coral have poorly constrained elevation errors but relatively precise age errors. There is little evidence to constrain precisely the

elevation of late Holocene sea level, apart from isolated reconstructions from micro atolls.

In the central area (Cairns to Mackay) sea-level reconstructions are much more numerous, with the majority from sedimentary deposits (Belperio, 1979; Grindrod and Rhodes, 1984; Pye and Rhodes, 1985; Crowley *et al.*, 1990; Carter *et al.*, 1993; Larcombe *et al.*, 1995; Larcombe and Carter, 1998; Harvey *et al.*, 2001). Reconstructions using sediments and the shells, macrofossils and microfossils contained within them, have relatively small elevation errors but often very large age errors (Figure 1.5 b). A small number of reconstructions also come from coral micro atolls and encrusting shells (Chappell *et al.*, 1983; Beaman *et al.*, 1994). This area has the longest relative sea-level record in North Queensland (to 10,500 cal BP), showing sea level rose rapidly through the early Holocene, rising above present between 7000-8000 cal years BP and remaining up to 3 m above present through the mid-late Holocene (Figure 1.5 b). Despite the range of evidence and the fact that this region has the largest number of reconstructions in North Queensland, the poor precision of some indicators during critical parts of the Holocene means that debates continue over the timing and amplitude of the Mid Holocene high stand.

Reconstructions in the southern area from Mackay to Bundaburg (Figure 1.5 c) are solely from cored coral (Hopley, 1983). These show sea level rising above present between 8000-6000 cal years BP, up to 2 m above present from 6000 to approximately 1000 cal years BP (Figure 1.4 c). With a Mid Holocene high stand of up to 2 m on islands up to 80 km offshore, the high stand may have been higher on the main coastline (Hopley, 1983). However, there are no sea-level reconstructions to support or disprove the theory.

1.8 CHAPTER SUMMARY, RESEARCH QUESTIONS AND HYPOTHESES

This chapter summarises background information relevant to this thesis. It outlines factors controlling relative sea-level change in far-field locations, in particular the North Queensland coast of Australia, and outlines existing research in this region.

Following the discussion of theory and previous work outlined in sections 1.3 to 1.7, broad research questions outlined in section 1.2 can be addressed using the following detailed research questions:

Research Question 1. What indicators can be used in reconstructing Holocene relative sea-level change in North Queensland?

1a. Is it possible to define age, elevation and error terms for each type of indicator used in reconstructing relative sea level in this region?

- Coral
- Micro-atolls
- Encrusting molluscs
- Sediments with and without microfossils

1b. Are microfossils abundant and readily preserved?

1c. Are microfossil assemblages controlled by elevation?

1d. Is there a good relationship between modern and fossil microfossil assemblages?

1e. Can fossil sedimentary sequences provide quantitative reconstructions of sea level change?

1f. Is there suitable in situ material for AMS radiocarbon dating to create an age model for reconstructions?

Research Question 2. What is the pattern of Holocene relative sea-level change in North Queensland?

2a. When did relative sea level first reach its current elevation?

2b. What was the amplitude and timing of the peak of the mid Holocene high stand?

2c. What was the nature of relative sea level fall through the late Holocene?

Research Question 3. Does application of sea-level index point analysis in sediments help to define the mid Holocene high stand?

3a. Do observed sea-level changes through the mid-late Holocene correlate at site and regional scales?

3b. Does index point analysis help to understand the nature of the mid Holocene high stand (e.g., duration, single or multiple maxima)?

Research Question 4. Is the resolution of sea-level data sufficient to differentiate between models of mid Holocene sea level high stand duration and amplitude?

Index point analysis at different sites in North Queensland may allow discrimination between models of mid Holocene sea level high stand duration and amplitude.

- Australian National University (ANU) school – models from several different authors in this group suggest Laurentide ice sheet melt by 6800 cal BP and between 3-5 metres of melt between 6800 cal years BP and 2000 cal BP/present from

Antarctica causing a pronounced high stand after 6800 cal BP and rapid fall to present levels where there is a wide continental shelf (Nakada and Lambeck, 1988; Nakada and Lambeck, 1989; Lambeck and Nakada, 1990; Fleming *et al.*, 1998; Shennan *et al.*, 2000a; Lambeck, 2002).

- Durham school - Rapid Antarctic melting until 7000 cal BP slowing to 0.5 mm/yr between 7000-5000 cal BP and no melt after 5000 cal BP – high stand with pronounced peak but significant period with sea level above present during the late Holocene (Milne *et al.*, 2005).
- Toronto school - Rapid Antarctic melting until decrease around 7000 cal BP with reduced melting of a few metres until 4000 cal BP and no melting after 4000 cal BP – rounded high stand with a significant period after 6000 cal BP with sea level above present (Peltier, 2002; Peltier *et al.*, 2002; Shennan *et al.*, 2002)

CHAPTER TWO - FIELDSITES

2.1 INTRODUCTION

The aim of this chapter is to introduce the field sites and to describe their main characteristics. Cocoa and Alligator Creeks are located in Cleveland Bay, close to Townsville in North Queensland. Big Mango is located in Edgecumbe Bay close to Bowen, 200 km south of Townsville in North Queensland (Figure 1.1).

Previous workers focus on reconstructing relative sea-level change in Cleveland Bay because there are fossil micro-atolls and encrusting oyster beds on Magnetic Island (Chappell *et al.*, 1983; Beaman *et al.*, 1994), buried intertidal deposits including mangrove 'peat' across the floor of the bay and intertidal deposits elevated above present around Sandfly Creek and Cocoa Creek (Belperio, 1979; Carter *et al.*, 1993; Harvey *et al.*, 2001). There are a range of modern surface environments around the coast of Cleveland Bay with microfossils present in surface sediments (Horton *et al.*, 2003). Despite these studies, the exact nature of the mid Holocene highstand and the nature of late Holocene sea-level fall remain contentious (Harvey *et al.*, 2001), therefore studying Cleveland Bay gives the opportunity to produce new sea-level data which may add definition to the mid-late Holocene where existing records diverge. On the basis of this previous work and the abundance of Holocene sea-level information available I chose Cleveland Bay as the location for this thesis and collect all fossil material from Cleveland Bay.

2.2 TOWNSVILLE REGION, NORTH QUEENSLAND

North Queensland is the northern half of the state of Queensland, divided by the Tropic of Capricorn at 22.5° south near Rockhampton (Figure 1.1). The Great Barrier Reef shelf-edge reefs rim the continental shelf of North Queensland and restrict water circulation and wave action within the shelf lagoon. Terrigenous mud and sand dominate the inner shelf of the lagoon along the whole coastline of northern Queensland, sourced from mainland rivers including the Burdekin, Houghton, Ross and Herbert (Figure 1.1) (Belperio, 1983).

The focus of this thesis is on an area of the coastal plain 200 km long close to the tropical city of Townsville, (19° South), Queensland's second largest city. The

shoreline of this area, also known as the central Great Barrier Reef province is characterised by a series of north-facing coastal embayments (e.g., Cleveland Bay, Bowling Green Bay, Upstart Bay, Edgecumbe Bay), which are protected from dominant south-east trade winds by granite headlands, islands or sand spits, but are open to northerly and northeasterly weather and the impact of occasional tropical cyclones (Belperio, 1983; Carter *et al.*, 1993).

The coastal plain in this region has a low gradient, continuing onto the shallow continental shelf, covered by alluvial and coastal marine deposits which have prograded through the Holocene, particularly in the vicinity of major rivers and in the north-facing embayments of the region.

Mangrove forests occur on the coastal plain from highest astronomical tide level to approximately mid tide level. Most diverse mangroves occur in the humid tropics, where rainfall exceeds 2000 mm/year. In more arid tropical areas such as the Townsville region, salt-pans and salt-marshes develop in the upper intertidal zone where evaporation causes excess salinity which is toxic to mangroves. There is also a progressive decrease in species diversity as aridity increases. In the extreme landward portion of salt pans, ground- and soil-water salinity may be in excess of 240 ‰ (Semeniuk, 1983).

There are contrasting approaches to modern data collection which both have their advantages and disadvantages. The first advises collection of modern microfossil data close to the location of cores used to reconstruct sea level (Gehrels, 1994; Allen and Haslett, 2002). Optimal precision is often achieved when modern distributions are related to tidal elevations as close as possible to where they are used as sea-level indicators (Gehrels, 1994). The alternative approach is to use regional or national microfossil data sets from a range of locations, environments and tidal ranges to incorporate a wide range of modern analogues, permitting a microfossil-based transfer function to perform reliably even if past environmental conditions at the study site differed significantly from those found today (Horton and Edwards, 2005). Therefore two modern data sites are in Cleveland Bay (Cocoa Creek and Alligator Creek) and form a local microfossil training set. I also took modern samples from a further location in Edgecumbe Bay to investigate regional microfossil distributions.

Cleveland Bay is a north-facing bay offshore from Townsville at approximately 19° 20' south and 146° 30' to 147° 20' east (Figure 2.1). The bay is approximately 20 km² and

bordered around its southern and eastern margins by the mainland. The granitic Magnetic Island, ~12 km in diameter and rising to 495 m high shields the northerly part of Cleveland Bay from prevailing winds and waves. The southern part of the bay is protected by the granite headland of Cape Cleveland (557 m). Cleveland Bay is relatively shallow with maximum water depth of 15 m at its seaward edge, and complex water motions occur within the bay, including the effects of refracted southeast-generated swell waves (Carter *et al.*, 1993; Larcombe *et al.*, 1995).

Edgecumbe Bay is a north-facing bay offshore of Bowen, 200 km south of Townsville at approximately 20° 17' south and 148° 21' to 149° east. The bay is approximately 24 km², bordered around southern and western margins by the mainland and protected by granitic Gloucester Island to the east (Figure 1.1).

2.3 ENVIRONMENTAL PARAMETERS

The Townsville region is seasonally dry with mean annual rainfall of 1130 mm, 85 % falling between December and April (Belperio, 1983). Streamflow patterns reflect intensity and duration of rainfall, with 92 % of the Burdekin river discharge (draining 129 500 km² of Queensland) occurring between December and April. Mean annual discharge is 9.8 x 10⁹ m³ (Belperio, 1983).

Maximum tide range at Townsville is 4.01 m and at Bowen is 3.73 m (Department of Transport, 2002), resulting in significant exposure of broad intertidal mudflats at low tide. Tide-gauge data are available from Townsville Port. Protection from ocean swell by fringing coral reefs causes slight to moderate seas. From April to November waves are generated by predominantly southeast trade winds with waves rarely exceeding 2.5 m, causing coastal turbidity and northwest drift of inner shelf water and suspended sediment into Cleveland Bay (Belperio, 1983). Edgecumbe Bay lies south of the mouth of the Burdekin river, has a sandier substrate and does not receive such large quantities of terrigenous mud as Cleveland Bay.

Table 2.1 Local tidal levels in Cleveland Bay in metres Australian Height Datum (m AHD).

Lowest Astronomic al Tides (LAT)	Mean Low Water Springs (MLWS)	Mean Low Water Neaps (MLWN)	Mean Sea level (MSL)	Mean High Water Neaps (MHWN)	Mean High Water Springs (MHWS)	Highest Astronomical Tides (HAT)
-1.86 m	-1.13 m	-0.27 m	0.10 m	0.36 m	1.21 m	2.15 m

2.4 FIELD LOCATIONS

2.4.1 Cocoa Creek, Cleveland Bay

Cocoa Creek is the most eastern of four tidal creeks entering Cleveland Bay. The main channel meanders for 9.5 km through an extensive chenier plain close to Cape Cleveland, and extends 600 m seawards of the last chenier ridge through a mangrove fringe, in places up to 400 m wide. The mangroves are mature and florally diverse, with trees up to 8 m in height. I chose a modern sampling transect across mangrove, intertidal and subtidal mud flats to incorporate all nearshore environments from mangrove to subtidal (Figures 2.3 and 2.4 b and c).

At 1.16 m AHD is the most seaward of 16 sand-rich chenier ridges in the Cocoa Creek area. The ridges are shore normal, up to 5 m high and located between 200 m and 1000 m apart through salt pans on the coastal plain, dissected by Cocoa Creek. Two coring transects across these upper tidal salt pans between Cape Cleveland and Cocoa Creek allow investigation of the general lithostratigraphy of the area (Figure 2.3).

2.4.2 Alligator Creek, Cleveland Bay

Alligator Creek is in the central, southerly part of Cleveland Bay. The field site is west of the main channel of Alligator Creek, close to the toe of the granitic Muntalunga mountain range (Figure 2.4). The coastal plain here is dominated by a smaller series of sand-rich chenier ridges which cover the ~2 km wide salt pans between the headland and modern fringing mangrove along the coast and around the mouth of the creek. Two fossil transects taken across salt pans west of Alligator Creek allow investigation of the general lithostratigraphy of this area (Figure 2.4). A further modern transect across Cleveland Bay starts close to the mouth of Alligator Creek at the seaward edge of fringing *Avicennia marina* mangrove and covers intertidal and subtidal muddy and sandy areas, partly colonised by seagrasses (Figure 2.4 d). This transect is positioned to incorporate all modern low intertidal and some subtidal environments in Cleveland Bay.

2.4.3 Big Mango, Edgecumbe Bay

One modern transect was taken at the southern edge of the bay close to a 8 ft high plastic mango on the highway advertising mangoes. The coastal plain here more steeply inclined, with intertidal sand flat and mangroves backed by a beach and

freshwater woodland. The modern transect taken here investigates intertidal environments and microfossils 200 km from Cleveland Bay (Figure 2.4 e).

2.5 CHAPTER SUMMARY

The three field sites described above allow the testing of hypotheses outlined in chapter 1. Locating fossil field sites in Cleveland Bay allows comparison with other published work, and modern environments and microfossils may be similar locally to those being reconstructed (Gehrels, 1994). Collecting modern samples from Edgecumbe Bay allows testing of whether modern microfossil distributions are locally controlled by environmental conditions or are regionally homogenous. Chapter 3 describes the methodology used to address the research hypotheses.

CHAPTER THREE - RESEARCH DESIGN

3.1 INTRODUCTION

This chapter introduces the research and sampling design used to address the hypotheses set out in chapter 1. It outlines how research hypotheses will be tested and fieldwork undertaken at Cocoa Creek and Alligator Creek in Cleveland Bay and Big Mango in Edgumbe Bay during field seasons in June 2003, November 2003 and June 2004 (refer to chapter 2 for description of field sites). It also outlines the methods used for microfossil analysis, numerical techniques applied to interpret results and dating methods.

3.1.1 *Research Question 1: What indicators can be used in reconstructing Holocene relative sea-level change in North Queensland?*

There are a range of proxy indicators used in Holocene sea-level reconstructions in North Queensland, including coral, coral micro atolls, encrusting molluscs and sediments with and without microfossils (Larcombe *et al.*, 1995). A standard rigorous method for reconstructing relative sea-level change is via sea-level index point analysis (Shennan, 1986; Van de Plassche, 1986). Sea-level reconstructions across the world are derived through the sea-level index point methodology, based on five variables which pinpoint sea-level position and allow inclusion of all data of varying precision in local and regional sea-level chronologies (e.g. Shennan, 1989; Shennan *et al.*, 2000a; Shennan and Horton, 2002). The five variables are: location, age, elevation, indicative meaning and sea-level tendency (Morrison, 1976; Shennan, 1986). Location is geographical, age is in calendar years BP, elevation is the elevation of the sample reduced to a national datum (in Australia this is Australian Height Datum (AHD)). Indicative meaning is the tide level at which the dated indicator accumulated and the error term associated with estimating this (indicative range), and tendency is an increase or decrease in marine influence immediately before and after the formation of the index point (Morrison, 1976; Shennan, 1986). Re-evaluating all Holocene sea-level data available from North Queensland in light of sea-level index point methodology allows all available evidence to be used in improving Holocene relative sea-level reconstructions. This allows comparison of sea-level index points with modelled Holocene relative sea-level change for the region (Nakada and Lambeck, 1989; Lambeck and Nakada, 1990; Lambeck, 2002).

Many reconstructions in North Queensland are based on indicators with poor precision (Figure 1.4 a-c) (e.g. Flood, 1983; Hopley, 1983). The main indicator used is coral, but it is not precise and only gives a general indication of Holocene relative sea-level changes (only as good as ± 5 m) (Hopley, 1983). Reef top micro atolls provide the most precise reconstructions from ~ 7000 cal BP to present with small error terms (a few centimetres) (McLean *et al.*, 1978; Chappell *et al.*, 1983). However, they are only easily sampled in North Queensland on fossil reef flats where relative sea level has since fallen, and only give information on sea-level tendency if a series of micro atolls are found and dated in a sequence (Chappell *et al.*, 1983). Molluscs are also excellent indicators but are only preserved in raised positions on rocky shorelines where they are protected from wave action and give sea-level index points with an error of ± 15 cm or more with no tendency information (Baker *et al.*, 2001). Sheltered rocky environments are uncommon in North Queensland, and molluscs only record the peak of the mid Holocene high stand.

Limitations in existing sea-level data highlight the need to use different proxy indicators to create new sea-level index points to complement and enhance existing data in this region. Significant amounts of fine-grained sediments are deposited onto the inner continental shelf and coastal plain in the Townsville area by the Burdekin, Haughton and Ross rivers and have been redistributed by longshore drift since the Mid Holocene (Figure 1.1 and 2.1). Some of these sediments have formed a system of beach ridges and mudflats overlying a weathered Pleistocene clay surface, with progradation rates through the late Holocene of up to 2m/yr established for some areas (Belperio, 1983; Carter *et al.*, 1993). Progradational environments, which occur most commonly in north facing bays, are ideal for preservation of fossil sediments and microfossils. Microfossils such as foraminifera, pollen and diatoms are widely used in temperate areas to reconstruct sea-level changes (e.g. Gehrels, 1994; Shennan *et al.*, 2000a; Horton and Edwards, 2005), providing relatively precise sea-level index points from mainly organic sedimentary units.

Using precise indicators and statistically robust quantitative reconstruction methods may address the problem of uncertainties in existing reconstructions (Figure 1.5). However, accuracy and precision of reconstructions based on microfossils is dictated in part by the quality of modern investigations into the relationship between relative sea level, environmental conditions and succession of microfossil assemblages (Horton *et al.*, 2000). Numerous studies develop and apply transfer functions to reconstruct

relative sea level and its changing precision using a range of microfossils including foraminifera, diatoms and testate amoebae (e.g., Horton, 1997; Horton, 1999; Gehrels, 2000; Horton *et al.*, 2000; Gehrels *et al.*, 2001; Edwards *et al.*, 2004b; Sawai *et al.*, 2004; Gehrels *et al.*, 2005; Horton and Edwards, 2005; Horton and Edwards, 2006). Transfer functions have advantages in some environments but they also have problems which must be overcome or taken into account (Table 3.1).

Table 3.1 Advantages and problems relating to transfer functions.

Advantages of the transfer function technique:
1. Applicability: Reconstructions of past environments are possible from organic and minerogenic sequences if the indicative meaning of microfossils contained in them can be established and bioturbation since burial has not occurred.
2. Sensitivity: changes in microfossil assemblages are often observed where there are no changes in lithostratigraphy (e.g.,preseismic relative sea-level signal recorded in microfossils where no changes occur in stratigraphy (Nelson <i>et al.</i> , 1996)).
3. Precision: highly precise late Holocene reconstructions are possible using microfossils e.g.,Gehrels <i>et al.</i> (2002) showing rapid sea-level rise in the Gulf of Maine since AD 1800, and the recent (~last 300 years) sea-level rise in Nova Scotia (Gehrels <i>et al.</i> , 2005). Hamilton and Shennan (2005) also show pre-seismic relative sea-level rise and post-seismic recovery over <50 years.
Potential problems with the transfer function technique:
1. In unimodal techniques taxa are assumed to have a unimodal relationship with their environment, similarly linear methods assume a linear response to the environment. The two different methods cannot be mixed (Birks, 1995).
2. Taxa are assumed to respond to a single environmental variable, but in fact may respond to a number of interrelated variables (Birks, 1995).
3. Analysis cannot occur on low microfossil counts. Microfossil counts also show some noise, redundancy and outliers which may affect reconstructions (Birks, 1995).
4. Preservation issues: dissolution or disaggregation of microfossils causing selective preservation down the sediment column may lead to no modern analogue situations.
5. Life habitat of organisms: infaunal or epifaunal activity, seasonal and spatial variability in micro-organism populations causes problems if this variability is not captured in the modern training set.

- To address research question 1, I followed this methodology:
1. Apply the sea-level index point methodology to existing sea-level reconstructions from North Queensland:
 - Split sea-level reconstructions into regional areas.

- Recalibrate radiocarbon dates to calendar years BP using Oxcal 3.10 (Bronk Ramsey, 1995; Hughen *et al.*, 2004).
 - Re-evaluate elevation estimates and elevation errors using the indicative meaning and range of each type of indicator, relating each elevation estimate to a common datum (AHD) using local tide levels.
 - Where possible indicate sea-level tendency for each index point.
 - Discard sea-level reconstructions if each component of the index point cannot be defined.
2. Develop a complementary microfossil proxy indicator technique, using a quantitative, transfer function method:
- Collect field data to investigate which microfossil group is best suited to this application (presence and preservation, correlation to tidal levels).
 - Amass an extensive modern training set of microfossil and environmental variable information.
 - Test whether the chosen microfossil group are vertically zoned using numerical techniques (Cluster Analysis and Detrended Correspondence Analysis (DCA)), and investigate the relationship of microfossil assemblages to their controlling environmental variables using Partial Canonical Correspondence Analysis (PCCA).
 - Investigate potential sources of error caused by taphonomic processes.
 - Develop a tide level microfossil-based transfer function capable of reconstructing relative sea level and creating sea-level index points from Cleveland Bay.
 - Count microfossils from fossil sequences which address research questions 2 – 4 (Section 1.8).
 - Collect in situ material from fossil sequences for AMS radiocarbon dating.

3.1.2 Research Question 2: What is the pattern of Holocene relative sea-level change in North Queensland?

Plotting re-evaluated and new sea-level data together will define mid-late Holocene sea-level changes in Cleveland Bay. Separating sea-level data into regions may show differences in Holocene relative sea-level change across North Queensland. Any differences in the timing and amplitude of the mid Holocene high stand across the region may be due to differential hydro-isostatic warping of the continental shelf (Nakada and Lambeck, 1989; Lambeck and Nakada, 1990).

To address research question 2, I followed this methodology:

1. To create new sea-level reconstructions, select field locations in Cleveland Bay where fossil materials recording mid-late Holocene sea-level change are preserved as shallow, quiet water sediment sequences over bedrock. Modern environments from LAT to 3 m above current MTL will likely provide suitable sequences which record the peak of the high stand.
2. Collect fossil sediment cores from these locations containing abundant microfossils to allow microfossil-based transfer function reconstructions.
3. Use all sea-level index points available to develop a sea-level chronology for Cleveland Bay (using ^{14}C dating of calcareous foraminifera for new reconstructions), which may define when relative sea level first reached its current value, the amplitude and timing of the mid Holocene high stand and the nature of relative sea-level fall through the late Holocene.
4. Draw revised Holocene sea-level chronologies for other regions of North Queensland using revised sea-level index points created to address research question 1.

3.1.3 Research Question 3: Does application of sea-level index point analysis in sediments help to define the mid Holocene high stand?

The improved sea-level chronology for Cleveland Bay developed to address research question 2 may increase definition of the mid Holocene high stand. Sea-level index points with tendency information may also provide further data on the nature of this high stand; its duration, single or multiple maxima and the nature of late Holocene sea-level fall.

To address research question 3, I followed this methodology:

1. For new sea-level reconstructions, collect multiple sedimentary sequences from 2 different locations in Cleveland Bay which record mid-late Holocene sea-level change to correlate sea-level tendencies at site and regional (within Cleveland Bay) scales.
2. Use the tendency of each index point (new and existing) in the sea-level chronology for Cleveland Bay to infer any perturbations within the mid Holocene high stand and during late Holocene sea-level fall.

3.1.4 Research Question 4: Is the resolution of sea-level data sufficient to differentiate between models of Mid Holocene high stand duration and amplitude?

The sea-level chronology developed for Cleveland Bay may also inform debate on models of high stand duration and amplitude in North Queensland (described in section 1.8).

To address research question 4, I followed this methodology:

1. Compare the sea-level chronology for Cleveland Bay with predicted mid-late Holocene sea-level change using different global ice models (no models were available from the Toronto school to test in this thesis);
 - Laurentide ice sheet melt by 6800 cal BP and continued reduced rate of Antarctic melt until more recently causing a pronounced high stand after 6800 cal BP and rapid fall to present levels where there is a wide continental shelf (Figure 1.4 c) (Nakada and Lambeck, 1989; Lambeck and Nakada, 1990). Lambeck recently revisited this work to infer a small eustatic signal of ~ 3 m between 7000 and 3000-2000 cal BP from Antarctica, Greenland and mountain glaciers (Lambeck, 2002), while Fleming *et al.* (1998) argue for 3-5 m of eustatic rise between 7000 and 2000-1000 cal BP.
 - Rapid Antarctic melting until 7000 cal BP slowing to 0.5 mm/yr between 7000-5000 cal BP and no melt after 5000 cal BP – high stand with pronounced peak but significant period with sea level above present during the late Holocene (Milne *et al.*, 2005).

3.2 FIELD AND LABORATORY METHODS

This section focuses on why each field and laboratory technique is used and possible sources of error arising from them. General techniques (e.g., levelling, lithostratigraphic analysis, microfossil analysis, ¹⁴C dating) are described elsewhere (Shennan, 1986; Van de Plassche, 1986; Horton, 1999; Gehrels, 2002).

3.2.1 Selection of appropriate microfossil types

Analysis of preliminary cores and previous studies from fossil field locations allow me to address research question 1 b (section 1.8) on usefulness of different microfossil groups as proxy sea-level indicators in North Queensland. After preparing samples for diatom and foraminiferal analysis using standard procedures (Palmer and Abbott, 1986; Scott and Medioli, 1986; Moore *et al.*, 1991; Gehrels, 2002), I analysed previous work and samples from relatively organic-rich and minerogenic horizons for presence of pollen, diatoms and foraminifera.

Pollen is not widely used as a quantitative proxy sea-level indicator because it is air- and water-dispersed which may give a larger than local vegetation signal and blur vertical zonation across the intertidal zone. However, a recent study of salt marshes in Connecticut demonstrates differentiation of vegetation zones may be possible, especially between upper and high marsh zones with an error term of 20-30 cm (Roe and Van de Plassche, 2005). This finding is not tested for tropical mangrove environments. Pollen is well preserved in organic horizons but not minerogenic horizons of cores from Cleveland Bay (Carter *et al.*, 1993; Larcombe *et al.*, 1995; Larcombe and Carter, 1998). Despite being preserved in organic horizons, thick (> 50 cm) organic horizons are not common and only constitute a small proportion of Holocene deposited core material in Cleveland Bay, therefore using pollen limits possible time periods for reconstruction.

Diatoms are used as quantitative proxy sea-level indicators in temperate and sub-arctic areas (e.g., Zong and Horton, 1999; Zong *et al.*, 2003; Hamilton and Shennan, 2005) and theoretically outperform foraminifera and testate amoebae as quantitative proxy sea-level indicators in the UK (Gehrels *et al.*, 2001). However, I found no diatoms in any horizons of cores from Cleveland Bay.

Foraminifera-based transfer functions in temperate areas give precise sea-level reconstructions (e.g., Gehrels *et al.*, 2002) but in tropical environments are only theoretically developed and not tested on fossil material (Horton *et al.*, 2003; Horton *et al.*, 2005b). I discovered that foraminifera are absent from organic horizons but are preserved in minerogenic horizons of cores from Cleveland Bay during my MSc project (Woodroffe, 2002). The vast majority of material in fossil cores collected for this thesis is minerogenic and foraminifera-rich, so this gives the opportunity to test applicability of calcareous foraminifera in reconstructing relative sea-level change in tropical intertidal and subtidal environments.

Ideally, I would use a pollen as an indicator in organic horizons and foraminifera in minerogenic horizons. However, there is a practical issue of time taken to count sufficient modern pollen samples to give meaningful reconstructions from small organic horizons in fossil cores, or developing a large foraminiferal training set providing modern analogues for assemblages from large minerogenic sections in cores. Therefore, I decided to use only the foraminifera group, particularly calcareous foraminifera as proxy indicators throughout this thesis.

3.2.2 Collection of modern samples

Modern foraminiferal sample collection follows standard methods (Scott and Medioli, 1980b; Palmer and Abbott, 1986; Scott *et al.*, 2001; Gehrels, 2002). Standard sample volume (10 cm² by 1 cm thick) allows comparison with similar studies (e.g. Horton *et al.*, 2003; Horton *et al.*, 2005b). At each sample station I also take samples for environmental analysis. These samples are 20 cm³ (20 cm² by 1 cm thick), collected for grain size, loss on ignition, pH and salinity analyses. All material is collected at low tide during a neap tidal cycle in the southern hemisphere winter. Material from MTL upwards is collected on foot using a knife or trowel, material from lower elevations is collected using a small dredge sampler off the side of an inflatable dinghy.

Transects at Cocoa Creek and Alligator Creek extend into low intertidal and shallow subtidal environments to allow sea-level reconstructions using calcareous foraminifera. In addition, some transfer function regression techniques perform best when biological data is evenly spaced along the environmental gradient of interest (Birks, 1995). Therefore modern sample stations are at equal 10 cm vertical intervals wherever possible. This is impossible above MTL because of dense vegetation. Elevation intervals above MTL range from 10-40 cm, placed where there are distinct changes in topography or vegetation. On mudflats between MTL and LAT 10 cm elevation intervals is possible, but below LAT elevation intervals range from 10-50 cm because of water depth and time limitations.

In June 2003, I sampled along a series of transects at Cocoa Creek, covering a range from Mean High Water of Spring Tides (MHWST) to 2.7 m below Lowest Astronomical Tide with 35 sample stations (Figures 2.4 b, c and 3.1). This series of transects covers the majority of the intertidal zone, including all mangrove and intertidal mudflat environments and extends sampling into shallow subtidal environments. Above MHWST is upper-intertidal vegetation-free salt pan where microfossils were not recorded in 2002 (Woodroffe, 2002), and therefore was not sampled. A transect at Big Mango in Edgumbe Bay also collected in June 2003 provides further samples to increase elevation resolution in the intertidal zone and covers mangrove mud and sandflat environments from MHWST to LAT with 19 sample stations (Figure 2.4 e and 3.1).

Following preliminary analysis it was clear that sampling at a higher elevational resolution was required from intertidal and shallow subtidal mudflats to increase precision in reconstructions and give modern microfossil analogues. In June 2004 I

sampled at Alligator Creek in a transect from just below Mean Tide Level to -5 m LAT with 32 sample stations (Figure 2.4 d and 3.1). The transects taken at Cocoa Creek, Alligator Creek and Big Mango provide modern microfossil samples and related environmental variables, and together form the modern training set of microfossil and environmental variable information.

3.2.3 *Collection of fossil samples*

Fossil cores taken at 2 field locations in Cleveland Bay allow investigation of the pattern of Holocene sea-level changes in North Queensland, and the correlation of observed sea-level tendencies at site and local scales. Coring using a 25 mm diameter gouge along transects across upper intertidal salt pans and mangroves at Cocoa Creek and Alligator Creek allows investigation of the buried lithostratigraphy of the upper intertidal zone in Cleveland Bay. I use the Troels Smith (1955) scheme to describe the sediments and organic material within them. At Cocoa Creek I took 22 exploratory cores in 2 transects over 2.5 km of upper intertidal saltpan, each core between 50 cm and 4.5 m deep (Figures 2.3, 5.1 and 5.2). At Alligator Creek I took 15 exploratory cores in two 2 km long transects across upper intertidal salt pans, each between 1.5 and 3.5 m deep (Figures 2.5 a, 5.4 and 5.5). Each transect is levelled to timed still water and related to Australian Height Datum using Townsville tide-gauge records.

After drawing up summary stratigraphy for each site I decided on locations to collect sample cores, to test research questions 2-4. At Cocoa Creek I chose the deepest core taken, likely to give the earliest sea-level reconstruction and a second shallower core likely to record the maximum height of the mid Holocene high stand and late Holocene sea-level fall. Collecting 2 sample cores from Cocoa Creek allows site scale correlation between cores. At Alligator Creek I similarly chose cores to record early-mid Holocene sea-level change and the maximum height of the mid Holocene high stand and late Holocene sea-level fall.

Sample cores for laboratory analysis at both locations are taken using a 'Russian' corer or 'Livingstone' hand operated piston corer. These coring devices have the advantage of collecting largely uncontaminated samples. Samples were extruded in the field, cut into 50 cm sections, wrapped in plastic and stored in a refrigerator (see Table 3.2 for error terms associated with fossil sampling).

3.2.4 *Levelling*

Most modern sample stations are levelled using a Leica NA720 level and staff. These stations are reduced to Australian Height Datum by either levelling the altitude of the

swash mark from the previous high tide, or levelling to the sea and using a 'timed still' water reading to relate the altitudes to hourly tide gauge readings for Townsville (total root squared error of this method is 7.6 cm – see section 3.2.12) (following Horton *et al.*, 2003). Stations sampled from a boat are levelled using a long measuring stick in quiet tidal water and height related directly to hourly tide gauge readings for Townsville (total root squared error of this method is 7.9 cm – see section 3.2.12).

3.2.5 Modern foraminiferal analysis

Surface samples from Cocoa Creek, Alligator Creek and Big Mango provide a modern training set, ranging from shallow subtidal flat to upper intertidal mangrove environments.

Each sample was placed in buffered ethanol with the protein stain rose Bengal, sealed in vials and refrigerated to prevent bacterial oxidation of the foraminiferal tests. The protein stain rose Bengal identifies organisms living at the time of collection (following Murray, 1991). Rose Bengal is used extensively to differentiate living from dead foraminifera (e.g., Scott and Medioli, 1980a; Horton, 1999; Scott *et al.*, 2001). Protoplasm is stained red while test walls are either unstained or lightly stained. Tests with protoplasm in the last few chambers were assumed to be live. Despite problems with protoplasm remaining in tests after death, staining with rose Bengal is as reliable as other, more high-tech and time-consuming methods available (Murray and Bowser, 2000). I sieved 50 ml of sediment, retaining the fraction greater than 63 μm for analysis, then subdivided samples into eight aliquots using a wet-splitter and used 200 dead specimens from one aliquot as the basis for each count, noting how many live foraminifera I also found during the count (Scott *et al.*, 2001). Samples were counted wet under a binocular microscope at 40 x or 50 x magnification.

Taxonomy follows Albani (1968), Haig (1988), Bronniman and Whittaker (1993), Wynn-Jones (1994), Yassini and Jones (1995), Hayward *et al.* (1999a), Revets (2000) and Horton *et al.* (2003). Recent advances in molecular and morphometric analysis (Hayward *et al.*, 2004a) allow different morphological types to be distinguished from the morphologically variable taxa *Ammonia beccarii*, which live worldwide in shallow marine and intertidal environments (Murray, 1991). In light of this I name most *Ammonia* specimens in this thesis as *Ammonia aoteana*, the molecular type group for Australia (Albani, 1968).

3.2.6 Foraminiferal sample size

For practical reasons it is only possible to examine a proportion of the total microfossil population in a sample. Many researchers state that an optimum count to be representative of a sample is between 300-400 specimens (Patterson and Fishbein, 1989; Moore *et al.*, 1991; Murray, 1991; Scott *et al.*, 2001). However, there is a trade off between increasing count size to be representative of the population, the increased time taken in counting and therefore the total number of samples processed. This trade off is influenced by the decrease in counting error which comes with larger count sizes.

Calculating the 95% confidence interval of error as count sizes increase informs the decision on how many foraminifera to count per sample (Mossiman, 1965). For example, a species representing 20 % of the foraminiferal sum in a count of 200 will have 95 % confidence limits between 15 and 26 % (Figure 3.2). The decrease in confidence interval of error between counting 200 (11 %) and 300 (9 %) specimens is very small given the large increase in time (50 % extra) required for the larger count size (Figure 3.2). I decided that counting 50 % more samples at 200 specimens per sample is more important than decreasing counting error by 2 %.

3.2.7 *Live, dead and total foraminifera*

The issue of using live, dead or total assemblages remains contentious (e.g. Scott and Medioli, 1980a; Murray, 2000). Some argue that total assemblages most accurately represent general environmental conditions because they integrate seasonal and temporal fluctuations (Scott and Medioli, 1980a; de Rijk, 1995), however total assemblages combine data on living assemblages (which have not experienced taphonomic change) with dead assemblages (which have been taphonomically modified) and are therefore artefacts (Murray, 2000). Murray (1991; 2000) and others (Horton and Edwards, 2005; Horton *et al.*, 2005b; Horton and Edwards, 2006) argue that the live component is variable and may not be transferred into sub-surface environments, therefore including it would degrade the utility of the dataset. I therefore express foraminiferal data as a percentage of dead assemblages (following Horton, 1999).

3.2.8 *Infaunal foraminifera*

The modern training set consists of foraminifera collected from the top 1 cm of sediment. Microfossil-based sea-level reconstructions based on 1 cm deep modern samples rely on the principle that very little bioturbation or infaunal activity occurs below the sediment surface to mix the modern death assemblage with fossil

assemblages below 1 cm depth. To test whether foraminifera are useful proxy sea-level indicators in this environment (research question 1 e. – Section 1.8) I must address this issue.

In temperate marshes, studies indicate the top centimetre is likely to provide the best modern analogue for interpretation of subsurface assemblages, as bioturbation and infaunal activity are low (Gehrels, 2000; Tobin *et al.*, 2005). However, in tropical intertidal environments a range of nektonic, terrestrial and resident fauna potentially disturb mangrove and tidal flat sediment (Grindrod, 1988). A cross section through a productive mangrove soil reveals living and dead root systems and buried plant remains, evidence of faunal occupations such as burrows inhabited by living animals including clams, worms, crabs and fish, the filled traces of disused burrows and the remains of dead crustaceans and molluscs (Grindrod, 1988). Burrowing organisms may mix sediment to many centimetres depth, draw live and dead foraminifera up and down the sediment column and destroy any fine detail in the fossil record. Infaunal organisms (e.g., clams, worms, crabs etc.) live in most of the intertidal zone including lower intertidal mudflats. Horton *et al.* (2005b) find that 97% of live foraminiferal specimens occur above 12 cm depth in Indonesian mangroves, and there is a strong correlation between surface dead and sub-surface assemblages, inferring that some bioturbation occurs down to 12 cm depth. There are few other investigations into infaunal activity in tropical intertidal environments.

To investigate infaunal foraminifera down core, I followed this methodology (Section 4.3 discusses the results of infaunal foraminiferal analysis):

1. Collect three cores through the upper 50 cm of sediment at 3 different locations in the intertidal zone;
 - 0 m AHD (seaward edge of *Rhizophora stylosa* mangrove zone, 10 cm below MTL),
 - -0.20 m AHD (fringing *Avicennia marina* mangrove zone, 20 cm below MTL)
 - -2.25 m AHD, 40 cm below LAT in subtidal mudflat (Figure 3.1).
2. Sample each core for foraminifera at 5 cm intervals to 50 cm deep and stain samples with rose Bengal.
3. Count 200 dead foraminifera as the basis for each sample, noting how many live foraminifera I also find during the count.

4. Analyse the percentage of live foraminifera at each depth, comparing samples for particular species which may prefer to live infaunally.
5. If particular species are commonly found living infaunally, exclude them from the transfer function to assess their impact on reconstructed palaeo-surface elevations.

3.2.9 *Disappearance of agglutinated foraminifera down core*

Agglutinated foraminifera are readily preserved in fossil tidal marsh deposits in northern Europe and North America (e.g. Gehrels, 2000; Horton and Edwards, 2005), but are not readily preserved in fossil mangrove deposits from NE Australia (MSc thesis, Woodroffe, 2002; Woodroffe *et al.*, 2005). Debenay *et al.* (2002; 2004) find that, in coastal French Guiana the number of agglutinated foraminiferal tests decreases dramatically between surface and sub-surface samples taken between 8-12 cm depth. In young and well-developed mangrove forests, sub-surface samples are completely devoid of foraminifera, while the corresponding surface samples contain over 200 individuals per 50 cm³ of sediment (Debenay *et al.*, 2002; Debenay *et al.*, 2004). Debenay *et al.* (2004) state that preservation of tests down core in mangrove sediments is 'exceptional', and the use of these assemblages as sea-level indicators is therefore impossible. Culver (1990) also recognises that preservation potential of small, delicate agglutinated foraminifera in fossil mangrove deposits is low due to post-depositional diagenetic effects, and Wang and Chappell (2001) find foraminifera degradation and loss in mangrove cores from South Alligator river, Northern Territory. These diagenetic effects are poorly understood, and they limit the range of environments which can be reconstructed using fossil foraminifera. Some degradation is likely to be due to post-depositional changes in porewater chemistry, or due to bioturbation by fiddler crabs introducing sufficient oxygen promoting bacterial oxidation and degradation of test linings (Tobin *et al.*, 2005), but it is also argued that major loss may occur whilst cores are stored at room temperature in the laboratory (Wang and Chappell, 2001). To investigate agglutinated foraminifera disappearance down core, I followed this methodology:

1. Count foraminifera from 3 short cores (described in section 3.2.8) at 5 cm intervals down to 50 cm.
2. Ensure all fossil cores are quickly removed from the field locations and stored in a fridge prior to analysis.
3. Create two modern foraminiferal training sets, one using the whole data set and one replicating agglutinated foraminifera disappearance down core and

compare palaeo-surface elevation reconstructions for other fossil cores to see if potential dissolution affects reconstructions.

3.2.10 Fossil foraminiferal analysis

I took 2 cm³ samples for fossil foraminiferal analysis from cores using a sharp knife. These samples are not stained or split, are sieved retaining the fraction greater than 63 µm, and 200 specimens counted where possible. The sampling interval for all cores is initially 10 cm. After running an preliminary transfer function, I chose smaller sampling intervals (down to 1 cm) where the transfer function reconstructs large changes in palaeo-surface elevation.

3.2.11 Environmental variables

A series of variables potentially control foraminifera assemblages and quantifying their contribution in explaining foraminiferal assemblages indicates whether foraminifera are useful sea-level indicators. The environmental variables are; grain size, organic content (loss on ignition), pH, salinity and elevation.

I recorded salinity and pH by adding 25 ml of distilled water to 5 g of sediment, centrifuging the sample and measuring salinity and pH levels in supernatant water using a Jenway Conductivity Meter 4320 and a Jenway pH Meter 3320. I analysed sediment samples (0.5 g) for grain size using a Coulter lazer particle size granulometer. Samples are pre-treated with hydrogen peroxide to dissolve organic material and sonicated when loaded into the granulometer. Calcareous material is not removed during pre-treatment. By weighing and burning 5 g of dry sediment in a furnace at 550°C for four hours I can calculate percentage Loss on Ignition (LOI) using the following equation (Heiri *et al.*, 2001):

$$\% \text{ LOI} = \frac{100 \times (\text{weight of dry sediment} - \text{weight of burnt sediment})}{\text{Weight of dry sediment}}$$

Grain size and LOI samples are analysed at all horizons in fossil cores where samples were taken for foraminiferal analysis to give information on the environment of deposition which may corroborate transfer function elevation reconstructions.

3.2.12 Sources of error in modern and fossil sampling

Modern sampling error

A lack of bench marks close to field sites makes relating sample elevations to Australian Height Datum complex. Tide levels can vary from tidal predictions due to atmospheric conditions (e.g., pressure and wind speed) so I use hourly readings of tidal height at Townsville Port to relate still-water levels to national datum. Cocoa Creek is approximately 15 km from the tide gauge at Townsville port and although tidal distortion in Cleveland Bay is unknown, tidal time varies by only 15 minutes between Townsville and Lucinda, 90 km away (Department of Transport, 2002). Quiet tidal water and wide low relief mud flats at modern field sites in Cleveland Bay allowed relatively good precision in measuring still water level for upper intertidal samples, as little error is introduced by waves. In Scotland, this technique is used on remote islands without national datum benchmarks. Repeated tests show accuracy is possible within 0.02 m over distances of 10 km or less (Sissons and Dawson, 1981; Smith and Dawson, 1983). Slightly more error is introduced when collecting low intertidal/subtidal samples from a boat, by measuring the depth of the water column (Table 3.2).

Fossil sampling error

Shennan (1982) identifies a number of largely unavoidable errors arising when using a hand operated corer, including angle of borehole, measurement of depth and compaction (Table 3.2). Some materials compact during sampling and extrusion. The only known depth for each sample tube is its base, and any altitudinal error after extrusion will be unequally distributed through each sample. I used a simple correction based on the ratio between known depth sampled and extruded sample length to approximately correct samples for compaction during sampling and extrusion. This is inappropriate when inter-calated sediments are recorded in a single sample tube, as the different characteristics of each deposit will likely result in differential compaction on extrusion. Sandy clays give 100% recovery on extrusion, while wet silts compact by up to 33%. Errors described above are also introduced whilst reducing core-top elevations to Australian Height Datum. Changes in palaeo-tidal range during the past 6000 cal yrs are an additional source of error which I have not been able to quantify for this thesis.

Sampling error is calculated using the formula for total root squared error:

$$\sqrt{e_1^2 + e_2^2 + e_3^2 \dots e_n^2}$$

(Equation 1)

Where e_1 = Levelling to timed still water level

e_2 = Variation in timed still water level due to waves

e_3 = Variation in tidal time and height between Townsville tide gauge and field site

e_4 = Closing error of levelled transect (see Table 3.2)

Where sampling errors are combined with other errors (e.g.,transfer function model errors and sample specific errors – see section 5.5.2), Equation 1 still applies. Each category of error is combined as $e_1 \dots e_n$ etc. and fitted into the equation above.

Table 3.2: Estimated errors accumulated during modern and fossil sampling.

Source of error	Estimated total elevation error (cm)
Modern sampling in intertidal environments: 1. Levelling to timed still water level 2. Variation in timed still water level due to waves 3. Variation in tidal time and height between Townsville tide gauge and field site 4. Closing error of levelled transect Total root squared error	 2 cm 2 cm 5 cm 5 cm 7.6 cm
Modern sampling in subtidal environments: 1. Angle of staff/rope in water when measuring depth 2. Measuring depth of water column due to waves 3. Variation in timed still water level due to waves 4. Variation in tidal time and height between Townsville tide gauge and field site Total root squared error	 3 cm 2 cm 5 cm 5 cm 7.9 cm
Core sampling: 1. Measurement of depth using hand corer 2. Angle of borehole 3. Compaction (corrected using simple algorithm) 4. Variation in timed still water level due to waves 5. Variation in tidal time and height between Townsville tide gauge and field site Total root squared error	 1 cm 4 cm 5 cm 2 cm 5 cm 8.4 cm

3.3 NUMERICAL TECHNIQUES

I used a range of numerical techniques to establish relationships between modern foraminiferal data and their associated environmental variables, and which allow comparison between the modern data set and fossil samples.

3.3.1 *Cluster analysis*

I carried out cluster analysis on the combined modern foraminiferal training set using Constrained Incremental Sum of Squares Analysis (CONISS) within the TILIA program version 2.0 b5 (Grimm, 1987; Grimm, 1993), which produces a dendrogram. Cluster analysis describes modern foraminiferal assemblages by grouping most similar samples together, not taking into account their original order, allowing objective subdivision of a large data set for summary description. It shows clustering of samples without any underlying assumptions about species (e.g., unimodal or linear distribution). In CONISS I chose the Euclidian distance method (no data transformation), which classifies clusters based on major taxa.

If clusters contain samples from exclusive elevation ranges this infers elevation control on species assemblages, and permits further investigation into vertical zonation using other numerical techniques (e.g., DCA) (to address research question 1 c, Section 1.8). Modern foraminiferal assemblages must be primarily controlled by elevation to carry out quantitative sea-level reconstructions.

I analysed fossil cores using stratigraphically constrained cluster analysis. Clustering is constrained by the position of samples in the stratigraphic column. This technique indicates major changes in species composition through cores and highlights zone boundaries where a transfer function should predict changes in relative sea level. The dendrogram produces zones in a core but does not provide quantitative estimates of relative sea-level change.

3.3.2 *Detrended Correspondence Analysis, Detrended Canonical Correspondence Analysis and Partial Canonical Correspondence Analysis*

Detrended correspondence analysis (DCA) represents modern foraminiferal species and samples in environmental/ordination space. DCA supports and furthers cluster analysis results (to address research question 1 c. – Section 1.8) because it groups similar samples together using an independent analysis technique and gives further information on variation within and between cluster groups. Species are located at the point in ordination space where they are most abundant, and sample locations reflect

average position of species contained in them (Jongman *et al.*, 1987). Axis one denotes the major gradient in the data and samples are positioned to reflect major changes along this gradient.

Cluster analysis and DCA are complementary techniques which together give information on vertical zonation of foraminiferal assemblages. This is a vital first step in assessing whether intertidal and shallow subtidal foraminifera are useful proxy sea-level indicators.

Detrended Canonical Correspondence Analysis (DCCA) is a direct gradient analysis technique used to calculate the length of the foraminiferal gradient present in the training set. This determines whether a linear or unimodal response model within Partial Canonical Correspondence Analysis (PCCA) and transfer function development is the most appropriate for the training set.

PCCA performs a direct gradient analysis (or constrained ordination) of modern foraminiferal data in relation to environmental predictor variables: elevation, pH, salinity, sand %, silt %, clay % and LOI % (Jongman *et al.*, 1987). It shows how much variance in foraminiferal assemblages is explained by each environmental variable. Knowing the variance explained by elevation indicates the likely confidence in using the transfer function technique to reconstruct relative sea level. PCCA is a unimodal regression method which assumes that the biological response model is unimodal.

Detrended Correspondence Analysis, Detrended Canonical Correspondence Analysis and Partial Canonical Correspondence Analysis were performed using the program CANOCO (version 4.5, ter Braak and Šmilauer, 1998).

3.3.3 *Transfer function*

A transfer function (Imbrie and Kipp, 1971) quantifies the relationship between an environmental variable of interest (e.g., elevation), and an environmental proxy (foraminiferal assemblages) allowing elevation to be expressed as a function of foraminiferal assemblages (Birks *et al.*, 1990; Birks, 1995). In this thesis the aim of the transfer function is to address the research question (1 e. – Section 1.8) that foraminiferal assemblages can provide quantitative reconstructions of sea-level change, by predicting elevation for a fossil foraminiferal sample using the relationship established from the modern foraminiferal training set.

Transfer function regression models the relationship between the elevation of the samples in the modern training set and the relative abundances of foraminiferal taxa contained within them. Regression techniques assume either linear or unimodal underlying taxon-environment response models, creating modern ecological response functions or regression coefficients (Birks, 1995). The second stage is calibration of fossil foraminiferal assemblages from sediment cores with ecological response functions derived during regression to produce estimates of past surface elevation. Transfer function results (changes in palaeo-surface elevation) combine with depths in core, age and sedimentation rates, location and sea-level tendency to produce sea-level index points. Plotting each index point on an age-elevation graph produces a chronology of relative sea-level changes over time.

3.3.4 Modern Analogue Technique

I use Modern Analogue Technique (MAT) to assess the validity of transfer function reconstructions. The transfer function will always give a result, but MAT compares numerically, using an appropriate dissimilarity measure, similarity between the assemblage of a fossil sample with all assemblages in the modern training set. This allows independent assessment of whether fossil samples possess good modern analogues. This provides a basis to decide whether to accept transfer function reconstructions (e.g. Edwards and Horton, 2000; Zong *et al.*, 2003). The program C2 (version 1.4 beta, Juggins, 2003) runs transfer functions and Modern Analogue Technique.

3.4 DATING METHODS

I use ^{14}C dating to produce a chronology for sampled sediment cores. This chronology allows correlation of sea-level changes between sites to address research questions 2-4 (Section 1.8). Approval of 31 AMS radiocarbon dates by the Natural Environment Research Council (NERC - allocations 1066.0404 and 1121.0405) allowed dating of 27 foraminiferal and 4 shell samples from cores from Cocoa and Alligator Creeks. I picked clean, whole foraminifera and whole bivalves from sediments at each 1 cm thick level dated. Foraminiferal samples contain multiple species and foraminiferal sizes to include juvenile and adult specimens. Weights of 6-12 mg of foraminifera and 10-15 mg of shells are needed to provide enough carbon to be analysed at the NERC Radiocarbon Laboratory (NERC-RCL) at East Kilbride.

The NERC RCL reports ages as conventional radiocarbon years BP (relative to AD 1950) and percentage modern ^{14}C , both expressed at the $\pm 1 \sigma$ level for overall

analytical confidence. I calibrated all ages in this thesis to calendar years BP with 2 σ errors using the program Oxcal 3.10 (Bronk Ramsey, 1995; Hughen *et al.*, 2004). Results in following chapters report calibrated ages as the range between calculated minimum and maximum value, with median age marked on figures.

3.4.1 Reworking and radiocarbon ages

Reworking of foraminifera may occur up and down the sediment column by bioturbators (section 3.2.8), and by high magnitude, low frequency storm events causing sediment mixing in subtidal and intertidal zones. These are potential limiting factors when using foraminifera from sediments to give an age chronology to sea-level movements. To address research question 1 f. (Section 1.8) that calcareous foraminifera are suitable *in situ* organisms for radiocarbon dating sea-level movements, I submitted for AMS ^{14}C dating 4 paired samples of foraminifera and unarticulated bivalve shells (not clearly in living position) from Core 7 at Cocoa Creek. If single bivalve shells are older or the same age as foraminifera from the same horizon, bivalves are either reworked or *in situ*, respectively. If single bivalve shells are younger than foraminifera from the same horizon, either foraminifera are reworked or bivalves have infaunally burrowed into older layers. Results of dating are reported in section 5.3, and discussed in section 6.4.5. As it is not clear what habitat the bivalve shells lived in, I did not apply a Marine Reservoir Correction to any dates on shells or foraminifera.

3.5 CHAPTER SUMMARY

This chapter outlines the main techniques used throughout this thesis and the adopted sampling strategies. Following chapters present results of using these techniques from modern and fossil data.

CHAPTER FOUR – FORAMINIFERA AS SEA-LEVEL INDICATORS

4.1 INTRODUCTION

In order to create new relative sea-level reconstructions using a foraminifera-based transfer function in North Queensland (Research Question 1) this chapter investigates modern foraminiferal distributions and their relation to elevation at three study locations: Cocoa Creek and Alligator Creek in Cleveland Bay and Big Mango in Edgecumbe Bay. These data provide a modern training set of foraminiferal and environmental variable information. In this chapter I also develop a series of transfer functions relating foraminiferal assemblages to elevation. In chapter 5 I apply these transfer functions to fossil foraminifera giving sea-level reconstructions for Cleveland Bay.

This chapter has the following sections:

1. Developing a modern training set of foraminiferal and environmental variable information:
 - Description of intertidal/subtidal environments sampled in North Queensland;
 - Distribution of modern foraminifera and analysis of vertical zonation using cluster analysis and DCA;
 - Relating foraminifera to environmental variables using CCA.
 - Deciding on training set parameters;
 - Count size
 - Local or regional samples
2. Investigating potential sources of error using foraminifera as proxy sea-level indicators:
 - Infaunal foraminifera;
 - Selective preservation down core.
3. Developing transfer functions allowing reconstruction of past water levels from fossil foraminiferal assemblages:
 - Unimodal or linear methods?
 - Include or exclude agglutinated foraminifera?
 - Statistical assumptions of the transfer function technique.

4.2 DEVELOPING A MODERN TRAINING SET

Successful use of intertidal/subtidal foraminifera to reconstruct relative sea level requires analysis of their modern distributions and their relationship to the environmental variables responsible for shaping these patterns (Thomas and Varekamp, 1992; Horton and Edwards, 2006).

4.2.1 Modern environments sampled

Cocoa Creek

The transect at Cocoa Creek is perpendicular to the shoreline covering the range from -4.75 m AHD (-2.85 m LAT) to 1.16 m AHD (0.05 m below MHWST) (Figure 2.4 b and c and Figure 4.1). A clay-rich substrate (~70 % clay) with low organic content (< 5 %), low salinity and neutral pH dominates the shallow subtidal and lower intertidal mud flats (-4.75 m AHD to -0.05 m AHD). Around the transition between intertidal mud flat and mangrove (~0 m AHD) grain size changes from ~70 % clay to ~90 % silt, organic content increases to ~10 %, salinity increases to 15-20 ‰ and pH drops marking the start of a *Rhizophora stylosa* dominated floral zone (Figure 2.4 c and 4.1). The *Rhizophora stylosa* mangroves are mature and vegetation cover is dense. At 0.78 m AHD within the mangrove zone organic content increases to ~19%, salinity remains stable between 15-20 ‰ and pH drops further around the transition to a *Cerriops* sp. floral zone (Figure 2.4 c and 4.1). The transect stops at 1.16 m AHD against an unvegetated, sand rich, 3 m high chenier ridge.

Alligator Creek

The transect starts 20 cm below mean tide level, continuing to -7.16 m AHD (5.30 m below LAT), confined to unvegetated silt and sand rich environments (Figure 2.4 d and Figure 4.2). Silt-rich substrate (~ 60 %) dominates from the uppermost sample station (20 cm below MTL) to midway between MLWNT and MLWST (-0.75 m AHD), with roughly 8 % organic content, salinity between 17-23 ‰ and pH between 7.5 to 8 (Figure 4.2). Midway across the intertidal flat, a transition (between -0.75 to -0.91 m AHD) between predominantly silt-rich to sand-rich substrate (silt decreases to ~30 % and sand increases to 60 %) is claimed to roughly define the lower intertidal boundary (Harvey *et al.*, 2001). Organic content and salinity also decrease in this zone (organic content from ~8 % to 2-3 %, salinity from 17-23 ‰ to 8-11 ‰). Below this transition zone the rest of the transect is a largely homogenous sand-rich unit (~75 % sand) with low organic content (~3% - derived from decomposition of seagrasses), low salinity (8-11 ‰) and constant pH (7.5-8) (Figure 4.1 b).

Big Mango

This transect covers a range from 1.20 m AHD (5 cm above MHWST) to -1.86 m AHD (LAT). *Avicennia marina* mangroves dominate open vegetation structure between the uppermost sample station and 0.37 m AHD. Substrate is sand-rich (90 % sand) and organic content is low (~3 %) (Figures 2.4 e and 4.3). At 0.37 m AHD *Rhizophora stylosa* begin to dominate. Substrate remains sand-rich interspersed with silt and clay-rich horizons (~90 % sand interspersed with 50 % silt and 50 % clay) and organic content remains low (~3 %). The rest of the transect (-0.54 m to -1.86 m AHD) is seagrass beds on the sand-rich intertidal flat (~95 % sand) with very low organic content (~1 %) (Figure 4.3).

4.2.2 Modern foraminifera

Using biological organisms as sea-level indicators rests on the assumption that their distribution is related to sea level in a quantifiable manner and by establishing this vertical relationship with a specified tide level, former positions of relative sea level may be determined. Pioneers of this approach, Scott and Medioli (1980b) visually group modern saltmarsh foraminifera to define vertical zones with respect to mean sea level and closely parallel marsh floral zones. More recent work groups saltmarsh foraminiferal assemblages on statistical grounds related to distinct depositional environments (e.g., de Rijk, 1995; Horton, 1999).

Foraminiferal assemblages from tropical intertidal environments are seldom considered as potential proxy indicators for Holocene sea-level reconstructions (Culver, 1990; Haslett, 2001; Horton *et al.*, 2003; Barbosa *et al.*, 2005; Horton *et al.*, 2005b). Studies of swamps in French Guiana (Debenay *et al.*, 2002; Debenay *et al.*, 2004) show that in some locations vertical elevation is not the dominant parameter controlling distribution of foraminiferal assemblages. Other factors including presence of mangrove trees and litter preventing heating and drying may be equally important at explaining variations in assemblages at higher elevations.

In total there are 76 foraminiferal samples with 50 or more specimens counted in each sample from Cocoa Creek (35), Alligator Creek (32) and Big Mango (9) (Figure 4.4). There are 71 different foraminiferal species in total, the majority (81 %) are calcareous benthic species. Generally counts of 200 are possible below MTL in mixed and calcareous zones, but above MTL where agglutinated foraminifera dominate it is often only possible to count 50-150 specimens per sample (Figure 4.4). Calcareous species dominate all transects below -0.20 m AHD. A mixed calcareous and agglutinated

assemblage occurs between -0.20 and 0.21 m AHD at Cocoa and Alligator Creeks and agglutinated species dominate above 0.21 m AHD at Cocoa Creek (Figure 4.4).

4.2.3 Foraminiferal distributions

Analysing foraminiferal distributions of all 3 transects together (Figures 4.4 and 4.5) gives a preliminary analysis of foraminiferal assemblages and whether they are similar at comparable elevations at different locations. Most species change in abundance at similar elevations at each location (Figure 4.4).

Species diversity varies dramatically from ~11 agglutinated species in vegetated mangrove zones above MTL to ~30 calcareous species in samples from lower elevations (Figures 4.4 and 4.5). Agglutinated species occur in the upper half of the intertidal zone from -0.20 m upwards. *Miliammina fusca* and *Trochammina inflata* dominate at highest sampled elevations within *Rhizophora stylosa*, *Avicennia marina* and *Ceriops* sp. mangrove zones, with moderate frequencies of *Haplophragmoides* sp. and *Ammotium directum*. At approximately MTL calcareous species become more frequent, with *Ammonia aoteana* rapidly rising at the expense of agglutinated species. This transition zone corresponds with the lower limit of mangrove vegetation at all locations. Agglutinated species have virtually disappeared by -0.2 m AHD (30 cm below MTL), although persistently low numbers of some agglutinated species (mostly *Paratrochammina stoeni* and *Monotalea salsa*) are found down to -5.4 m AHD. Two main species, *Ammonia aoteana* and *Pararotalia venusta*, dominate the mid-low intertidal environment (Figure 4.4). *Ammonia aoteana* peaks around -0.7 m AHD (80 cm below MTL) and *Pararotalia venusta* around -1.75 m AHD (close to LAT). *Ammonia aoteana* slowly declines with lower elevation while *Pararotalia venusta* is dominant from MLWNT to LAT, declining subtidally to low frequency at -7.16 m AHD. Other dominant species in the mid-intertidal zone are *Parrellina hispidula*, *Quinqueloculina incisa* and *Rosalina* sp., but these are present in low numbers compared to the two main species.

Below LAT species diversity remains high. Many calcareous species found at higher elevations are still present in lower numbers. *Pararotalia venusta* is still dominant to -5 m AHD, with other major species including *Parrellina hispidula*, *Quinqueloculina cuvieriana*, *Triloculina oblonga* and *Triloculina tricarinata*. Species which peak below LAT include *Quinqueloculina crassicarinata*, *Quinqueloculina suborbicularis*, *Triloculina tricarinata* and *Planispirinella exigua*.

Below -5 m AHD a wide range of species are present with no one species dominating. Between 12-15 species each account for 6-8 % of sample total (Figure 4.4 and 4.5). In general calcareous species have wider tolerances than agglutinated species, and the major calcareous species, *Ammonia aoteana* and *Pararotalia venusta*, are found in most samples between -7.16 m and 0 m AHD.

Despite general agreement in foraminiferal assemblages at each elevation between field locations, there are some discrepancies in abundances of *Pararotalia venusta* between 0.2 and -0.5 m AHD at Cocoa and Alligator Creeks (Figures 4.4 and 4.5). Variability in abundances of *Pararotalia venusta* at Cocoa and Alligator Creeks are greater than expected at a local scale. However, individual transects rarely reflect true variability at a site. Where more than one transect is taken at a single site and data combined, often less variance is explained by elevation than by one transect alone (Gehrels *et al.*, 2001). I checked levelling procedures to ensure different transects are correlated correctly to local tidal heights and related correctly to Australian Height Datum, so I believe transects are not vertically offset. Therefore I believe variability in the abundance of *Pararotalia venusta* at Cocoa and Alligator Creeks more closely reflects true variability in foraminiferal abundances on a local scale than using one transect from either Cocoa or Alligator Creek alone.

4.2.4 Analysis of vertical zonation

To use foraminifera as proxy sea-level indicators I must test their zonation in relation to elevation. Vertical zonation is tested in limited tropical locations (north Queensland, Horton *et al.*, 2003; southeast Sulawesi, Indonesia, Horton *et al.*, 2005b) for agglutinated assemblages but there is little research into zonation of intertidal or shallow subtidal calcareous assemblages (e.g. Hardbattle, 2004; Hayward *et al.*, 2004b). I use two different techniques to test for vertical zonation, unconstrained cluster analysis and detrended correspondence analysis, both of which group like samples together which may relate to elevation. If both techniques show foraminifera assemblages are related to elevation, I can have confidence in the correlation.

Unconstrained cluster analysis

Cluster analysis is a technique commonly used to group microfossil samples on statistical grounds (see Section 3.3.1) (Grimm, 1993). The CONISS program produces a dendrogram which shows cluster groups and boundaries between groups (Figure 4.6). Conducting cluster analysis on all available modern foraminiferal data from Cocoa Creek, Alligator Creek and Big Mango allows objective subdivision of this large

foraminiferal data set for summary description and preliminary statistical evidence for vertical zonation of foraminifera. The most commonly used cluster algorithm is Euclidian distance, which does not transform species data in any way. This technique is generally reliable (Birks, 1995) and is a suitable approach here for descriptive purposes only. Cluster analysis differentiates the following cluster groups (Figures 4.6 and 4.7):

Group 1 – agglutinated group with approximately 10 different species per sample. Dominant species are *Miliammina fusca*, *Trochammina inflata*, *Ammotium directum* and *Haplophragmoides* sp. Elevation range from 0.21 to 1.15 m with an average elevation of 0.79 m AHD (0.94 m vertical range). This group differs most from the rest of the data set as it is separated first by the dendrogram (Figure 4.6).

Group 2 – mixed agglutinated and calcareous group with diverse fauna (~25 species per sample). Dominant species are *Ammonia aoteana*, *Pararotalia venusta*, *Quinqueloculina incisa* and *Parrellina hispidula*. Elevation range from 0.05 to -2.64 m with an average elevation of -0.75 m AHD (2.69 m vertical range). One outlier at -2.64 m AHD (Figure 4.7) gives this group a large vertical range. Without the outlier, vertical range of this group is 1.36 m and average elevation is -0.68 m AHD.

Group 3 – calcareous group with diverse fauna (~25 species per sample). Dominant species are *Pararotalia venusta*, *Ammonia aoteana*, *Parrellina hispidula* and *Elphidium advenum*. Elevation range from -0.20 to -1.86 m with an average elevation of -1.09 m AHD (1.66 m vertical range).

Group 4 – calcareous group with very diverse fauna (~36 species per sample). Dominant species are *Pararotalia venusta*, *Parrellina hispidula*, *Planispirinella exigua* and *Triloculina oblonga*. Elevation range from -2.55 to -7.16 m with an average elevation of -4.62 m AHD (4.61 m vertical range).

There are similar faunal assemblages to group 1 in other tropical locations. Horton *et al.* (2003) identify two faunal zones dominated by agglutinated foraminifera at the landward edge of a separate transect at Cocoa Creek, Cleveland Bay (foraminiferal information from that transect is not included here because recent advances in taxonomic identification mean to have consistent taxonomy I would need to recount those samples). In Indonesia, Horton *et al.* (2005b) also identify an agglutinated upper mangrove assemblage with *Trochammina inflata* and *Miliammina fusca* on islands off

SE Sulawesi. Debenay *et al.* (2000) and Hayward and Hollis (1994) identify agglutinated foraminifera (*Jadammina macrescens* and *Trochammina inflata*) in upper marshes in New Caledonia and Cairns, NE Queensland and in upper intertidal environments in New Zealand. A mid to upper marsh (around MHWST) agglutinated assemblage with *Miliammina fusca* and *Trochammina inflata* is also found in temperate locations such as the UK and North America (e.g. Jennings and Nelson, 1992; de Rijk and Troelstra, 1997; Gehrels, 2000; Edwards *et al.*, 2004b; Horton and Edwards, 2006).

Group 2 has a mixed agglutinated and calcareous assemblages dominated by *Ammonia aoteana*, accounting for 15 – 54 % of the total count at each sample station in this zone. Other studies from tropical and sub-tropical locations show an *Ammonia* dominated assemblage in the mid intertidal zone e.g., Haslett (2001) in the upper part of the tidal flat at the Barron River estuary, Cairns, NE Queensland, Hayward *et al.* and Hayward and Hollis (1994; 1999b) in tidal flats and mangrove forests in New Zealand (with *Elphidium excavatum*, *Miliammina fusca* and *Haplophragmoides wilbertii*) and Horton *et al.* (2005b) in Indonesia. It is also found in a lower estuarine environment in Brazil (Barbosa and Suguio, 1999; Barbosa *et al.*, 2005). In the UK low marsh environments (close to MHWNT) have a mixed agglutinated/calcareous zone dominated by calcareous species *Elphidium williamsoni*, *Haynesina germanica* and *Cibicides lobatulus* and declining agglutinated species *Trochammina inflata* and *Miliammina fusca* (Horton and Edwards, 2006).

Groups 3 and 4 have diverse calcareous assemblages, group 3 dominated by *Pararotalia venusta* and *Ammonia aoteana* and group 4 dominated by *Pararotalia venusta*, *Parrellina hispidula*, *Triloculina oblonga* and *Planispirerella exigua*. Haslett (2001) find a diverse foraminiferal assemblage, dominated by *Ammonia beccarii* (called *Ammonia aoteana* in this thesis) but with many other shallow marine benthic and planktonic species in the lower intertidal zone of the Barron River estuary and Horton *et al.* (2003) observe a similar calcareous dominated assemblage at Cocoa Creek on intertidal mudflats. In New Zealand estuaries at the interface of brackish and marine conditions is a marginal marine association containing *Ammonia beccarii*, *Haynesina depressula* and *Elphidium advenum* (Hayward and Hollis, 1994). Diverse calcareous assemblages are also found on lower intertidal mudflats in temperate areas (de Rijk and Troelstra, 1997; Edwards *et al.*, 2004b; Horton and Edwards, 2006).

This thesis is one of the first in tropical Australia to extend the sampling of intertidal mudflats to below the limit of LAT, into the shallow subtidal area. It shows a diverse calcareous zone extends beneath the intertidal zone to at least 5.3 m below LAT.

Visually analysing the foraminiferal data from Cocoa and Alligator Creeks and Big Mango (Section 4.2.3 and Figures 4.4 and 4.5) shows changes in foraminiferal abundance appear to correspond with elevation. Cluster analysis gives 4 cluster groups (Figures 4.6 and 4.7) which are vertically zoned. This data shows that foraminifera correspond reasonably well with changes in elevation.

Detrended Canonical Correspondence Analysis

Detrended Canonical Correspondence Analysis (DCCA) is a direct gradient analysis technique to calculate gradient length of foraminiferal and environmental data which helps determine whether a linear or unimodal response model (Figure 4.8) is the most appropriate for analysing the training set. Data sets with gradient length greater than 3 SD units are considered unimodal, while lengths between 2-3 SD units are considered to be in a 'grey area' between linear and unimodal distributions (ter Braak and Prentice, 1988; Birks, 1995). DCCA of the full data set (Figure 4.4) gives a gradient of 3.55 standard deviation (SD) units, suggesting that unimodal methods are appropriate. I use DCCA to test the nature of reduced data sets in section 4.4.4.

Detrended Correspondence Analysis

Detrended Correspondence Analysis, based on an underlying unimodal model of species distributions is a gradient analysis technique representing samples in ordination/environmental space. Samples which are plotted closely together are similar whilst ones far apart are dissimilar. If samples are ordered by elevation along the dominant DCA axis this reinforces the hypothesis that foraminifera from Cocoa Creek, Alligator Creek and Big Mango are vertically zoned by elevation. Labelling samples by their elevation order allows interpretation of the DCA biplot in terms of vertical zonation (Figure 4.9 a).

All foraminiferal data give a maximum sample score along DCA Axis one of 5.3 (Figure 4.9 a). This means the data set is diverse, given that samples which differ by 4 SD units are expected to have no taxa in common (Birks, 1995). The second DCA axis has a sample score of 1.98 standard deviation units. Thus axis 1 is more important than axis two and contains most of the variability in the combined foraminiferal data set. Samples are ordered along axis 1 with sample 1 (1.16 m AHD) to the extreme

right and sample 76 (-7.16 m AHD) to the extreme left of the biplot, with most diversity in the data set occurring between samples 14 (-0.06 m) and 1 (1.16 m) which are dominated by agglutinated species (Figure 4.9 a). Samples dominated by calcareous taxa are relatively similar and closely grouped on the biplot (Figure 4.9 a). Sample order by elevation is further demonstrated by Figure 4.9 b, which shows samples are distributed generally in order of elevation on DCA axis one.

4.2.5 Relating foraminiferal zones to environmental variables

Partial Canonical Correspondence Analysis is a unimodal technique performing a direct gradient analysis (or constrained ordination) of biological response data in relation to two or more environmental predictor variables. Predictor variables in this thesis are elevation, pH, salinity, organic content (measured by Loss on Ignition), sand %, silt % and clay % (Figures 4.1, 4.2 and 4.3). This technique assesses the importance of each environmental variable in explaining variance in foraminiferal samples in the modern data set.

The seven environmental variables account for 61 % of the explained variance in the foraminiferal data (Figure 4.10). Results show variance is explained by elevation (12.5 %), salinity (7 %), loss on ignition (2 %), pH (2 %) and particle size distribution (0.5 %) (Figure 4.10). Associated Monte Carlo permutation tests indicate that all variables except % sand, silt and clay are statistically significant.

A large proportion of explained variance (37 %) is due to intercorrelations between environmental variables (Figure 4.10). Some variables are strongly correlated with each other and all variables except silt have relatively strong correlation to elevation (Table 4.1).

Table 4.1: Pearsons correlation coefficient table showing correlations between environmental variables analysed.

LOI	0.66					
pH	-0.65	-0.83				
Salinity	0.53	0.70	-0.44			
% sand	-0.66	-0.51	0.59	-0.26		
% silt	0.05	-0.25	0.25	-0.13	-0.49	
% clay	0.68	0.76	-0.85	0.39	-0.70	-0.28
	Elevation	LOI	pH	Salinity	% sand	% silt

Despite large intercorrelation between variables, results of PCCA show elevation is the single most significant explanatory variable, therefore it is possible to use modern foraminiferal assemblages in a transfer function to predict past elevation.

4.2.6 Summary

On the basis of tests on data presented above, I propose that modern death assemblages from Cocoa Creek, Alligator Creek and Big Mango show are related to elevation, and that elevation is an important environmental variable governing their distribution.

4.2.7 Training set considerations

Deciding on the size of the modern training set of foraminiferal and environmental variable information and which data to include is the next step in developing a tide-level transfer function. Figure 4.11 outlines the range of data sets and decisions which result in the best possible training set to reconstruct tide level in fossil cores.

Count size

Samples from Cocoa and Alligator Creeks generally have counts of 200, apart from where agglutinated taxa dominate (Figure 4.4). At Big Mango there are no foraminifera in samples from mid-upper intertidal elevations (-0.55 to 1.0 m AHD) and low intertidal samples have low foraminifera counts compared to samples from similar elevations at Cocoa Creek and Alligator Creek (green bars on Figure 4.4). As counting errors are high with count sizes under 100 (a count size of 50 has a counting error of 22 %, a count size of 100 has a counting error of 15 % (see Section 3.2.6 and Figure 3.2)), samples from all locations with low count sizes (<100) are excluded from the training set. This reduces the number of useful modern samples from 76 to 69.

Local or regional training set?

After excluding low counts I can use a local training set (all modern foraminiferal data from Cocoa Creek and Alligator Creek, a total of 64 samples) or a regional training set also including data from Big Mango (a total of 69 samples). Often combining local data into a single regional data set reduces the correlation between elevation and microfossil species, introducing spatial variability in microfossil assemblages not captured using individual sites (Gehrels *et al.*, 2001). This variability may be due to regional differences in relationships between foraminifera and environmental variables, or because individual transects rarely reflect true variability at a site. Any increase in variability in a large data set lowers precision in reconstructions, but a larger data set

increases the possibility of good analogues for fossil samples. As there are only 5 samples from Big Mango with counts over 100 it is not possible to investigate differences in local (Cleveland Bay) and regional (North Queensland) foraminifera and environmental variables. I include the 5 samples from Big Mango on the basis that their elevations are between -1.31 and -1.86 m AHD where sampling is sparse at Cocoa and Alligator Creeks.

4.3 SOURCES OF ERROR USING FORAMINIFERA AS PROXY INDICATORS

Limited understanding of the effects of biological, physical and geochemical ‘overprinting’ processes (e.g., infaunal activity and dissolution/disaggregation of certain species) on species abundance and assemblage composition restricts the resolution and reliability of foraminiferal proxy data (Schafer, 2000). I collected several cores from mangrove and mudflat environments to investigate two potentially limiting factors of foraminiferal proxy data: infaunal foraminiferal activity and potential dissolution/disaggregation of certain species. The cores are from the same elevation range as modern foraminiferal samples from Cleveland Bay. Unfortunately, only 2 cores remained intact through transport to the UK (Table 4.2). These are used to investigate potential infaunal populations and issues of foraminiferal preservation in shallow fossil sediments at Cocoa Creek (core 1 is missing a sample at 5 cm because the core slumped during transport).

Table 4.2 Details of cores taken from Cocoa Creek to investigate foraminiferal taphonomy.

Core Location/Number/Length	Environment	Elevation (m AHD)
Cocoa Creek Core 1 / 40 cm	Seaward edge of fringing Avicennia marina zone 30 cm below MTL	-0.26 m
Cocoa Creek Core 2 / 25 cm	Halophila seagrass bed 3 cm above LAT	-1.83m

4.3.1 Infaunal populations

Developing a tide-level transfer function using 1 cm deep modern samples relies on the premise that modern foraminifera do not live below the sediment surface. My modern training set is constructed from surficial (0-1 cm deep) samples. If foraminifera live below 1 cm depth in the sediment and constitute a significant proportion of total foraminifera at depth, their presence down core will affect sea-level reconstructions (Culver and Horton, 2005). When live foraminifera (which have not undergone

taphonomic change and are not part of the fossil record) travel down the sediment column and assimilate with fossil assemblages, these assemblages are altered and no longer reflect the environment before they were buried.

Very few foraminifera live infaunally in core 1, which contains only 8 specimens found live in 13 samples with counts of 200 (Figure 4.12 a). Therefore only 1 % of assemblages live infaunally in this core, up to 20 cm deep. Core 2 from close to LAT has a larger infaunal population; 14 live specimens at 5 and 10 cm deep, 9 specimens at 15 cm deep, 4 specimens at 20 cm deep and 1 specimen at 25 cm deep in counts of 200 (Figure 4.12 b). Of these 42 specimens, 30 (71 %) are the calcareous species *Dendritina striata*, which is found live at all depths sampled, whilst other infaunal species (11 specimens) are only found to 10 cm deep. Live infaunal *Dendritina striata* are more common in core 2 than dead specimens in every sample in this core except 25 cm deep (Figure 4.12 b). Therefore, the presence of *Dendritina striata* in a modern foraminiferal training set and fossil cores will influence palaeo-surface elevation reconstructions. I decide on the basis of these short cores to exclude *Dendritina striata* from the modern training set, where its maximum abundance is 4.8 %, and recalculate percentages of other species in the training set.

4.3.2 Selective preservation down core

In some tropical and subtropical locations scientists observe rapid disappearance of agglutinated foraminifera beneath the surface 1 cm slice of mangrove sediment (Puerto-Rica, Culver, 1990; South Georgia, USA, Goldstein and Watkins, 1999; French Guiana, Debenay *et al.*, 2002; Debenay *et al.*, 2004). Although agglutinated foraminifera disappear down core in these locations, there is currently no process proven in laboratory tests to cause this disappearance. However, Goldstein and Watkins (1999) argue preservation of agglutinated tests in sub-tropical South Georgia is more selective than in temperate areas. Taxa with finely agglutinated, flexible tests such as *Miliammina fusca* and *Ammotium* sp., may disappear quickly down core due to bacterial degradation of organic cements causing fragmentation and eventually disappearance of these taxa. It is important to note, however, that Tobin *et al.* (2005) argue that marsh foraminiferal assemblages in Georgia studied by Goldstein and Watkins (1999) may be unique to Georgia and selective disappearance of agglutinated foraminifera does not represent the picture elsewhere in the southeastern USA.

In North Queensland agglutinated foraminifera are not found in sub-surface assemblages, but they are present in the top 1 cm slice of sediments above -0.2 m

AHD at Cocoa and Alligator Creeks (Figure 4.4). A 35 cm long core taken from Cocoa Creek at 0 m AHD contains no agglutinated foraminifera from 10-35 cm deep. Unfortunately, the top 10 cm slumped during transit so I have no samples from this horizon, but other surface samples from Cocoa Creek at similar elevations indicate agglutinated foraminifera live on the surface at 0 m AHD. Unfortunately, because this and other short cores retrieved from mangrove environments above -0.2 m AHD in Cleveland Bay slumped in transit I cannot investigate this issue further.

Dissolution of calcareous foraminifera in the low pH salt marsh environment, common in temperate locations (Parker and Athearn, 1959; de Rijk and Troelstra, 1997; Edwards and Horton, 2000), may also occur in tropical mangroves and mudflats. Two short cores (Table 4.2) collected from environments dominated by calcareous foraminifera allow me to investigate this process using the Modern Analogue Technique (MAT).

MAT compares numerically, using an appropriate dissimilarity measure, the fossil assemblage with all assemblages in the training set. Having found the training set sample(s) to which it is most similar, the past environment is inferred to be the same as for the training set sample(s). This technique reconstructs the environmental variable for fossil samples, but also assesses the similarity between modern and fossil samples. The technique uses a Squared Chord Distance dissimilarity method which compares a fossil sample and the weighted mean of the 2, 5 or 10 most similar modern samples, and produces a dissimilarity coefficient for each fossil sample (Birks, 1995). Weights are inverse of the dissimilarity values so the modern samples with the lowest dissimilarity have the greatest weight (Birks, 1995).

Using MAT and the modern training set allows assessment of whether calcareous species are altered after death in the top 40 cm of sediment in cores 1 and 2. Comparing the dissimilarity coefficient between samples at different depths indicates whether assemblages change down core. If environmental change (e.g., relative sea-level change) down core causes changes to foraminiferal assemblages, the assemblages should still have close modern analogues within the training set. However, if foraminiferal assemblages below the surface are altered by post-mortem dissolution the minimum dissimilarity coefficient will be larger down core.

In core 1 some species found in every sample in the top 5 cm are absent from the rest of the core (*Bolivina cacozele*, *Cibicides lobatulus*, *Quinqueloculina*

crassicarinata, *Vertebralina striata* and *Wiesnerella auriculata*) (Figure 4.12 a). However, MAT dissimilarity coefficients (indicating similarity between surface and fossil samples) do not change markedly with increasing depth (Table 4.3), inferring that samples up to 40 cm deep are similar to surface samples.

In core 2 most calcareous species are present at all levels, and all species at the surface are present at 5 cm deep. However, the agglutinated species *Paratrochammina stoeni* is absent below 15 cm deep (Figure 4.12 b). It is present in low numbers in the modern training set to -5.4 m AHD (Figure 4.4), implying that its disappearance from core 3 in the top 15 cm is due to a post-mortem process not a change in environment down core. MAT dissimilarity coefficients again show little change between surface and fossil samples (Table 4.3), inferring that samples up to 25 cm deep are similar to surface samples.

Table 4.3: Modern Analogue Technique dissimilarity coefficients for samples in short cores 1 and 2, with largest minimum dissimilarity coefficient value calculated between all samples in the modern training set.

Core 1 depth (cm)	MAT minimum dissimilarity coefficient (Largest minDC = 49.27)	Core 2 depth (cm)	MAT minimum dissimilarity coefficient (Largest minDC = 49.27)
0	21.96	0	25.2619
5	24.42	5	31.9636
10	17.85	10	25.9609
15	20.91	15	26.6405
20	22.19	20	24.5101
25	24.90	25	32.2484
30	23.87		
35	23.23		
40	20.84		

4.3.3 Summary

1. Infaunal foraminifera are not common close to MTL (core 1), but live to at least 25 cm deep around LAT (core 2). The majority of specimens living infaunally at LAT are *Dendritina striata*, which constitutes a maximum of 4.5 % of the count sum (at 10 cm deep). *Dendritina striata* is therefore removed from the modern training set to correct for effects on sea-level reconstructions.
2. I cannot resolve the issue of whether agglutinated foraminifera are dissolved or disaggregated after death and burial in mangrove sediments from Cleveland Bay.
3. There is no evidence for dissolution of calcareous foraminifera around LAT (core 2). At MTL (core 1) visually foraminiferal assemblages change slightly between the surface and 10 cm deep. However MAT shows that surface and shallow fossil

assemblages are relatively similar implying dissolution does not significantly alter calcareous assemblages in the top 40 cm of sediment.

4.4 DEVELOPING A TIDAL LEVEL TRANSFER FUNCTION

A transfer function uses a uniformitarian approach to reconstruct the past value of an environmental variable (e.g., elevation) using the modern relationship between biological data (e.g., foraminifera) and the environmental variable. This approach assumes that taxa in the modern training set and their ecological affinities have not changed over the time span represented by the fossil assemblage (Imbrie and Kipp, 1971; Birks, 1995).

In an ideal situation, intertidal and shallow subtidal foraminiferal species will be solely controlled by their elevation in the tidal frame. In reality, other environmental factors are also important, including salinity, substrate and pH (section 4.2.4). These additional factors introduce scatter into the ideal one to one relationship between observed and predicted elevations and reduce precision of reconstructions.

There are many different statistical methods to quantify the relationship between modern foraminifera and elevation, and to apply this relationship to fossil foraminifera to reconstruct past elevation. Weighted averaging (WA) regression and calibration is a well-used unimodal technique which considers variance along a single environmental gradient. The technique estimates the optimum value of each taxon on the environmental gradient by averaging all the values of the environmental gradient where it occurs, weighted by the taxon's relative abundance. Taxon tolerance is the weighted standard deviation of the environmental variable value. Weighted averaging considers each environmental variable separately, disregarding any residual correlations in the biological data which still exist after fitting the first environmental variable. Some transfer functions based on British foraminifera use this technique (e.g. Horton *et al.*, 1999a; Edwards and Horton, 2000; Gehrels *et al.*, 2001).

Incorporating Partial Least Squares into Weighted Averaging (WA-PLS) goes some way to overcoming the problem of disregarding residual correlation in biological data by using them in an attempt to improve estimation of the optima for each taxa (Birks, 1995). The first component of WA-PLS is selected to maximise covariance between the vector of weighted averages and the environmental variable. Further components are chosen to maximise the same criteria but are unrelated to earlier components.

Weighted averaging takes averages of taxa's optimum on the environmental gradient twice, during regression and calibration. This results in shrinkage of the range of inferred values towards the mean environmental gradient value, and poor estimation of optima due to truncation of the response curves at the ends of the gradient (Birks, 1995). This is overcome to some extent by classical or inverse deshrinking within weighted averaging, but WA-PLS improves this further by including an equation which updates optima by inverse deshrinking.

An inherent problem of all unimodal methods using weighted averaging is the edge effect which results in non-linear distortions at the ends of the gradient. Although the weighted inverse deshrinking regression implicit in WA-PLS helps to reduce the edge effect, it has its own problems in 'pulling' the predicted values towards the mean of the calibration set, resulting in bias with some overestimation at low values and underestimation at high values. At present there is no way to reduce this edge effect of truncation of taxa responses, and hence under and over estimation of their optima, except by using shorter environmental gradients and linear-based methods (Birks, 1998).

Despite problems with the WA-PLS method, ter Braak *et al.* (1993 p. 556) conclude that 'until the time that such sophisticated methods mature and demonstrate their power for species-environment calibration, WA-PLS is recommended as a simple and robust alternative', and Birks (1995 p. 204) goes on to say 'for data that span an environmental gradient of 2 or more SD units, WA-PLS is an appropriate and robust reconstruction procedure'.

4.4.1 Models of foraminiferal assemblage composition

Cores from Cleveland Bay collected for my MSc project contained foraminifera in minerogenic horizons but did not contain foraminifera in organic horizons (Woodroffe, 2002). Preliminary cores from field locations in this thesis also do not contain any agglutinated foraminifera. I therefore concentrate modern sampling in this study on environments dominated by calcareous species. However, some modern samples collected contain both agglutinated and calcareous foraminifera. As it was not possible to investigate whether agglutinated foraminifera disappear in fossil sediments (section 4.3.2), two potential transfer function models remain plausible (Figure 4.11):

1. All data model – There has been no taphonomic loss of agglutinated foraminifera from the sediment cores because the environment of deposition of the fossil cores

is dominated by calcareous foraminifera with no agglutinated species present. Therefore include all samples which contain calcareous and agglutinated foraminifera in the modern training set. Delete samples which only contain agglutinated foraminifera, since they are redundant to the analysis.

2. Dissolution model - Agglutinated foraminifera are not present in fossil cores because they are removed due to a post-mortem taphonomic process. Therefore exclude all agglutinated foraminifera from the modern training set and recalculate percentages of calcareous species in mixed samples (calcareous species must exceed a total of 175 specimens to remain).

4.4.2 Optima and tolerances

A way of assessing likely transfer function model performance is by looking at foraminiferal optima and tolerances estimated during transfer function development with weighted averaging using the C2 program (version 4.1 beta, Juggins, 2003). Small tolerances (indicative range) indicate that a species has a small range of environments where it lives. The transfer function performs best where species have small tolerances and there are a range of species optima along an elevation gradient. Figure 4.13 shows optima and tolerances of 71 foraminiferal species from Cocoa Creek, Alligator Creek and Big Mango. Foraminifera optima range from 1.01 m AHD (*Miliammina obliqua*) to -5.26 m AHD (*Stilostomella lepidula*) and show a disjoint distribution with relation to elevation. Most optima are equally spread along the elevation gradient, apart from two disjoints; 'Disjoint 1', a 0.67 m gap between -0.11 m and -0.78 m AHD and 'Disjoint 2', a 0.54 m gap between -4.62 and -5.16 m AHD (Figure 4.13). The more significant of the two is the gap at -0.11 m, where the two species concerned do not have overlapping tolerances (Figure 4.13).

Agglutinated species generally have small tolerances (between 0.09 and 1.66 m). In contrast all calcareous species (with the exception of 2 species - *Planorbulina mediterraneansis* and *Rupertianella rupertiana*) have tolerances greater than 1.27 m (Figure 4.13). Agglutinated foraminifera are often used as proxy sea-level indicators in temperate areas because of their small vertical zonation and small ecological tolerances, especially at the limit of tidal influence, and they live on saltmarshes where there is dateable organic material present (Scott and Medioli, 1978). Agglutinated species at Cocoa Creek, Alligator Creek and Big Mango also have small ecological tolerances (Figure 4.13), but their absence from sediment cores precludes their usefulness in any transfer function developed. Calcareous species have much larger

tolerances which will impact on the precision of sea-level reconstructions in Cleveland Bay where agglutinated foraminifera are absent.

4.4.3 Assessing model performance

The aim is to select a minimal adequate model which allows the most precise reconstruction of elevation from fossil data. A minimal adequate model follows the principle of parsimony in statistics stating that a model should be as simple as possible containing no redundant parameters or components (Birks, 1998). I assess model performance using a series of indicators: Root Mean Squared Error of Prediction (RMSEP), coefficient of determination and average and maximum bias.

RMSEP is a measure of the overall predictive abilities of the training set. To be used, a component should give a reduction in prediction error of 5% or more of the RMSEP of a higher component (ter Braak and Juggins, 1993; Birks, 1998). The model component chosen should also have low systematic error compared to other components, measured by average bias (assessed by the mean of the differences between observed and predicted values in cross-validation) and comparatively low maximum bias (the maximum mean bias of equal sampling intervals).

Bootstrapping gives sample specific errors of prediction by resampling to create pseudo-replicate data sets the same size as the modern training set. The procedure randomly samples the original training set, repeated many times, each time producing a calibration function (regression equation able to predict elevation for fossil foraminiferal samples). To be statistically significant there should be at least as many pseudo-replicate data sets as the number of sites (samples) in the modern training set. Comparing predicted elevations from each calibration function with the observed elevation of each modern sample gives bootstrapped RMSEP, which more closely reflects true error in reconstructions than simple cross validated RMSEP (Birks, 1995).

Models based on WA or WA-PLS with the lowest RMSEP and bias are invariably those based on all taxa, even though many of the taxa may have only 1-3 occurrences in the training set (Birks, 1994; Birks, 1998). Performance of the WA-PLS model does not improve if taxa with total abundance less than 2% are excluded. Birks (1998) argues that rare taxa contribute some ecological information or 'signal' to the inference model, rather than having no effect or negatively affecting performance by introducing statistical 'noise' or random variation into the model.

4.4.4 Linear or unimodal methods?

As there are two potential training sets of modern foraminifera and elevation information I estimate the length of the elevation gradient in each training set again using DCCA. The gradient of the all data modern training set is 3.35 SD units, and the dissolution modern training set is 2.41 SD units. Although 2.41 SD units is in the ‘grey’ area between linear and unimodal distributions, WA-PLS usually outperforms the linear technique Partial Least Squares (PLS) in this area because WA-PLS generally requires fewer components to create a minimal adequate model (Birks, 1998). In this case WA-PLS outperforms PLS at the third component, the WA-PLS model has lower RMSEP and maximum bias and a higher bootstrapped r^2 than the PLS model (Table 4.4).

Table 4.4: WA PLS and PLS model performance measures for the dissolution model (excluding agglutinated foraminifera and recalculating percentage abundances of calcareous species). Components highlighted in yellow give the minimal adequate models.

Model/Method	Component Number	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias
Weighted Averaging Partial Least Squares Calcareous foraminifera only (62 samples) Gradient length 2.41 SD units	1	0.90	0.65	1.31	0.01
	2	0.95	0.47	0.64	0.01
	3	0.96	0.44	0.56	-0.01
	4	0.96	0.43	0.49	-0.002
	5	0.96	0.45	0.46	0.01

Model	Component number	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias
Partial Least Squares Calcareous foraminifera only (62 samples) Gradient length 2.41 SD units	1	0.82	0.91	1.40	0.02
	2	0.88	0.76	0.85	-0.01
	3	0.94	0.54	0.58	0.01
	4	0.94	0.52	0.56	0.01
	5	0.95	0.51	0.54	0.01

4.4.5 Statistical assumptions of transfer function technique

All unimodal transfer function models efficiently estimate foraminiferal species’ optima if a range of parameters are met:

1. Abundances are unimodally distributed;
2. Sites are equally spaced over the whole range of the taxon's occurrences (Birks, 1995);
3. Taxa are not tightly clumped along the elevation gradient;
4. There is fairly even turnover of species along the elevation gradient.

Samples in my training set are not evenly distributed along the elevation gradient. Elevation differences between samples vary from 1 to 49 cm (Figure 4.5). Combining foraminiferal data for samples within 10 cm of each other (recalculating raw counts to percents) gives a more evenly distributed training set, with samples between 10 and 49 cm apart. However, this reduces the training set size from 69 to 46 samples. Combining samples to even up distribution also loses species composition changes recorded in samples closer together than 10 cm. As raw counts are combined, new percentage abundances reflect total change over whole 10 cm intervals. Table 4.5 shows the performance measures for Model 1 with evenly distributed samples.

Combining samples significantly reduces the total training set sample number. Despite this, performance measures (Table 4.5) show relatively low RMSEP, maximum bias and average bias and high r^2 values for this model. This model works relatively well, but does not perform as well as the calcareous only training set model (dissolution model WA PLS performance Table 4.4). Efficient estimation of optima and tolerances depends on a number of factors including a large modern training set and even distribution of samples where possible. Because an evenly spaced training set performs worse than the original training set I decide not to use this model.

Table 4.5: WA PLS model performance measures for the all data model with samples evenly spaced on the elevation gradient. Component highlighted in yellow gives the minimal adequate models.

Model/Method	Component Number	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias
Weighted Averaging Partial Least Squares	1	0.76	1.19	1.94	-0.02
	2	0.94	0.60	0.86	-0.01
Evenly spaced modern training set (46 samples)	3	0.95	0.57	0.92	-0.03
Gradient length SD units	4	0.96	0.56	0.76	-0.05
	5	0.96	0.54	0.76	-0.06

4.4.6 Final model performance

After excluding samples with low counts and addressing local v regional influences (Section 4.2.6), potential infaunal activity (Section 4.3.1), unimodal or linear techniques (Section 4.4.2) and spacing of samples on the elevation gradient (Section 4.4.3), two species models remain (Section 4.4.1). Table 4.6 shows the performance measures using WA-PLS for each of these species models and Figure 4.14 shows observed and predicted elevations and residuals using each training set and WA-PLS component 3. Both models have similar performance, with comparable r^2 values at the third component, low average bias and a relatively linear relationship between observed and predicted elevation. However, the dissolution model performs marginally better in terms of RMSEP and maximum bias. These small differences in performance indicate using either training set will result in similar relative sea-level reconstructions.

Because models with and without agglutinated foraminifera perform similarly the only way I can decide which to use when calibrating fossil data is to calibrate each fossil core data in turn with each modern model and compare palaeo-surface elevation predictions. In Chapter 5 I apply these models to fossil foraminiferal data from Cocoa Creek and Alligator Creek.

Table 4.6: WA-PLS model performance measures for 2 models (all data model and dissolution model) of foraminiferal assemblage composition. Components highlighted in yellow give the minimal adequate models.

Model	Component number	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias
All data model All agglutinated and calcareous foraminifera (67 samples) Gradient length 3.35 SD units	1	0.76	1.04	2.29	-0.02
	2	0.95	0.52	1.06	0.01
	3	0.96	0.46	0.90	0.02
	4	0.96	0.46	0.75	0.02
	5	0.96	0.45	0.69	0.02

Model	Component Number	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias
Dissolution model Calcareous	1	0.90	0.65	1.31	0.01
	2	0.95	0.47	0.64	0.01

foraminifera only (62 samples)	3	0.96	0.44	0.56	-0.01
Gradient length 2.41 SD units	4	0.96	0.43	0.49	-0.002
	5	0.96	0.45	0.46	0.01

4.5 CHAPTER SUMMARY

This chapter analyses modern foraminiferal and environmental data taken from Cocoa Creek, Alligator Creek and Big Mango. It describes foraminiferal assemblages along the surface elevation gradient and develops quantitative regression models. The major results of this chapter and how they relate to research hypotheses are as follows:

Research question 1 b ‘Microfossils are abundant and readily preserved’. To address this question data presented in this chapter shows foraminifera are abundant in surface and shallow fossil sediments at Cocoa Creek, Alligator Creek and at some elevations at Big Mango. Calcareous foraminifera are readily preserved, showing little difference in assemblages between surface and shallow fossil assemblages. However, I cannot investigate potential post-mortem disappearance of agglutinated specimens. Agglutinated foraminifera are absent from fossil cores collected in Cleveland Bay.

Research question 1 c ‘Microfossil assemblages are controlled by elevation’ Data presented in this chapter show that elevation is not the only controlling variable on foraminiferal assemblages from Cocoa Creek, Alligator Creek and Big Mango, but it is the most important variable measured. Large sampling errors associated with low counts indicate I must exclude from the modern training set samples with less than 100 specimens and investigation of short cores indicates I should exclude the calcareous species *Dendritina striata* because it is able to live infaunally to a depth of at least 25 cm.

Because agglutinated foraminifera are not present in preliminary fossil cores collected from Cleveland Bay, two potential assemblage composition models remain plausible (Figure 4.11):

1. All data model – There has been no taphonomic loss of agglutinated foraminifera from the sediment cores because the environment of deposition of the fossil cores is dominated by calcareous foraminifera with no agglutinated species present. Therefore include all samples which contain calcareous and agglutinated

foraminifera in the modern training set. Delete samples which only contain agglutinated foraminifera, since they are redundant to the analysis.

2. Dissolution model - Agglutinated foraminifera are not present in fossil cores because they are removed due to a post-mortem taphonomic process. Therefore exclude all agglutinated foraminifera from the modern training set and recalculate percentages of calcareous species in mixed samples (calcareous species must exceed a total of 175 specimens to remain).

After modification (Figure 4.11) modern training sets with or without agglutinated foraminifera give transfer function model prediction error (RMSEP) between 44-46 cm. In chapter 5 I apply these transfer function models to fossil data from Cocoa Creek and Alligator Creek allowing quantification of relative sea-level change through time.

CHAPTER FIVE – FOSSIL RESULTS

5.1 INTRODUCTION

In chapter 4, I developed two transfer functions (all data and dissolution models) to reconstruct tide-level changes using modern intertidal and subtidal foraminifera. In this chapter, I use these transfer functions to interpret fossil foraminiferal assemblages from Cocoa and Alligator Creeks, presented in chapter 2. This provides information on changing water depth through fossil sediments which is put in a vertical and temporal framework by developing sea-level index points using AMS radiocarbon-dated material. Comparing sequences of change from different sites and using different reconstruction methods allows identification of regional versus site-specific signals, used to construct a record of mid-late Holocene relative sea-level change.

This chapter has the following sections:

1. Description of fossil transects, material collected and AMS radiocarbon dates from Cocoa Creek.
2. Description of fossil transects, material collected and AMS radiocarbon dates from Alligator Creek.
3. Development of final transfer function by applying modern assemblage models to fossil cores:
 - 2 models of foraminifera assemblage composition developed in Chapter 4;
 - 2 further models excluding further modern samples from low elevations.
4. Relative sea-level reconstructions for Cocoa and Alligator Creeks using transfer function results.

5.2 FOSSIL CORES FROM COCOA AND ALLIGATOR CREEKS

Cocoa Creek

A series of cores taken along two transects across salt pans close to Cocoa Creek (Figures 2.3, 5.1 and 5.2) reveal a consistent stratigraphic sequence between 1 and 4 m deep stopping on an impenetrable compacted gravel and silt rich sand substrate. The generalised sequence starts as this basal, compacted gravel and silt-rich sand between 2-4 m below the surface (the uppermost level of this basal unit sampled is at -0.48 m AHD), overlain by 0.5-2.5 m of organic clay-rich silt with well preserved wood and other organic material. This is overlain by a thick unit of shell and sand-rich silt or

silt-rich sand (0.7-1.8 m thick), with a second smaller organic clay-rich silt layer (0.1-1 m thick) on top in some locations. The uppermost unit, between 0.5 and 1 metre in depth is compacted oxidised silt-rich clay, representing a modern salt pan environment, based on observations and grain size data (Figures 5.1 and 5.2).

Transect one starts close to the base of Cape Cleveland, and cores 1 and 2 are dominated by sand and gravel assumed to be alluvial material from the granitic headland (Figure 5.1). The remaining cores are from upper-intertidal salt pans, interspersed with 10 chenier ridges on the coastal plain. Chenier ridges form when a severe storm (e.g., cyclone) erodes prograding mangroves and constructs a sand ridge on the exposed tidal flat platform (Figure 5.3). Chenier ridges are sand and shell-rich with material sourced from low tidal flat sands. Chenier plains such as at Cocoa Creek have characteristically thin frontal mangrove fringes backed by wide, mature upper intertidal salt pans (Belperio, 1983).

Transect two (Figures 2.3 and 5.2), which traverses wide salt pans following the course of Cocoa Creek starts close to the watershed between Cleveland and Bowling Green Bays. Cape Cleveland was periodically an island during the mid Holocene high stand and displacement of the Burdekin/Haughton river mouth in Bowling Green Bay brought significant sediment to the region, building out a system of ~100 beach ridges which prograded over 6.5 km and, it is argued linked Cape Cleveland to the mainland as a tombolo by ~3000 BP (its influence on the sedimentary record in cores is discussed in Chapter 6) (Belperio, 1983; Carter *et al.*, 1993). Core 1 on transect 2, situated close to the toe of the tombolo, is dominated by beach ridge sand and does not contain marine sediments. Other cores on this transect record a similar sequence of sediments to transect 1 (Figure 5.2).

I chose two cores from transect 1 (cores 7 and 14) for detailed litho- bio- and chrono-stratigraphical analysis. Core 7 is relatively close to Cape Cleveland, where the basement surface is more steeply angled than on the coastal plain. This core may preserve evidence of the maximum extent of the mid Holocene high stand. Core 14 is from landward of the most seaward chenier ridge at Cocoa Creek (Figure 5.1). This is the deepest core retrieved at Cocoa Creek and potentially provides the longest record of sea-level change back to the mid Holocene.

Alligator Creek

Alligator Creek, at the centre of the Cleveland Bay coastline (Figure 2.4), shows a similar sequence of sediments between 1 and 4 m deep as found at Cocoa Creek in the eastern part of the bay (Figures 5.4 and 5.5). The generalised sequence starts as a similar basal, compacted gravel and silt-rich sand to that found at Cocoa Creek between 2-4 m below the surface, overlain by a relatively thick unit of shell and sand rich silt or silt-rich sand (0.6-2.1 m thick). There is no evidence for the lower organic unit found in most cores at Cocoa Creek. On top of the silt and sand-rich unit is an organic clay-rich silt layer (0.5-1.2 m thick), sandwiched with a small (~ 0.1 m thick) silty clay horizon around 1 m below the surface. The uppermost unit, between 0.27 m and 0.65 m in depth is a compacted oxidised silt-rich clay similar to that found at Cocoa Creek, representing the modern salt pan environment.

I chose cores 1 and 10 from transect 2 for detailed litho- bio- and chrono-stratigraphical analysis. Core 1 is from the salt pan directly behind modern fringing mangroves and is the deepest core from Cleveland Bay, with the potential to provide the earliest relative sea-level reconstructions in this study. Core 10 is a shallow core from the highest area of salt pan at Alligator Creek, close to the Muntalunga Range where the basement surface is more steeply angled than on the coastal plain. This core complements core 7 from Cocoa Creek which preserves evidence of the maximum extent of the mid Holocene high stand.

5.2.1 Cocoa Creek Core 7

Cocoa Creek Core 7 is 295 cm long and was retrieved using a hand-operated piston corer from a modern salt pan environment. Figure 5.6 and Table 5.1 summarise the lithology, AMS dates and bio-stratigraphy of Cocoa Creek core 7, showing all foraminiferal species found within the core. Samples for particle size and loss on ignition analysis taken at 10 cm intervals throughout the core reveal a relatively homogenous clay-rich silt with varying degrees of sand up to 36 % (Figure 5.6). Loss on ignition (LOI) values are low throughout the core, peaking at 9 % at 252 cm depth, but are generally between 5-6 % (Figure 5.6). Organic material between 40-100 cm and 244-283 cm is made up of large isolated pieces of well preserved mangrove wood in clay-rich silt.

Table 5.1: Summary stratigraphy of Cocoa Creek core 7.

Depth (cm)	Core 7 Stratigraphy	Troels-Smith description
0-40	Mottled mid grey/brown stiff silt-rich clay	As 3 Ag 1
40-100	Mottled grey/brown slightly organic clay-rich silt with occasional rootlets	Ag 3 As 1 Th +
100-150	Grey/brown sand, clay and shell-rich silt	Ag 2 As 1 part. test. (moll) 1 Ga + test. (moll) +
150-244	Dark grey clay and sand-rich silt	Ag 3 As 1 Ga +
244-283	Dark brown organic clay-rich silt	Ag 2 As 1 Sh 1 Th +
283-295	Hard light grey gravel and silt-rich sand	Ga 2 As 2 Ag + Gmin + Gmaj +

Sampling for foraminiferal analysis was initially at 10 cm intervals. I reduced the sampling interval to between 2-8 cm in sections where the initial counts showed significant changes in fauna. Where there is little change in foraminiferal fauna, larger sampling intervals suffice. No foraminifera are preserved below 240 cm or above 107 cm in slightly organic horizons. This limits environments available for transfer function reconstruction to clay and sand-rich silts between 107-240 cm. Stratigraphically constrained cluster analysis produces foraminiferal clusters which help describe general trends in foraminiferal assemblages through the central section of core and zone boundaries may indicate inflection points in water depth changes. These zones are summarised below and on Figure 5.6.

Assemblage zone 1: 240-170 cm

This zone is dominated by *Ammonia aoteana*, *Parrellina hispidula*, *Pararotalia venusta* and *Wiesnerella auriculata* at the base but *A. aoteana* and *P. hispidula* decline up through the zone and are replaced to some extent by *P. venusta*, *Quinqueloculina incisa* and *Quinqueloculina laevigata*. A few agglutinated specimens are preserved through the top half of the zone. Change in dominance from *A. aoteana* to *P. venusta* suggests increasing water depth up core. Lithology is clay-rich silt with increasing sand up core.

Assemblage zone 2: 170-107 cm

In this zone *P. hispidula* and *Elphidium discoidale multiloculum* increase upwards through the zone at the expense of *P. venusta*, *Q. incisa*, *Q. laevigata* and *W. auriculata*. *Ammonia aoteana* remains dominant throughout. A few agglutinated specimens are preserved through this zone. Rising *A. aoteana*, *E. multiloculum* and *P.*

hispidula at the expense of *P. venusta* suggest decreasing water depth up core. Lithology is clay-rich silt with decreasing sand up core.

Qualitative analysis of foraminifera assemblages shows no sharp boundary between these assemblage zones, and cluster analysis only indicates a general trend of first increasing then decreasing water depth through the core. The zone boundary may mark the inflection point between increasing and decreasing water depth, investigated further using transfer function results (see Section 5.6).

Chrono-stratigraphy of Cocoa Creek Core 7

The NERC radiocarbon laboratory at East Kilbride AMS dated 7 foraminiferal samples from Cocoa Creek Core 7 (Table 5.2 a). In addition, I dated pairs of foraminiferal and unarticulated bivalve samples from 107, 131, 155 and 185 cm to investigate potential reworking of foraminiferal material (see section 5.3 for discussion) (Table 5.2 b).

Tables 5.2 a and b: Summary of AMS radiocarbon data from Cocoa Creek Core 7

Table 5.2a : AMS dates on foraminifera

Sample	Laboratory publication code	Depth below surface (cm)	Elevation (m AHD)	¹⁴ C Enrichment (% Modern +/- 1 σ)	Carbon content (% by wt.)	δ ¹³ C _{VPOB} ‰ +/- 0.1	Conventional radiocarbon age (years BP +/- 1 σ)	Calibrated age range (BP +/- 2 σ)
CC/7/107	SUERC-4753	107	0.66	64.54 +/- 0.21	11.2	-1.7	3518 +/- 26	3680-3840
CC/7/131	SUERC-4754	131	0.43	62.95 +/- 0.20	10.4	-1.0	3718 +/- 26	3920-4150
CC/7/155	SUERC-4755	155	0.19	61.60 +/- 0.18	10.8	-1.1	3892 +/- 23	4150-4420
CC/7/185	SUERC-4757	185	-0.11	55.37 +/- 0.18	10.1	0.8	4748 +/- 27	5320-5500
CC/7/215	SUERC-5575	215	-0.41	50.88 +/- 0.17	9.4	0.4	5428 +/- 28	6120-6290
CC/7/225	SUERC-6253	225	-0.51	52.50 +/- 0.18	10.0	-1.5	5161 +/- 27	5760-5990
CC/7/235	SUERC-5576	235	-0.61	50.19 +/- 0.19	8.9	0.4	5537 +/- 31	6280-6410

Table 5.2b: AMS dates on calcareous shells

Sample	Laboratory publication code	Depth below surface (cm)	Elevation (m AHD)	¹⁴ C Enrichment (% Modern +/- 1 σ)	Carbon content (% by wt.)	δ ¹³ C _{VPOB} ‰ +/- 0.1	Conventional radiocarbon age (years BP +/- 1 σ)	Calibrated age range (BP +/- 2 σ)
CC/7/107 Shell	SUERC-4758	107	0.66	66.65 +/- 0.21	11.8	0.2	3260 +/- 26	3380-3550
CC/7/131 Shell	SUERC-4761	131	0.43	65.98 +/- 0.21	11.7	0.4	3341 +/- 26	3470-3640
CC/7/155 Shell	SUERC-4762	155	0.19	61.89 +/- 0.20	11.4	0.5	3854 +/- 26	4090-4360

Sample	Laboratory publication code	Depth below surface (cm)	Elevation (m AHD)	¹⁴ C Enrichment (% Modern +/- 1 σ)	Carbon content (% by wt.)	δ ¹³ C _V PDB‰ +/- 0.1	Conventional radiocarbon age (years BP +/- 1 σ)	Calibrated age range (BP +/- 2 σ)
CC/7/185 Shell	SUERC-4764	185	-0.11	53.27 +/- 0.16	11.1	0.6	5060 +/- 25	5710-5900

5.2.2 Cocoa Creek Core 14

Cocoa Creek Core 14 is 394 cm long, also retrieved using a hand-operated piston corer from a modern salt pan environment, with lithology summarised in Table 5.3 and Figure 5.7 along with AMS dates and bio-stratigraphy. Samples for particle size and loss on ignition analysis taken at 10 cm intervals show similar lithostratigraphy to core 7, with clay-rich silt at the base, grading into silt-rich sand at 305 cm, into sand-rich silt between 190 -240 cm and back into silt-rich sand at 190 cm. This grades into shell-rich organic clay-silt at 109 cm with silt-rich clay to the surface (Figure 5.7). Loss on ignition values are also low throughout this core, peaking at 16 % at 325 cm depth, but are generally between 2-7 % (Figure 5.7). Organic material between 75-90 and 305-385 cm is made up of large isolated pieces of well preserved mangrove wood in clay-rich silt, similar to those in core 7.

Table 5.3: Summary stratigraphy of Cocoa Creek Core 14.

Depth (cm)	Core 14 Stratigraphy	Troels-Smith description
0-75	Mottled grey/brown slightly organic stiff silt-rich clay	As 3 Ag 1 TI +
75-90	Light grey, organic, wet clay-rich silt	Ag 3 As 1 TI ++
90-109	Light grey slightly organic shell and clay-rich silt	Ag 3 As 1 TI + part. test (moll) +
109-190	Dark grey silt, clay and shell-rich fine sand	Ga 2 Ag 1 As 1 part. test (moll) + test. (moll) +
190-240	Dark grey clay, sand and shell-rich silt	Ag 2 As 1 Ga 1 part. test (moll) +
240-305	Dark grey silt, clay and shell-rich fine sand	Ga 2 Ag 1 As 1 part. test (moll) +
305-385	Dark gery/brown organic clay-rich silt	Ag 2 As 1 Sh 1 TI ++
385-394	Hard light grey silt and clay-rich sand	Ga 2 As 2 Ag + Gmin + Gmaj +

As in core 7, no foraminifera are preserved in slightly organic units below 300 cm or above 75 cm. This limits environments available for transfer function reconstruction to sandy silts and silty sands between 75-300 cm deep. Stratigraphically constrained assemblage zones are summarised below and on Figure 5.7:

Assemblage zone 1: 300-228 cm

This zone is dominated by *A. aoteana*, fluctuating *P. venusta* and increasing *W. auriculata* up core, with progressive reduction in *Planispirinella exigua* up core. All other species are fairly constant through this zone. The lithology is silt-rich sand, with increasing silt up core. The foraminifera and lithology indicate this is a subtidal environment.

Assemblage zone 2: 228-203 cm

This zone is dominated by *A. aoteana*, *W. auriculata* and *P. hispidula*. *P. hispidula* rises dramatically at the expense of *P. venusta*. Lithology is sand and clay-rich silt with decreasing sand up core. Replacement of *P. venusta* with *P. hispidula* and decreasing sand content suggest decreasing water depth.

Assemblage zone 3: 203-160 cm

Pararotalia venusta dominates this cluster at the expense of *P. hispidula* and *A. aoteana*. *W. auriculata* nearly completely disappears, dropping from ~27 % of total count in cluster 2 to ~3.5 % in cluster 3. Lithology is the same silt-rich sand found in zone 1. Increase in *P. exigua* together with *P. venusta* and increasing sand content suggest an increase in water depth.

Assemblage zone 4: 160-75 cm

In this zone *A. aoteana*, *P. venusta* and *P. hispidula* dominate, with rising *E. multiloculum* and declining *P. exigua*. Lithology is clay-rich silt with declining sand. These species and declining sand content suggest decreasing water depth.

Cluster analysis shows the general trend of a subtidal environment between 300-228 cm followed by decreased water depth between 228-203 cm and a second period of increasing water depth between 203-160 and decreasing water depth from 160-75 cm depth. There is a sharp boundary between assemblage zones 2 and 3, which correlates with a peak in *Wiesnerella auriculata* and dip in *Pararotalia venusta*. This zone boundary may also be present in transfer function reconstructions, investigated in Section 5.6.

Chrono-stratigraphy of Cocoa Creek Core 14

The NERC radiocarbon laboratory at East Kilbride AMS dated 7 foraminiferal samples from Cocoa Creek Core 14 (Table 5.4).

Table 5.4: Summary of AMS radiocarbon data from Cocoa Creek Core 14

Sample	Laboratory publication code	Depth below surface (cm)	Elevation (m AHD)	¹⁴ C Enrichment (% Modern +/- 1 σ)	Carbon content (% by wt.)	δ ¹³ C _{V-PDB} ‰ +/- 0.1	Conventional radiocarbon age (years BP +/- 1 σ)	Calibrated age range (BP +/- 2 σ)
CC/14/75	SUERC-5577	75	0.78	71.16 +/- 0.26	10.7	0.4	2734 +/- 29	2760-2920
CC/14/145	SUERC-5578	145	0.08	69.43 +/- 0.25	10.4	0.5	2931 +/- 29	2960-3210
CC/14/173	SUERC-5579	173	-0.20	63.21 +/- 0.23	10.1	-1.3	3685 +/- 29	3910-4150
CC/14/205	SUERC-6255	205	-0.52	48.55 +/- 0.17	9.1	-1.5	5804 +/- 28	6500-6720
CC/14/235	SUERC-5580	235	-0.82	52.61 +/- 0.20	10.5	-1.7	5159 +/- 30	5760-5990
CC/14/265	SUERC-5583	265	-1.12	56.81 +/- 0.19	10.0	-2.1	4542 +/- 27	5050-5320
CC/14/295	SUERC-5584	295	-1.42	58.71 +/- 0.20	10.4	-0.1	4278 +/- 27	4826-4870

5.2.3 Alligator Creek Core 1

Figure 5.8 and Table 5.5 summarise the lithology, biostratigraphy and AMS chronology of Alligator Creek core 1. Stratigraphically constrained cluster analysis gives 3 foraminiferal assemblage zones, described below:

Assemblage zone 1: 365-330 cm

This is a diverse assemblage dominated by *W. auriculata*, *Q. incisa* and *Triloculina oblonga* with low percentages of *P. venusta* and *P. hispidula*, high percentage of sand and low LOI. The foraminifera and particle size data suggest that this is a subtidal environment.

Assemblage zone 2: 330-212 cm

This is also a diverse assemblage with significant decrease in *W. auriculata* and increase in *P. hispidula*, *P. venusta* and *Quinqueloculina suborbicularis*. Lithology is still dominated by sand with low LOI values. The foraminifera and particle size data suggest this is also a subtidal environment.

Assemblage zone 3: 212-115 cm

This is a less diverse assemblage dominated by *A. aoteana*, *P. venusta* and increasing values of *P. hispidula* and *E. multiloculum*, with virtually no *W. auriculata*. Lithology is still dominated by sand, but silt and clay increase above this assemblage zone towards the surface, and LOI values increase marginally up core. The increase in *P. hispidula* and *E. multiloculum* along with increased LOI values suggest decreasing water depth.

The dramatic decline in *W. auriculata* marks the boundary between assemblage zones 1 and 2 but the zone boundary between zones 2 and 3 is not marked by sharp increase or decrease in species abundances (Figure 5.8). Cluster analysis only indicates a general trend of decreasing water depth through the core.

Table 5.5: Summary stratigraphy of Alligator Creek core 1.

Depth (cm)	Core 7 Stratigraphy	Troels-Smith description
0-31	Light grey mottled slightly organic stiff clay-rich silt	Ag 3 As 1 TI + Sh +
31-75	Mid/dark grey organic, wet clay-rich silt	Ag 3 As 1 TI ++ DI ++
75-81	Dark grey mottled stiff clay-rich silt	Ag 3 As 1
81-104	Mid/dark grey organic, wet clay-rich silt	Ag 3 As 1 TI ++ DI ++
104-137	Mid grey very shelly, sand-rich silt	Ag 2 Ga 1 part. test (moll) 1 test.(moll) +
137-370	Mid grey clay and silt-rich sand	Ga 2 As 1 Ag 1 part. test (moll) +
370-373	Hard light grey gravel and silt-rich sand	Ga 2 As + Ag + Gmin + Gmaj +

Chronostratigraphy of Alligator Creek Core 1

The NERC radiocarbon laboratory AMS dated 9 foraminiferal samples from this core. At 150 and 220 cm there are two mixed foraminiferal samples from the same horizons (Table 5.6 and Figure 5.8).

Table 5.6: Summary of AMS radiocarbon data on foraminifera from Alligator Creek Core 1

Sample	Laboratory publication code	Depth below surface (cm)	Elevation (m AHD)	¹⁴ C Enrichment (% Modern +/- 1 σ)	Carbon content (% by wt.)	δ ¹³ C _{VPOB} ‰ +/- 0.1	Conventional radiocarbon age (years BP +/- 1 σ)	Calibrated age range (BP +/- 2 σ)
AC/1/150	SUERC 7216	150	-0.58	83.55 +/- 0.2	9.6	0.0	1444 +/- 20	1290-1390
AC/1/150a	SUERC 7217	150	-0.58	83.16 +/- 0.19	7.4	-0.6	1481 +/- 18	1310-1410
AC/1/185	SUERC 7218	185	-0.94	83.87 +/- 0.25	8.0	-1.0	1413 +/- 24	1285-1350
AC/1/220	SUERC 7219	220	-1.36	79.13 +/- 0.24	10.2	-2.0	1881 +/- 24	1720-1880
AC/1/220a	SUERC 7222	220	-1.36	78.79 +/- 0.18	10.8	-2.7	1914 +/- 18	1820-1920
AC/1/262	SUERC 7223	262	-1.78	59.32 +/- 0.18	11.1	0.3	4195 +/- 25	4620-4840
AC/1/288	SUERC 7224	288	-2.01	70.09 +/- 0.17	10.2	-0.6	2854 +/- 20	2870-3080

Sample	Laboratory publication code	Depth below surface (cm)	Elevation (m AHD)	¹⁴ C Enrichment (% Modern +/- 1 σ)	Carbon content (% by wt.)	δ ¹³ C _{V-PDB} ‰ +/- 0.1	Conventional radiocarbon age (years BP +/- 1 σ)	Calibrated age range (BP +/- 2 σ)
AC/1/324	SUERC 7225	324	-2.38	71.07 +/- 0.17	11.0	-0.7	2743 +/- 20	2775-2870
AC/1/366	SUERC 7226	366	-2.79	47.42 +/- 0.14	10.2	-0.9	5994 +/- 23	6730-6890

5.2.4 Alligator Creek Core 10

Figure 5.9 and Table 5.5 summarise the lithology, biostratigraphy and AMS chronology of Alligator Creek core 10. Stratigraphically constrained cluster analysis gives 3 foraminiferal assemblage zones. Assemblage zone 3 is made up of two samples with very low foraminiferal counts (~ 20 specimens), not used in quantitative analysis.

Assemblage zone 1: 205-175 cm

This is a diverse assemblage dominated by *A. aoteana*, *Cribrononion oceanicus* and *Haynesina depressula*. Lithology is clay and silt-rich sand and LOI is low (~4 %). Indicative of a deep water (subtidal) environment.

Assemblage zone 2: 175-125 cm

This is also a diverse assemblage dominated by *A. aoteana*, *P. venusta* and *P. hispidula*, with declining abundance of *H. depressula* and *C. oceanicus* and increasing *P. hispidula* and *E. multiloculum* up core. Lithology is silt-rich sand changing up core to sand and clay-rich silt. LOI is low (~4 %) throughout the zone. Increasing *P. hispidula* and *E. multiloculum* and declining sand content suggest decreasing water depth up core.

Assemblage zone 3: 125-92 cm

This zone, made up of two samples with low counts has few foraminiferal species, is dominated by the agglutinated species *Haplophragmoides* sp. and *Trochammina inflata*. Lithology is sand and clay-rich silt with slightly increasing LOI values up core. The foraminiferal species and increasing LOI values suggest an upper-intertidal environment.

Cluster analysis of this core infers a relatively stable deep water (subtidal) environment between 205-175 cm followed by decreasing water depth between 175-125 cm depth grading into an upper intertidal environment between 125-92 cm. The zone boundary between clusters 1 and 2 may mark the inflection point between stable and decreasing water depth, investigated using a transfer function in Section 5.6.

Table 5.7: Summary stratigraphy of Alligator Creek core 10.

Depth (cm)	Core 7 Stratigraphy	Troels-Smith description
0-50	Light grey/brown mottled stiff clay-rich silt	Ag 3 As 1
50-94	Light grey organic, wet clay-rich silt	Ag 3 As 1 TI ++ DI ++
94-100	Dark grey/brown mottled stiff clay-rich silt	Ag 3 As 1
100-125	Light grey organic, wet clay-rich silt	Ag 3 As 1 TI ++ DI ++
125-211	Mid grey clay and silt-rich sand	Ga 2 As 1 Ag 1 part. test (moll) +
211-214	Hard light grey gravel and silt-rich sand	Ga 2 As + Ag + Gmin + Gmaj +

Chronostratigraphy of Alligator Creek Core 10

The NERC radiocarbon laboratory AMS dated 4 foraminiferal samples from this core (Table 5.8 and Figure 5.9).

Table 5.8: Summary of AMS radiocarbon data from Alligator Creek Core 10

Sample	Laboratory publication code	Depth below surface (cm)	Elevation (m AHD)	¹⁴ C Enrichment (% Modern +/- 1 σ)	Carbon content (% by wt.)	δ ¹³ C _{VPOB} ‰ +/- 0.1	Conventional radiocarbon age (years BP +/- 1 σ)	Calibrated age range (BP +/- 2 σ)
AC/10/124	SUERC-7734	124	-0.19	71.94 +/- 0.22	8.9	-1.0	2645 +/- 24	2744-2782
AC/10/149	SUERC-7228	149	-0.44	68.66 +/- 0.21	8.7	-1.0	3020 +/- 25	3080-3330
AC/10/174	SUERC-7229	174	-0.69	58.39 +/- 0.18	8.7	-1.0	4323 +/- 25	4830-4970
AC/10/201	SUERC-7232	201	-0.94	67.37 +/- 0.25	9.9	-1.0	3172 +/- 29	3350-3470

5.3 RADIOCARBON DATING OF FORAMINIFERA AND SHELLS

Radiocarbon dating calcareous foraminifera is occasionally used in sea-level studies where organic material is not present to create sea-level index points (e.g. Edgecombe *et al.*, 1999; Horton *et al.*, 2000). Radiocarbon dated foraminifera from all my cores reveal unforeseen problems. In Cocoa Creek Core 7 the oldest date is at the base of the foraminifera sequence (235 cm depth – 6280-6410 cal yrs BP). However there is an age reversal at 215 cm, with the age at 225 cm younger than the age above at 215 cm (Table 5.2 a and Figure 5.6). Above 215 cm all dates in this core are in sequence. In Cocoa Creek Core 14 a similar problem occurs, with three dates in the bottom half of the core out of sequence (Table 5.4 and Figure 5.7). It is not clear in this core whether

the basal date is correct. Similarly in Alligator Creek Core 1 three dates in the bottom half of the core are out of sequence (Table 5.6 and Figure 5.8) and in Alligator Creek Core 10 one date in the bottom half of the core is out of sequence (Table 5.8 and Figure 5.9). Dates which are out of sequence must be due to foraminifera reworking at that horizon. There are two possible reworking scenarios causing the pattern of dates in my cores:

1. Large scale reworking of all material in the bottom half of each core, which means all dates during the period encompassed by reversals must be discarded (13 dates must be discarded).
2. Episodic reworking with older material from elsewhere brought to the core location and deposited during an isolated event or events. Only dates which are out of sequence must be discarded (8 dates). This model allows me to include in-sequence dates at the base of each core which may be correct.

Because I am unable to distinguish between these two reworking models I must create sea-level index points using each and compare reconstructions. However the timing of the reversals, all in the bottom half of each core, may indicate reworking during sea-level transgression. This is discussed in Section 6.6.1.

During initial consultation the NERC Radiocarbon Steering Committee questioned the approach of dating calcareous foraminifera due to potential reworking caused by bioturbation. They stipulated that I must test the approach to identify whether foraminifera are prone to biological reworking by dating paired samples of foraminifera and shells from the same horizons. Unfortunately, this was only possible using available core material already collected and choosing horizons with shells (only unarticulated bivalves are present in my cores) for paired dates. I chose 4 horizons from Cocoa Creek Core 7 for paired dates (Figure 5.10 a and Tables 5.2 a and b). The results are inconclusive. At 185 cm the shells are older than the foraminifera, which may be due to reworking of shells from older material or infaunal foraminifera, although the broken nature of the bivalve sampled suggests reworking. At 155 cm they are a very similar age, which infers that neither are reworked or both live infaunally, which may be because I dated 10 shells at this horizon. At 131 and 107 cm shells are younger than foraminifera, which could be due to bivalve shells dated in these horizons living infaunally beneath the sediment surface, or reworking of foraminifera. For the bivalve shells at 131 cm to be younger than foraminifera they must have burrowed more than 24 cm into the sediment column because the foraminiferal date at 107 cm is slightly older than the shell date at 131 cm (Figure 5.10 a). This is possible as Grindrod (1988) suggests bioturbation in tropical intertidal environments can occur to at

least 30 cm deep. The results do not allow me to differentiate between the following scenarios:

1. Bivalve shells younger than foraminifera:
 - Due to infaunal activity of bivalves (impossible to test as life habitat of dated bivalves is unknown).
 - Due to reworking of older foraminifera.
2. Bivalve shells older than foraminifera:
 - Due to reworking of older bivalve shells which are larger than foraminifera and may be moved by currents etc. (the only shell available for dating at 185 cm is broken which may be a sign of reworking – see Figure 5.10 b).
 - Due to infaunal activity of foraminifera (investigated in Section 4.3.1, which shows infaunal activity of modern foraminifera in tropical intertidal environments is low).

I believe that an 8-15 mg sample consisting of ~800-1000 mixed species foraminifera (including juveniles and adult specimens) is more likely to be *in situ* than one or two large unarticulated bivalve shells in the same horizon. However none of the hypotheses above can be ruled out. This experiment is flawed because I was unable to collect material to test the hypothesis directly, and I do not know the life habitat of the bivalve shells dated.

Another related issue is potentially reworked and mixed foraminiferal material giving different age results in the same horizon. To address this issue I date two mixed foraminiferal samples from the same horizons in Alligator Creek Core 1 at 150 and 220 cm. At both dated horizons 2 σ calibrated age ranges substantially overlap (Figure 5.10 c) giving confidence that in the upper section of this core (clay and silt-rich sand) individual foraminiferal dates reflect the true age of the sediment. However it is important to note that although conventional ages differ by only 37 years (1444 and 1481 at 150 cm) and 33 years (1881 and 1914 at 220 cm), when calibrated the total age range of both samples is 120 years (150 cm) compared to 100 years for a single sample and 160 years (220 cm) compared to 120 years for a single sample (Table 5.6). The calibrated age range of a single dated sample may therefore under-estimate the true 2 σ range of the foraminifera in that horizon by 20-40 years (Figure 5.10 c), but this is minor compared to the calibrated age range of most sea-level index points from North Queensland (Tables 1 and 2 in Volume 2).

5.4 APPLICATION OF TRANSFER FUNCTION MODELS TO FOSSIL CORES

This section aims to quantify relative sea-level changes recorded by the biostratigraphy of cores from Cocoa and Alligator Creeks using two transfer function models described in chapter 4. The regression model Weighted Averaging Partial Least Squares performs best in predicting elevation, using either:

1. All data model – Modern training set consisting of calcareous and agglutinated foraminifera (67 samples).
2. Dissolution model – Modern training set consisting only of calcareous foraminifera, with agglutinated foraminifera excluded and percentages of calcareous species in mixed assemblages recalculated (calcareous species must exceed 75 % of the sample sum to remain) (62 samples).

5.4.1 Transfer function with all data and dissolution models

In order to decide which transfer function model ultimately provides the most reliable estimates of palaeo-surface elevation in fossil cores, I compare reconstructions for each core using each model in turn (Tables 5.9 to 5.12). As well as analysing differences in reconstructed palaeo-surface elevation between model predictions, it is important to assess the reliability of each reconstruction using MAT (see section 4.3.2). Modern Analogue Technique assesses similarity on the closest match between modern and fossil samples and the weighted mean of the 2, 5 or 10 most similar modern samples using the Squared Chord Distance dissimilarity coefficient.

Some authors take a dissimilarity coefficient below the extreme 10th percentile of dissimilarities calculated between all modern samples as the upper threshold of a 'good' analogue between modern and fossil samples (Birks *et al.*, 1990; Birks, 1995; Edwards *et al.*, 2004b; Horton and Edwards, 2005). However, other authors use lower percentiles, including 2, 3 and 5 % (Bartlein and Whitlock, 1993; Webb *et al.*, 1993), and Horton (1997) uses the 20th percentile as a cut off. Using a 10th percentile value as a threshold value for a good analogue infers that 10 % of the modern data set could be analogues for each other, and that the other 90 % of modern samples represent different environments. However, if all modern samples are from very different environments I would not consider any sample to represent an analogue for another and even the 1st percentile would be too high a threshold value for a good analogue (Juggins, 2006; personal communication). MAT provides a general guide to the relative similarities between fossil and modern data, but defining a single percentile value as the threshold between 'good' and 'no' analogues for all modern and fossil data

sets is incorrect, because values vary depending on which distance metric is used, characteristics of the modern and fossil data sets and the ecological scale of analysis (Jackson and Williams, 2004). Because of these problems with defining a threshold value I use the largest Minimum Dissimilarity Coefficient calculated between all modern samples as an general indication of whether a fossil sample is similar to samples in the modern training set, and has a ‘good’ analogue in the modern training set.

A transfer function model with relatively low RMSEP, maximum and average bias and a high r^2 value is only useful if reconstructions have modern analogues. I discard any reconstructions with a minimum dissimilarity coefficient higher than the largest value for the modern data set, so in deciding which model to use there is a trade off between the model being precise and widely applicable (fossil samples having modern analogues) (Horton and Edwards, 2006).

Tables 5.9 to 5.12: Reconstructed palaeo-surface elevations and MAT minimum dissimilarity coefficients for all data and dissolution models using each core in turn (cells highlighted in yellow are outside the highest minimum dissimilarity value calculated between all modern samples, used as a threshold value for modern analogues).

Table 5.9: Cocoa Creek Core 7

		All data model	Highest MinDC value = 49.27	Dissolution model	Highest MinDC value = 38.70
Depth in core (cm)	Sample elevation (m AHD)	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient
107.8	0.68	-0.83	73.23	-0.64	70.74
123.4	0.53	-1.69	60.27	-1.52	57.81
131.3	0.45	-1.09	49.77	-1.04	47.89
139.1	0.37	-1.61	44.41	-1.53	44.01
146.9	0.29	-1.30	41.90	-1.33	41.52
155	0.21	-2.12	39.43	-1.85	38.60
165	0.11	-2.33	30.91	-2.42	30.76
175	0.01	-3.30	72.73	-3.25	71.90
185	-0.09	-3.08	50.93	-3.06	50.74
195	-0.19	-3.03	64.23	-3.07	64.12
205	-0.29	-2.49	71.91	-2.35	71.24
215	-0.39	-2.89	65.58	-2.64	63.51
217.6	-0.42	-2.76	60.18	-2.49	60.06
225	-0.49	-2.38	60.69	-2.01	55.35

Table 5.10: Cocoa Creek Core 14. (cells highlighted in yellow are outside the highest minimum dissimilarity value calculated between all modern samples, used as a threshold value for modern analogues).

		All data model	Highest MinDC value = 49.27	Dissolution model	Highest MinDC value = 38.70
Depth in core (cm)	Sample elevation (m AHD)	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient
75	0.78	-1.14	41.93	-1.10	41.40
80	0.73	-1.42	38.56	-1.46	38.25
85	0.68	-1.75	36.49	-1.69	37.27
90	0.63	-1.62	30.02	-1.44	29.33
95	0.58	-1.72	36.69	-1.53	35.62
100	0.53	-1.51	27.31	-1.41	26.97
105	0.48	-1.71	31.52	-1.69	31.26
110	0.43	-1.89	30.09	-1.81	30.14
115	0.38	-1.42	21.40	-1.34	21.05
120	0.33	-2.30	29.94	-2.29	30.05
125	0.28	-1.82	28.84	-1.71	28.85
130	0.23	-2.02	36.44	-2.06	36.22
132	0.21	-2.30	27.09	-2.16	26.97
135	0.18	-3.57	49.48	-3.36	49.13
137	0.16	-3.11	29.49	-3.06	29.37
140	0.13	-2.92	36.62	-2.74	36.74
145	0.08	-1.76	41.41	-1.70	41.67
150	0.03	-2.56	39.69	-2.49	39.47
158.1	-0.051	-1.75	26.93	-1.54	26.82
166.1	-0.131	-2.70	26.00	-2.70	26.09
169.1	-0.161	-2.56	25.65	-2.60	25.45
174.2	-0.212	-3.58	44.09	-3.59	43.97
177.4	-0.244	-2.77	27.26	-2.68	26.27
182.3	-0.293	-2.61	36.89	-2.80	37.04
190.3	-0.373	-2.50	33.63	-2.38	33.44
200	-0.47	-2.57	28.78	-2.64	28.88
205	-0.52	-3.26	75.60	-2.67	70.67
210	-0.62	-2.95	69.35	-2.53	65.23
215	-0.67	-2.81	76.17	-2.25	70.93
220	-0.72	-3.11	68.31	-2.52	63.13
225	-0.77	-2.65	47.71	-2.39	49.42
230	-0.82	-3.03	62.12	-2.73	57.16
235	-0.87	-2.10	45.85	-1.81	44.75
240	-0.92	-2.93	53.90	-2.79	54.03
245	-0.97	-2.37	41.56	-2.30	41.50
250	-0.99	-4.11	66.16	-4.14	66.15
252	-1.02	-3.37	62.42	-3.32	62.27
255	-1.04	-2.80	55.13	-2.76	57.42
257	-1.07	-2.77	45.88	-2.59	46.64
260	-1.12	-2.91	60.64	-2.79	60.74
265	-1.17	-3.35	57.53	-3.32	57.64
270	-1.22	-3.62	55.24	-3.56	55.17
275	-1.27	-3.31	63.51	-3.22	62.46
280	-1.32	-3.89	68.18	-4.04	67.78

		All data model	Highest MinDC value = 49.27	Dissolution model	Highest MinDC value = 38.70
Depth in core (cm)	Sample elevation (m AHD)	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient
285	-1.34	-4.10	38.65	-4.10	38.56
290	-1.37	-2.57	44.10	-2.69	44.94
295	-1.42	-3.41	48.14	-3.40	47.98
300	-1.47	-3.08	51.16	-3.15	51.11

Table 5.11: Alligator Creek Core 1 (cells highlighted in yellow are outside the highest minimum dissimilarity value calculated between all modern samples, used as a threshold value for modern analogues).

		All data model	Highest MinDC value = 49.27	Dissolution model	Highest MinDC value = 38.70
Depth in core (cm)	Sample elevation (m AHD)	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient
115	-0.29	-0.82	64.55	-0.43	65.21
120	-0.34	-1.36	49.25	-0.96	48.67
125	-0.39	-1.47	33.82	-1.23	33.78
130	-0.44	-1.85	31.17	-1.64	31.13
135	-0.49	-0.95	21.80	-0.71	21.40
145	-0.59	-1.12	20.58	-0.92	20.32
156.8	-0.70	-1.12	19.31	-1.03	19.40
168.2	-0.82	-1.21	17.44	-1.10	17.59
179.5	-0.93	-1.45	23.82	-1.44	24.75
190.9	-1.05	-1.38	19.08	-1.31	19.81
201.1	-1.15	-1.66	21.43	-1.57	21.10
206.5	-1.20	-2.36	32.29	-2.19	32.22
212	-1.26	-3.00	32.94	-2.86	32.58
222.8	-1.36	-2.91	34.14	-2.73	33.78
233.7	-1.47	-3.05	43.31	-2.81	41.91
244.6	-1.58	-3.52	35.56	-3.46	35.74
255.3	-1.69	-4.74	57.11	-4.35	56.76
264.2	-1.78	-4.99	52.36	-4.58	52.42
269.5	-1.83	-4.69	41.35	-4.45	40.99
274.8	-1.88	-5.19	47.21	-4.90	44.49
281.9	-1.96	-4.72	27.52	-4.57	28.88
287.2	-2.01	-4.39	29.87	-4.10	30.71
299.6	-2.13	-4.45	25.91	-4.18	25.85
312	-2.26	-4.47	36.59	-4.37	36.90
319.1	-2.33	-3.77	49.14	-3.57	50.94
324.5	-2.38	-3.61	38.54	-3.40	38.64
330	-2.44	-4.00	73.54	-3.56	73.41
335	-2.49	-4.64	83.17	-3.95	83.26
340	-2.54	-4.34	77.59	-3.81	77.38
345	-2.59	-4.06	65.79	-3.81	65.71
350	-2.64	-4.18	46.88	-3.90	46.66
355	-2.69	-4.80	60.23	-4.41	60.01

		All data model	Highest MinDC value = 49.27	Dissolution model	Highest MinDC value = 38.70
Depth in core (cm)	Sample elevation (m AHD)	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient
360	-2.74	-4.29	76.24	-3.83	76.05
365	-2.79	-4.35	69.35	-3.88	69.44

Table 5.12: Alligator Creek Core 10 (cells highlighted in yellow are outside the highest minimum dissimilarity value calculated between all modern samples, used as a threshold value for modern analogues).

		All data model	Highest MinDC value = 49.27	Dissolution model	Highest MinDC value = 38.70
Depth in core (cm)	Sample elevation (m AHD)	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient	WA-PLS Component 3 Palaeo-surface elevation (m)	Minimum Dissimilarity Coefficient
125	-0.19	-1.99	46.02	-1.83	45.94
130	-0.24	-1.82	31.48	-1.60	30.41
135	-0.29	-2.17	34.33	-2.02	34.59
140	-0.34	-1.46	37.25	-1.20	37.23
145	-0.39	-2.08	40.29	-1.80	39.76
150	-0.44	-2.15	34.99	-1.98	33.89
155	-0.49	-2.35	36.56	-2.12	34.90
160	-0.54	-2.42	63.42	-2.14	62.71
165	-0.59	-2.27	46.88	-1.93	45.73
170	-0.64	-2.06	44.10	-1.72	42.09
175	-0.69	-1.22	49.14	-1.05	48.31
180	-0.74	-1.76	37.65	-1.63	36.86
185	-0.79	-1.71	49.83	-1.53	49.07
190	-0.84	-1.03	50.17	-0.85	47.97
195	-0.89	-1.36	46.27	-1.20	45.37
200	-0.94	-1.80	34.71	-1.62	33.90

Results show a marginal decrease in the number of samples with modern analogues (increase in number of yellow highlighted samples in Tables 5.9 to 5.12) using the dissolution model compared to the all data model. This indicates that removing agglutinated foraminifera does not markedly affect representation of fossil foraminiferal assemblages in the modern training set, and each model is still equally valid.

More important are differences in reconstructed palaeo-surface elevation between the two models. Maximum differences in reconstructions are shown on Figure 5.11 and summarised in Table 5.13. Differences in estimated elevation are nearly always within the transfer function error term of the all data model (Figure 5.11). Excluding fossil

samples without modern analogues (yellow shaded areas on Figure 5.11) significantly reduces the difference in elevation estimates between the two models (Figure 5.11 and Table 5.13). Despite the decrease in variation in model predictions when samples without modern analogues are excluded, there is no clear relationship between minimum dissimilarity coefficient and variation in model predictions for each core (Figure 5.12).

Table 5.13: Summary of maximum differences in reconstructed palaeo-surface elevations using all data and dissolution models and each fossil core, and differences in reconstructions if samples without modern analogues are removed.

Core Name	Maximum difference in height of palaeo-surface (cm) between all data and dissolution models	Maximum difference in height of palaeo-surface (cm) between all data and dissolution models if no analogue samples are excluded	Maximum error (+/- cm 1 σ) of reconstructions using all data model	Maximum error (+/- cm 1 σ) of reconstructions using dissolution model
Cocoa Creek Core 7	36 cm	27 cm	50 cm	53 cm
Cocoa Creek Core 14	59 cm	30 cm	51.5 cm	60 cm
Alligator Creek Core 1	68 cm	45 cm	46 cm	47 cm
Alligator Creek Core 10	34 cm	28 cm	55 cm	70 cm

The choice of model makes a difference in reconstructions of palaeo-surface elevation in some cores at some levels (Figure 5.11 and Table 5.13). However all reconstructions using the dissolution model (in sections of cores with good modern analogues) are within 1 σ bootstrapped sample specific error of sample reconstructions using the all data model (Figure 5.11). On this criteria it does not matter which model is used to give reconstructions, each gives a sufficiently similar result.

5.4.2 Model enhancements - excluding modern samples from the analysis

To try to increase the accuracy of the regression models this section investigates forming a training set from a reduced elevation range. Decreasing scatter and increasing the linear relationship between observed and predicted elevation (e.g.,Figure 4.12) increases the predictive power of a transfer function. Different regression models may perform better in certain parts of the elevation range. In transfer functions based on Alaskan diatoms, Hamilton and Shennan (2005) create different modern training sets and regression models to decrease non-linearity present in tidal flat samples depending on whether peat is present in stratigraphy. Modern

peat-forming environments only occur above a certain elevation, therefore modern training set samples below that elevation (mostly tidal flat samples where non-linearity occurs) can be excluded from the regression model when only peat-rich lithology is present in cores. This allows more precise elevation estimates from peat-rich fossil samples.

A similar trend occurs in my modern training set. Both all data and dissolution models show non-linearity in samples below -5.8 m AHD which have a poor relationship between modern and inferred values and high associated error. This is shown by observed plotted against predicted elevations using the training set and the residuals in this calculation (Figure 4.12). Non-linearity at the base of the elevation gradient causes regression to under-predict elevation at all elevations when using the whole modern training set. This affects RMSEP and sample specific reconstruction errors at all parts of the elevation gradient. However there is no independent feature of the intertidal and subtidal environment in Cleveland Bay (other than foraminiferal distribution) to allow me to exclude samples below a certain elevation from the regression. Hamilton and Shennan (2005) have the lithological constraint of peat-forming environments which only occur above a certain elevation, allowing removal of non-linear mud flat samples where only peat is present in cores. The only way I can assess whether non-linear samples at the base of the elevation gradient can be removed is by looking at reconstructed palaeo-surface elevation for each fossil sample. If reconstructions using the whole training set are not close to the base of the elevation gradient, it may be possible to remove non-linear samples below -5.8 m AHD (Table 5.14). Birks (1998) suggests the range of the modern training set should be 0.5-1 standard deviations either side of the fossil samples.

Table 5.14: Summary of lowest elevation of palaeo-surface reconstructions for each core using all data and dissolution models (only reconstructions with modern analogues are included).

Core Name	Lowest reconstructed palaeo-surface (m AHD) with modern analogues using all data model	Lowest reconstructed palaeo-surface (m AHD) with modern analogues using dissolution model
Cocoa Creek core 7	-2.33	-2.42
Cocoa Creek core 14	-3.41	-2.70
Alligator Creek Core 1	-5.19	-4.57
Alligator Creek Core 10	-2.27	-2.12

Results show all reconstructed palaeo-surface elevations are above -5.19 m AHD (however only one sample is predicted at this elevation, all others are above -4.72 m AHD) (Table 5.14). Therefore removing samples below -5.8 m AHD may not adversely affect reconstructions but will provide greater accuracy than using the whole training set.

Performance measures for reduced all data and reduced dissolution models with samples below -5.8 m AHD removed (the reduced all data model has 62 samples, the reduced dissolution model has 57 samples) show lower RMSEP, lower maximum bias and similar r^2 and average bias values compared to the all data and dissolution models developed in Chapter 4 (Tables 4.6 and 5.15). Graphs of observed against model predicted elevations show less non-linearity at the base of the elevation gradient after 5 samples below -5.8 m AHD are removed, and less bias in elevation estimation residuals (Figures 5.13 and 5.14). In addition there are smaller variations in elevation reconstructions using the reduced models than using the all data or dissolution models (Table 5.16).

Table 5.15: WA-PLS model performance measures for 4 models of foraminiferal assemblage composition: all data model and dissolution model with agglutinated foraminifera excluded, reduced all data and reduced dissolution models with samples below -5.8 m AHD excluded. Components highlighted in yellow give the minimal adequate models

	Component number	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias	Model	Component number	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias
All data model All agglutinated and calcareous foraminifera (67 samples) Gradient length 3.35 SD units	1	0.76	1.04	2.29	-0.02	Dissolution model Calcareous foraminifera only (62 samples) Gradient length 2.41 SD units	1	0.90	0.65	1.31	0.01
	2	0.95	0.52	1.06	0.01		2	0.95	0.47	0.64	0.01
	3	0.96	0.46	0.90	0.02		3	0.96	0.44	0.56	-0.01
	4	0.96	0.46	0.75	0.02		4	0.96	0.43	0.49	-0.002
	5	0.96	0.45	0.69	0.02		5	0.96	0.45	0.46	0.01
Model	Component number	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias	Model	Component number	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias
Reduced all data model All agglutinated and calcareous foraminifera with samples below -5.8 m AHD removed (62 samples) Gradient length 3.05 SD units	1	0.70	0.94	1.88	-0.02	Reduced dissolution model Calcareous foraminifera with samples below -5.8 m AHD removed (57 samples) Gradient length 2.15 SD units	1	0.87	0.61	1.16	0.00
	2	0.93	0.48	0.61	0.01		2	0.94	0.42	0.90	0.01
	3	0.95	0.41	0.51	0.01		3	0.94	0.41	0.84	-0.01
	4	0.95	0.43	0.44	0.02		4	0.94	0.42	0.79	0.00
	5	0.95	0.43	0.44	0.02		5	0.94	0.46	0.71	0.00

One sample remains a significant outlier with a large residual value (between 1.44 and 1.68 m) in the reduced models (circled in red on Figure 5.14). This sample is the lowest at Cocoa Creek (-4.72 m AHD, the lowest blue bar on Figure 4.2). Removing it from the training set reduces WA-PLS RMSEP at the third component in the reduced all data model from 0.41 to 0.37 m, and causes a maximum of 10 cm variation in reconstructed palaeo-surface elevations for the fossil cores compared to leaving the sample in the training set. Despite apparent increase in precision by removing this sample, it may reflect natural variability in foraminiferal assemblages within subtidal environments. Therefore excluding it may artificially dampen natural variability and give an over-optimistic estimate of the transfer function model's predictive power. With no objective criteria for removing it, this sample must remain in the model despite its negative effect on precision. The issue of removing outlying modern samples is discussed in Section 6.5.1.

Table 5.16: Summary of maximum differences in reconstructed palaeo-surface elevations using the all data and dissolution models and the reduced models with each fossil core.

Core Name	Maximum difference in palaeo-surface elevations (cm) between all data and dissolution models if no analogue samples are excluded	Maximum difference in palaeo-surface elevations (cm) between the reduced all data and dissolution models if no analogue samples are excluded
Cocoa Creek core 7	9 cm	4 cm
Cocoa Creek core 14	22 cm	11 cm
Alligator Creek Core 1	29 cm	18 cm
Alligator Creek Core 10	25 cm	14 cm

Performance measures (Table 5.15) suggest both reduced models will produce similar palaeo-surface reconstructions. After excluding samples without modern analogues and samples within reworked horizons (identified by AMS radiocarbon dating of calcareous foraminifera), remaining palaeo-surface elevations show good correlation between the dissolution model and both reduced models (Figures 5.15 a and b). The all data model generally gives the lowest elevation reconstructions, offset from reconstructions using the other 3 models (e.g.,between 80-110 cm in Cocoa Creek Core 14, 120-230 cm in Alligator Creek Core 1 and 125-160 cm in Alligator Creek Core 10) (Figures 5.15 a and b). This infers that reconstructions using the dissolution model or either reduced models are relatively robust, and that any of these models is acceptable to use for final relative sea-level reconstructions.

5.4.3 Summary

On the basis of model selection procedures above and because I am not able to prove that agglutinated foraminifera have disappeared from fossil cores, I will use the reduced all data model (all agglutinated and calcareous foraminifera with modern samples below -5.8 m AHD removed from the training set) to calibrate all foraminiferal assemblages in fossil cores and produce relative sea-level reconstructions from new material.

5.5 RECONSTRUCTION RELIABILITY AND TOTAL RECONSTRUCTION ERROR

5.5.1 Estimating reconstruction reliability

Performance measures (e.g., RMSEP, maximum bias and r^2) provide information on the internal consistency of a transfer function. However they provide no information on reliability of reconstructions. All transfer function procedures produce a result in the form of computer output, but how reliable are the results? Ideally reconstructions should be compared to historical environmental records (e.g., tide gauge data), but given their short time series I must evaluate reconstructions indirectly using numerical criteria (Birks, 1998).

Modern analogue technique provides analogue statistics for each individual fossil sample in comparison with the modern training set. Reconstructed elevation is more likely to be reliable if the fossil sample has close modern analogues in the training set. This technique also gives a range of potential cut offs for assessing a good match and reliable reconstructions (5th, 10th and 20th percentile – see section 5.4.1). Many authors use MAT to identify fossil samples with poor modern analogues and test the reliability of transfer function results (e.g. (Whitlock *et al.*, 1993; Edwards *et al.*, 2004b; Hamilton and Shennan, 2005; Horton and Edwards, 2005). I therefore use MAT to assess reliability of transfer function results in this study (see sections 3.3.4, 4.3.2 and 5.4.1 for more details).

5.5.2 Estimating total reconstruction error

A series of bootstrapped error terms are produced for each transfer function reconstruction, combined as bootstrapped sample specific errors with 2 parts:

1. Bootstrapped sample error, unique to each fossil sample (RMSE_s1 (e_i)).
Calculated as error in estimating optima and tolerances of taxa, changing due to foraminiferal composition of each fossil sample.

2. Bootstrapped transfer function model error, which is the same for all reconstructions using one model (RMSE_s2 (e_2)). Calculated as the standard deviation of all sample residuals when estimating elevation using bootstrapping.

C2 calculates total bootstrapped sample specific error using the same formula as other error terms (Section 3.2.12 (Equation 1)):

$$= \sqrt{e_1^2 + e_2^2} \quad \text{(Equation 1)}$$

Although transfer function reconstructions give an error term, the true error associated with reconstructions must include modern and fossil sampling errors not accounted for in transfer function development (section 3.2.12). Total mean square error is calculated using the same formula above (Equation 1), but includes the following parts:

- a_1 = Total transfer function error (including RMSE_s1 and RMSE_s2 – Equation 1)
- a_2 = Modern measurement error (section 3.2.12)
- a_3 = Core sampling error (section 3.2.12)

Results for Cocoa Creek Core 14 show total reconstruction error is dominated by transfer function model error (Table 5.17). Sampling errors are insignificant when included in error calculations, adding less than 1 cm to total RMSEP for selected samples in Cocoa Creek Core 14 (Table 5.17) (The results are very similar for other cores and are therefore not shown here).

Table 5.17: Total error calculations for selected samples in Cocoa Creek Core 14.

Sample depth (cm)	Transfer function model error +/- 2 σ (m)	Transfer function sample error +/- 2 σ (m)	Total Transfer function error +/- 2 σ (m)	Modern sampling error +/- (m)	Fossil sampling error +/- (m)	Total error +/- (m)
100	0.751	0.176	0.772	0.038	0.042	0.774
150	0.751	0.177	0.772	0.040	0.042	0.774
200	0.751	0.156	0.767	0.040	0.042	0.770
250	0.751	0.341	0.825	0.040	0.042	0.827
300	0.751	0.272	0.799	0.040	0.042	0.801

5.6 RELATIVE SEA-LEVEL RECONSTRUCTIONS FROM CLEVELAND BAY

This section aims to analyse and quantify relative sea-level changes recorded by the biostratigraphy of cores 7 and 14 from Cocoa Creek using the modern data set described in Chapter 4. A regression model using the 'reduced all data' modern data model described in Section 5.4.2 produces the most accurate estimate of predicted elevations for all cores and is used to calibrate both cores from Cocoa Creek.

5.6.1 *Cocoa Creek Core 7*

Descriptions of palaeo-surface and relative sea-level changes along with the radiocarbon age model applied to this core and minimum dissimilarity coefficients for each sample using MAT are shown in Figure 5.16, Table 5.18 and Table 1 in Volume 2. The fossil sequence in Cocoa Creek core 7 begins with a thin gravel rich sand overlain by an organic clay rich silt containing frequent rootlets and pieces of mangrove wood. Although there are no foraminifera preserved in these horizons it is possible to reconstruct sea level at the upper and lower boundary of this organic material using the modern analogue of organic deposition in Cleveland Bay (Figures 4.1-4.3). Sea-level reconstructions using transfer function results start in the overlying shell and sand rich silt and silt rich sand at 225 cm deep, continuing through the overlying silt rich shell hash but not in the uppermost organic or silt-rich clay (Figure 5.16). Only 6 out of 14 reconstructions have good modern analogues (assessed using MAT). The cluster analysis assemblage zone boundary identified in Section 5.2.1 coincides with a change from slightly increasing water depth (positive tendency) between 225-175 cm and decreasing water depth (negative tendency) between 165-107 cm identified by the transfer function (Figure 5.16). Radiocarbon dating identifies a reworked layer around 215 cm deep, which may be an isolated period of reworking or may extend to the bottom of the core depending on which hypothesis on reworking is taken (see Section 5.3). There is no indication from particle size or foraminifera data that this horizon is reworked, although reworking coincides with a section of core with no modern analogues (Figure 5.16).

5.6.2 *Cocoa Creek Core 14*

Descriptions of palaeo-surface elevation changes, relative sea-level changes, the age model used in reconstructions and minimum dissimilarity coefficient values through the studied section of core are shown in Figure 5.17, Table 5.19 and Table 1 in Volume 2. The studied sequence in this core begins with a thin silt-rich sand overlain by an organic clay rich silt with frequent pieces of wood and well preserved organic material, which does not contain foraminifera, but allows sea-level reconstructions using the

upper and lower boundary of organic deposits as in Core 7 (Figure 5.17). Transfer function-based reconstructions start in the overlying shell and sand rich silt at 308 cm below the surface, continuing through sand and silt rich horizons, a silt rich shell hash and a 15 cm thick organic horizon to 75 cm deep (Figure 5.17). Palaeo-surface elevation reconstructions show increased and decreased water depth below LAT through most of the core, rising to a low intertidal environment in the shell hash and upper organic unit. Most reconstructions have good modern analogues. However, in the bottom half of the core there are several samples with poor analogues, which coincide with the section of core with reversed radiocarbon dates. The lowest transfer function reconstruction at 300 cm deep may be correct if the age reversals above are an isolated period of reworking between 265-205 cm deep. This hypothesis is supported by minimum dissimilarity values, indicating that samples at the base of the core (between 295-287 cm deep) have good modern analogues unlike those in the section of radiocarbon age reversals above between 285-205 cm (Figure 5.17). The cluster analysis boundary between zones 2 and 3 (between 200-205 cm deep) coincides with the uppermost sample with a poor modern analogue and the uppermost out of sequence radiocarbon date (Figure 5.17). Using MAT dissimilarity coefficient values and cluster analysis zone boundaries together may increase precision in identifying the upper limit of reworking in this core to between 200-205 cm, while radiocarbon dating only places this boundary between 173-205 cm.

Table 5.18: Description of relative sea-level changes through Cocoa Creek Core 7.

Depth (cm)	Lithology	Summary of foraminifera present	Sea-level tendency	Environmental reconstruction	Radiocarbon age reversals?	MAT modern analogues?
283-246	Organic clay-rich silt	No foraminifera present. Reconstructions based on upper and lower boundaries of organic sedimentation	Positive	Upper intertidal mangrove to lower intertidal flat	n/a	n/a
246-175	Shell and silt rich sand and sand rich silt	<i>Ammonia aoteana</i> and <i>Parrellina hispidula</i> dominate at the base, declining upwards with high <i>Wiesnerella auriculata</i> throughout, increased diversity up core.	Positive	Low intertidal grading into subtidal silt and sand	Out of sequence age at 215 cm	Few samples have good modern analogues
175-107	Shell and silt rich sand and sand rich silt grading into sand, clay and shell rich silt	Rising <i>Ammonia aoteana</i> and <i>Parrellina hispidula</i> , declining <i>Pararotalia venusta</i> and decreased diversity up core.	Negative	Subtidal grading into low then mid intertidal sand and shell rich silt	None	All samples have good modern analogues

Table 5.19: Description of relative sea-level changes through Cocoa Creek Core 14.

Depth (cm)	Lithology	Summary of foraminifera present	Sea-level tendency	Environmental reconstruction	Radiocarbon age reversals?	MAT modern analogues?
385-305	Organic clay-rich silt	No foraminifera present. Reconstructions based on upper and lower boundaries of organic sedimentation	Positive	Upper intertidal mangrove to lower intertidal flat	n/a	n/a
300-135	Shell and silt rich sand and sand rich silt	<i>Ammonia aoteana</i> , <i>Pararotalia venusta</i> and <i>Planispirinella exigua</i> dominate, but decline up core. Sudden disappearance of <i>Wiesnerella auriculata</i> at 205 cm	Stable	Fluctuations between subtidal silt and sand	Out of sequence ages between 265-205 cm	Few samples have good modern analogues
135-75	Silt and shell rich sand	<i>Ammonia aoteana</i> increases up core, <i>Pararotalia</i> decreases.	Slightly negative	Intertidal silt and sand grading into intertidal silt	None	All samples have good analogues

5.6.3 *Alligator Creek Core 1*

Descriptions of palaeo-surface elevation changes, relative sea-level changes, the age model used in reconstructions and minimum dissimilarity coefficient values through the studied section of this core are shown in Figure 5.18, Table 5.20 and Table 1 in Volume 2. The fossil sequence begins with a 213 cm thick horizon of slightly shelly, silt rich sand with abundant foraminifera preserved throughout. Foraminifera are also preserved in the overlying sand rich silt and silt and clay rich shell hash, but not in the overlying organic silt (Figures 5.8 and 5.18). Reconstructed palaeo-surface elevations show increasing water depth subtidally in the lower silt rich sand and declining water depth and emergence into an intertidal environment in upper silt rich sand, sand rich silt and shell hash (Figure 5.18). Some reconstructions through the increasing water depth phase have poor modern analogues, although all samples in the section of core with radiocarbon age reversals (between 324-262 cm) have good modern analogues (Figure 5.18). It is not clear whether the basal samples (between 365-330 cm) are reworked, that depends on the reworking hypothesis taken (Section 5.3). In this core cluster analysis assemblage zone boundaries (identified in Section 5.2.3 and on Figures 5.8 and 5.18) do not coincide with reworked horizons or changes in sea-level tendency, and do not provide additional information to precisely delimit reworking or sea-level tendencies.

5.6.4 *Alligator Creek Core 10*

Descriptions of palaeo-surface elevation changes, relative sea-level changes, the age model used in reconstructions and minimum dissimilarity coefficient values through the studied section of core are shown in Figure 5.19, Table 5.21 and Table 1 in Volume 2. This fossil sequence also begins with shell and silt rich sand at 214 cm deep, but this horizon is thin and contains no foraminifera. Overlying it is a similar sand rich silt with abundant foraminifera found in Alligator Creek Core 1, with a foraminifera-poor organic silt on top (Figure 5.9 and 5.19). Reconstructed palaeo-surface elevations show slightly increasing water depth through the bottom half of the sand rich silt and stable or slightly decreasing water depth in the upper sand rich silt (Figure 5.19 and Table 5.21). Some reconstructions through the bottom half of the core during increasing water depth have poor modern analogues, similar to in the bottom half of Alligator Creek Core 1. The out of sequence date at 174 cm coincides with the cluster analysis assemblage zone boundary (identified in Section 5.2.4), although samples in this part of the core have good modern analogues. This boundary may increase precision in identifying the upper limit of reworking in this core to between 170-175 cm (the radiocarbon date is at 174 cm (Table 5.8)), rather than between 174-149 cm indicated by radiocarbon results.

Sediment reworking may occur through the whole bottom half of core from 174 cm downwards, or just as an isolated episode around 174 cm, depending on the reworking hypothesis chosen (Figure 5.19).

5.7 FINAL RECONSTRUCTIONS FROM CLEVELAND BAY

The transfer function-predicted relative sea-level changes from 4 cores in Cleveland Bay using two different reworking models are shown in Figure 5.20 a and b. For the final reconstructions I use the following criteria to remove invalid reconstructions:

1. Minimum dissimilarity coefficient of the fossil sample above the value of the largest Minimum Dissimilarity Coefficient calculated between all modern samples. This gives a general indication of whether a fossil sample is similar to samples in the modern training set.
2. Out of sequence radiocarbon age at that depth. Where there are several out of sequence dates next to each other in a core I exclude all samples within the depth range covered by the dates. As I cannot be sure exactly where in a core reworking starts between two dates (i.e. one in sequence, one not in sequence), I take the best case scenario, where reworking only occurs at the dated horizon. I exclude samples around the dated horizon if there are high minimum dissimilarity coefficient values, which may or not be due to reworking.

In some cases cluster analysis and MAT minimum dissimilarity coefficients together with radiocarbon dating results infer a change from reworked to in situ material (e.g., 200-205 cm in Cocoa Creek Core 14 and 170-175 cm in Alligator Creek Core 10) giving a more precise limit to reworked horizons.

Regardless of which reworking model is chosen, relative sea-level reconstructions from two locations in Cleveland Bay cover a range from 5410-1199 cal years BP. Reconstructions from three of the cores cover overlapping time periods and their elevation errors overlap, although index points from Alligator Creek Core 10 are up to 50 cm lower than those from Cocoa Creek Core 14 (Figure 5.20). Index points from Alligator Creek Core 1 give the most recent reconstructions, between 1952-1199 cal years BP (large scale reworking model – Figure 5.20 a) or 2585-1199 cal years BP (episodic reworking model – Figure 5.20 b), but in either model this time period does not overlap with reconstructions from other cores. All index points show relative sea level above present during the mid/late Holocene, with the highest reconstruction of +3.55 m +/- 0.8 m at 3050 cal years BP from Cocoa Creek Core 14 (Figures 5.20 a and b). Reconstructions using either reworking model are very similar, the only changes

occur in the large scale reworking model by removing basal samples from Alligator Creek Core 10 and Cocoa Creek Core 14 (shown by index points with markers on Figure 5.20 b) (samples at the base of Alligator Creek Core 1 and Cocoa Creek Core 7 are already removed as they have high minimum dissimilarity coefficient values). This also affects the interpolated age of a few samples higher up some cores because interpolated ages for the few samples immediately above reworked zones (and below the next in sequence date) vary depending on whether the basal date is used to infer the age model for these samples or not (Figure 5.20 a). Removing the basal samples from Alligator Creek Core 10 and Cocoa Creek Core 14 improves the fit of their oldest reconstructions with the pattern of relative sea-level change from other cores (Figure 5.20 a). On this basis I decide to use the reconstructions developed using the large-scale reworking model in subsequent analysis and discussion.

Table 5.20: Description of relative sea-level changes through Alligator Creek Core 1.

Depth (cm)	Lithology	Summary of foraminifera present	Sea-level tendency	Environmental reconstruction	Radiocarbon age reversals?	MAT modern analogues?
365-255	Slightly shelly silt rich sand	Dominated by fluctuating values of <i>Ammonia aoteana</i> , <i>Triloculina oblonga</i> and <i>Planispirinella exigua</i> , with high percentages of <i>Wiesnerella auriculata</i> at the base	Slightly positive	Change within subtidal silt rich sand	Out of sequence ages between 262-324 cm	Most samples have good analogues
255-115	Silt rich sand, sand rich silt and shell hash	Rising values of <i>Ammonia aoteana</i> , <i>Pararotalia venusta</i> and <i>Parrellina hispidula</i> with decreased diversity up core and virtually no <i>Wiesnerella auriculata</i>	Negative	Subtidal silt rich sand grading into low intertidal sand rich silt	None	All samples have good analogues

Table 5.21: Description of relative sea-level changes through Alligator Creek Core 10.

Depth (cm)	Lithology	Summary of foraminifera present	Sea-level tendency	Environmental reconstruction	Radiocarbon age reversals?	MAT modern analogues?
200-160	Silt with variable sand	Dominant <i>Ammonia aoteana</i> with low but persistent occurrences of <i>Haynesina depressula</i> , <i>Wiesnerella auriculata</i> and <i>Cribrononion oceanicus</i> .	Slightly positive	Low intertidal silt with increasing sand content up core.	Out of sequence age at 174 cm	Most samples have good analogues
160-125	Silt with variable sand	Decreasing but still dominant <i>Ammonia aoteana</i> , rising <i>Pararotalia venusta</i> and <i>Parrellina hispidula</i> and declining <i>Haynesina depressula</i> and <i>Cribrononion oceanicus</i> .	Stable/ slightly negative	Low intertidal silt with decreasing sand content up core.	None	Most samples have good analogues

5.8 CHAPTER SUMMARY

This chapter outlines the development of the final transfer function model used to calibrate fossil cores from Cocoa and Alligator Creeks. I also show results of radiocarbon dating of fossil cores and problems of reworking of foraminifera and bivalve shells. I use the final transfer function model to create new relative sea-level reconstructions from each fossil core using two different models of reworking, and correlate reconstructions at the local scale. I decide to use reconstructions within the large-scale reworking model in subsequent analysis and discussion as they correlate better between cores within Cleveland Bay.

CHAPTER 6 - DISCUSSION

6.1 INTRODUCTION

This chapter discusses transfer function-based and other relative sea-level reconstructions from Cleveland Bay and further locations on the North Queensland coastline to answer research questions set out in Section 1.8. I also discuss the methodology used to create sea-level reconstructions, including the use of foraminifera and model performance and investigate ways of improving transfer function reconstruction precision and reliability.

6.2 SEA-LEVEL RECONSTRUCTIONS FROM NORTH QUEENSLAND AND MODEL TESTING

6.2.1 *Other proxy indicators*

North Queensland is relatively well studied in terms of sea-level reconstructions compared to other parts of Australia (Hopley and Thom, 1983), but there are problems with the indicative meaning of some proxy indicators and there are crucial gaps in the Holocene record. Larcombe *et al.* (1995) assembled a database of Holocene sea-level index points from a range of studies conducted over 20 years using many different indicators and created a summary Holocene sea-level curve for the area between Cape Tribulation and the Whitsunday Islands (Figure 6.1). However, much of the data is from coral coring projects with varying elevation data (local low tide level or national datum), and reconstructions from other indicators such as mangrove mud not corrected for their position in the tidal frame. Studies from a wide geographical area are included on one graph (Figure 6.1) when there may be up to 4 m of differential displacement due to crustal levering through the Holocene (Hopley 2005, pers. comm.), and all index points are on the radiocarbon timescale. Despite problems with the sea-level curve, the regional data set assembled by Larcombe has the potential to provide useful sea-level reconstructions through the Holocene if problems with standardisation and interpretation are solved.

In this study I have modified and built upon this database, by collating sea-level information from the existing database and from studies omitted from the database or conducted in North Queensland since 1995. I first disregard any index point which does not provide the full range of information to reconstruct relative sea level (detailed

below), and highlight index points which only provide upper or lower limiting information on sea-level position (yellow highlighted cells in Tables 1 and 2 in Volume 2). I re-evaluate all remaining index points by re-defining the indicative meaning of each indicator (see Table 6.1) and calibrate radiocarbon ages using Oxcal 3.10 (Bronk Ramsey, 1995; Hughen *et al.*, 2004) and the southern hemisphere calibration curve (Stuiver *et al.*, 1998). Some indicative meaning definitions are solely based on the largest range quoted by other authors in previous work (cored coral, coral microatolls) the rest are based on previous work and modified according to field evidence of the range of the indicator's distribution in Cleveland Bay (encrusting oysters, mangrove mud, upper limit of sand flat facies) (Table 6.1).

The new database now provides 186 Holocene sea-level index points from coastal locations of North Queensland (Figure 6.2) with the following information required to reconstruct relative sea-level change:

Site name and location; description of dated material; elevation of sample to Australian Height Datum; laboratory reference code; radiocarbon age estimate with 1 σ error term; indicative meaning and range of the indicator being used to reconstruct sea level; tidal information to place the indicator in context (Preuss, 1979; Shennan, 1989).

Table 6.1: Revised definitions of the indicative meaning of proxy sea-level indicators based on previous work and field evidence used to reconstruct Holocene sea level in North Queensland.

Indicator type and locations in North Queensland	References to their distribution	Re-evaluated indicative meaning and range	Indicative range +/- m	Comments	Material used for dating
Calcareous foraminifera investigated in this study in Cleveland Bay	(Horton <i>et al.</i> , 2003; Woodroffe <i>et al.</i> , 2005)	Modern calcareous species from intertidal and shallow subtidal environments studied (to - 3.94 m below LAT)	~0.81m	Calcareous species have a large indicative range compared to agglutinated species, which are poorly preserved in fossil sediments in Cleveland Bay	AMS dating of calcareous foraminifera, with potential issues over whether material is <i>in situ</i> . May require marine reservoir correction.
Cored coral/coral rubble - Many reconstruction -s from	(Davies and Montaggioni, 1985; Hopley, 1986, Hopley,	Anywhere between MLWST and 10 m below MLWST	5 m	Core material has great uncertainty (especially dated rubble), as species	AMS or bulk dates on what appears to be <i>in situ</i> calcareous material (sometimes

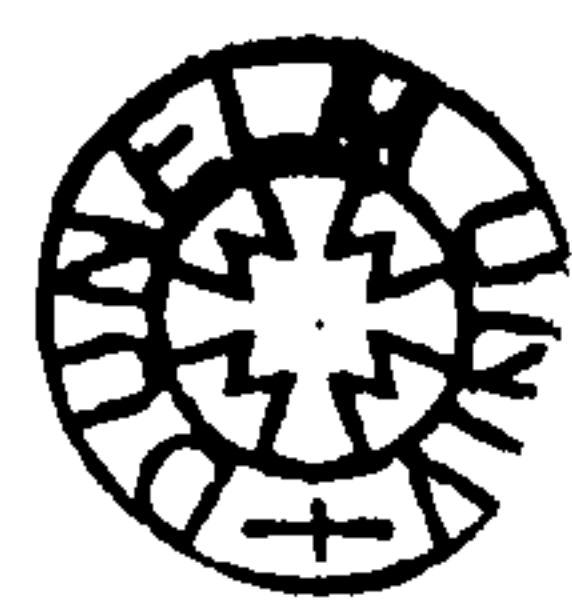
Indicator type and locations in North Queensland	References to their distribution	Re-evaluated indicative meaning and range	Indicative range +/- m	Comments	Material used for dating
offshore and fringing reefs along the whole coastline	2005, pers. comm.)			clearly limited to shallow water are not present in the Indo-Pacific	difficult with coral rubble), requiring marine reservoir correction
Coral micro atolls - found on fringing reefs along the whole coastline, present in Cleveland Bay	(Mclean <i>et al.</i> , 1978; Hopley, 1986; Smithers and Woodroffe, 2000)	In open water situations – MLWST. Where moated – only limited by degree of ponding and raised water level.	In open water - 0.05 m. Where moated the range can be higher MLWST-~MTL (up to ~0.6 m)	Unmoated reef-top microatolls are very precise indicators, but a sequence is required to infer sea-level tendency. Rubble ramparts or shingle banks on reef flat may indicate moating, but these may have been displaced over time (see Figure 6.3)	AMS or bulk dates on <i>in situ</i> calcareous material, requiring marine reservoir correction
Encrusting oysters - only recorded on Magnetic Island, Cleveland Bay on the North Queensland coastline	(Beaman <i>et al.</i> , 1994; Baker <i>et al.</i> , 2001)	Anywhere between MHWNT and MTL in open coast locations	0.12 m in Cleveland Bay, but greater where tidal range is higher	Within confined cave locations (where fossil oysters are most likely to be preserved) the range is higher due to wave splash (~+/- 0.3 m) (see Figure 6.4).	AMS or bulk dates on <i>in situ</i> calcareous material from the uppermost and outermost level. Is marine reservoir correction required?
Mangrove 'mud' – sampled and dated at several sites along the central North Queensland coastline	(Grindrod, 1988; Horton <i>et al.</i> , 2005a)	Anywhere between MTL and HAT	1.02 m in Cleveland Bay, but greater where tidal range is higher	In the seasonally wet tropics of Australia mangroves survive up to HAT, but in seasonally dry tropics mangroves only grow up to MHWST. However distinguishing past climate conditions may be difficult (Semeniuk, 1983)	Best dates are AMS on <i>in situ</i> small macrofossils, bulk dates on 'mud' introduce more error. Some studies use shells which live in the mangrove, but difficult to know if they are <i>in situ</i>
Boundary between intertidal sand	(Harvey <i>et al.</i> , 2001)	Anywhere between MTL and	0.61 m at sites investigate	This boundary is hard to pinpoint in	Articulated shells of known species

Indicator type and locations in North Queensland	References to their distribution	Re-evaluated indicative meaning and range	Indicative range +/- m	Comments	Material used for dating
facies and mangrove 'mud' – only used as an indicator at Cocoa Creek in Cleveland Bay		MLWST	-d in Cleveland Bay	Cleveland Bay because organic content of mangrove 'mud' is low (~10 %) and below its lowest limit are seagrass beds which make low intertidal sediment slightly organic. There is no obvious transition from organic 'mud' to intertidal sand at any modern sites investigated in Cleveland Bay in this study (see Section 4.2.1).	(e.g., <i>Anadara trapezia</i>) which live in this environment, also roots and other remains of mangrove vegetation, which may not be <i>in situ</i> . Is the marine reservoir correction required for dated shells?

There are many studies focusing on Cleveland and Halifax bays, with 73 valid sea-level index points and a further 17 index points of the total from North Queensland providing upper or lower limiting information on sea-level position (see Table 1 in Volume 2). New and re-calibrated sea-level index points from Cleveland and Halifax bays are plotted on Figure 6.5. Geophysical models infer that little differential crustal movement occurs between these locations during the mid/late Holocene so I can plot them on the same diagram (Nakada and Lambeck, 1989; Lambeck, 2002).

6.2.2 Holocene sea-level changes in Cleveland and Halifax Bays

All validated index points from 6700-500 cal years BP from Cleveland and Halifax bays show relative sea level above present, with the highest reconstruction of +3.55 m +/- 0.8 m at 3050 cal years BP from Cocoa Creek Core 14 (Figure 6.5). The general form of the record (grey curve on Figure 6.5 which summarises the majority of reconstructions since 8000 cal years BP) shows sea level rising above its present value prior to 6700 cal years BP, relatively stable sea level at an elevation of 1-2.3 m above present between 6700-5000 cal years BP, and between 1-2.8 m above present between 5000 cal years BP and 3000 cal years BP. This is followed by sea-level fall to



between 0.4-0.8 m above present until 1200 cal years BP, with subsequent slow fall to present. All index points developed from sand facies at Cocoa Creek (Harvey *et al.*, 2001) lie below the summary envelope of reconstructions through the late Holocene (Figure 6.5 b), and given potential errors in their age estimates (Table 6.1) are excluded from subsequent analyses. In addition index points based on cored coral (Hopley, 1983) with large error terms are also excluded from subsequent analyses.

I extract information on sea level tendency for each sea-level index point using a combination of lithology and the general trend of foraminifera-based reconstructions from each part of the core (see Figures 5.16-5.19). Positive tendency represents an increase in marine influence at the sampling site and negative tendency is a decrease. Tendency information forms the basis for correlation of processes acting at individual sites to identify regionally significant processes such as relative sea-level change (Shennan *et al.*, 1995). All sites need not show the same tendency at the same time since local processes, such as change in sediment supply, can obscure the regional signal. Correlation of tendencies between sites allows investigation of the balance between local and regional processes (Shennan *et al.*, 1995 p. 116).

Figure 6.6 a shows relative sea-level reconstructions from Cocoa and Alligator Creeks which are directly dated using ^{14}C AMS dating of calcareous foraminifera, excluding index points which have their age determined by interpolation between radiocarbon dated core horizons (see Table 1 in Volume 2). When these data are plotted with other indicators from Cleveland and Halifax bays (Figure 6.6 b) the general trend of sea-level change through the mid-late Holocene is the same as that deduced from using all new index points (Figure 6.5 a).

Figure 6.6 b shows directly dated relative sea-level reconstructions from Cocoa and Alligator creeks and other indicators from Cleveland and Halifax bays with tendency information added. Encrusting oysters on Magnetic Island (Beaman *et al.*, 1994) give tendency information, but micro atolls only give information due to the elevation relationship between individual dated micro atolls at a single site. I have not given them tendency information because it is not clear from the original publication the relation between individual micro atolls on each site (Chappell *et al.*, 1983). On a local scale not all tendencies correlate, as reconstructions from Core 7 between 4700-4000 cal years BP infer negative tendency while reconstructions from Core 14 in this period infer stable sea level (Figure 6.6 b). At Alligator Creek tendencies correlate between

cores, inferring negative tendency between 3600-1200 cal years BP, which correlates with negative tendency in Cocoa Creek Core 14 after 3500 cal years BP (Figure 6.6 b).

On a regional scale, the summary sea-level curve in Figure 6.5 suggests sea level was relatively stable between 1-2.3 m above present during the period 6700-5000 cal years BP, which is confirmed by sea-level tendencies. The single index point with a positive tendency during this period (from Cocoa Creek Core 7) likely reflects local sediment dynamics rather than regional sea-level change. The inflection point between positive/stable and negative sea-level tendency (the end of the peak of the high stand) inferred from the summary curve (grey curve on Figure 6.5) is around 3000 cal years BP (Figure 6.5). Tendency information indicates it may be earlier, with slight negative tendency present at both Alligator and Cocoa Creeks from 3500 cal years BP. If negative tendencies in Cocoa Creek Core 7 reflect regional sea-level change the end of the high stand peak may be even earlier, around 4800 cal years BP (Figure 6.6 b).

6.2.3 Holocene geomorphology of Cleveland Bay

Prior to the Holocene transgression, sea level was approximately 120 m below present (Fairbanks, 1989), and the continental shelf in Cleveland Bay was subaerially exposed and subject to erosion and terrestrial sedimentation (Belperio and Southgate, 1978). I find this weathered, stiff pre-Holocene surface at the base of cores from Cocoa and Alligator Creeks (Figures 5.1, 5.2, 5.4 and 5.5). During the early part of the marine transgression the sediment surface at core locations at Cocoa and Alligator Creeks was this pre-Holocene surface described above. As relative sea level rose to ~-5 m AHD intertidal mangroves developed at the base of the deepest cores at Cocoa Creek, and as relative sea level continued to rise this was overlain by intertidal/subtidal minerogenic foraminifera-rich sediments at Cocoa and Alligator Creeks.

With sea level up to 2.8 m above present during the mid/late Holocene the geomorphology of Cleveland Bay would have been very different to that today. Figure 6.7 shows the coastal geomorphology of south eastern Cleveland Bay with areas above the 2.5 m contour shaded in black. At the height of the high stand all areas below the 2.5 m contour were submerged at high tide. Cleveland and Bowling Green Bays were joined and Cleveland Bay would have been open to tidal and wind-driven flushing from south easterly trade winds. A model of coastal evolution suggests that during this period northward longshore drift delivered significant amounts of sediment from the Haughton/Burdekin river system to the south east, building out a series of beach ridges which develop at the break point of waves, towards the Cape Cleveland

island from the mainland (Driscoll and Hopley, 1968). It is proposed this beach ridge plain (Figure 6.7) prograded from the mainland during the period of highest sea level above present, completing a tombolo linking Cape Cleveland and the mainland around 3000 cal BP (Carter *et al.*, 1993). It is also proposed that during this period the chenier plain close to Cocoa Creek developed (Carter *et al.* 1993) (see Figures 5.3 and 6.7). Chenier plains consist of low, seaward-younging, shore-parallel sand and shell-rich ridges along the coastal plain that develop in semi-protected embayments which experience tropical storms and where wave action is sufficient to maintain a sand-rich intertidal flat (Belperio, 1983; Chappell and Grindrod, 1983; Larcombe and Carter, 2004). Coastal progradation in front of each successive chenier ridge only occurs during stable or falling sea level as chenier ridges are eroded during rising sea level (Chappell and Grindrod, 1983). There are many examples of chenier plains along the North Queensland coastline, the earliest dated from ~6300 cal years BP (Chappell and Grindrod, 1983), indicating relatively stable or falling sea level since that time. This correlates well with the timing of relatively stable sea level above present after it first rose above present prior to 6700 cal years BP (Figure 6.5).

6.2.4 Models of sea-level change

Models of mid Holocene high stand duration and amplitude in far-field locations proposed by geophysical modellers are influenced by earth model parameters and the melting history of ice sheets from the Last Glacial Maximum (e.g., Laurentide, Fennoscandia) and late Holocene melting from Antarctica, Greenland and mountain glaciers. The different schools of thought on ice-melt history and resultant sea-level curves in far-field locations are summarised below:

- Australian National University (ANU) school – models from several different authors in this group suggest Laurentide ice sheet melt by 6800 cal BP and between 3-5 metres of melt between 6800 cal years BP and 2000 cal BP/present from Antarctica causing a pronounced high stand after 6800 cal BP and rapid fall to present levels where there is a wide continental shelf (Nakada and Lambeck, 1988; Nakada and Lambeck, 1989; Lambeck and Nakada, 1990; Fleming *et al.*, 1998; Shennan *et al.*, 2000a; Lambeck, 2002) (Table 6.2).
- Durham school - Rapid Antarctic melting until 7000 cal BP slowing to 0.5 mm/yr between 7000-5000 cal BP and no melt after 5000 cal BP – high stand with pronounced peak but significant period with sea level above present during the late Holocene (Milne *et al.*, 2005).

- Toronto school - Rapid Antarctic melting until decrease around 7000 cal BP with reduced melting of a few metres until 4000 cal BP and no melting after 4000 cal BP – rounded high stand with a significant period after 6000 cal BP with sea level above present (Peltier, 2002; Peltier *et al.*, 2002; Shennan *et al.*, 2002; Peltier, 2004).

Comparing model predictions to far-field sea-level data during the mid/late Holocene allows better estimation of earth parameters and the meltwater component. Table 6.2 shows modifications made to geophysical models above using far- and near-field Holocene sea-level data.

Table 6.2: Earth and Ice models from different authors which have been tuned to late Holocene sea-level data in near- and far-field locations.

Authors and location of empirical data used for tuning	School	Best earth and ice models
(Fleming <i>et al.</i> , 1998), coral micro atolls in North Queensland, other indicators from West Africa, Jamaica, Malaysia	ANU	Lithospheric thickness between 50-100 km, upper mantle viscosity between 2×10^{20} and 6×10^{20} , lower mantle viscosity between 5×10^{21} and 2×10^{22} ARC3 an ANT3A ice models modified to give 3-5 m of ice melt between 7000 to 2/1000 cal BP
(Lambeck, 2002), Australian data, including coral micro atolls in North Queensland	ANU	Lithospheric thickness between 70-100 km, upper mantle viscosity between 1.5×10^{20} and 2.5×10^{20} , lower mantle viscosity 10^{22} ARC3 and ANT3B ice models – modified to give 3 m of ice melt between 7000-3000 cal BP
Milne <i>et al.</i> 2005, Caribbean-South America	Durham	Lithospheric thickness 71 km, upper mantle viscosity 5×10^{20} , lower mantle viscosity 10^{22} ICE-3G ice model Laurentide melt by 5000 cal BP
Shennan <i>et al.</i> 2006, UK	Durham	Lithospheric thickness 71 km, upper mantle viscosity 5×10^{20} , lower mantle viscosity 4×10^{22} ICE-3G ice model modified by decreasing ice melt by 0.2-2 m between 7000-3000 cal BP

In this section I compare a series of geophysical model predictions from different schools (Table 6.3) with existing and new sea-level data from Cleveland and Halifax Bays described in Section 6.2.2, and with sea-level data from other parts of North Queensland in Section 6.2.5. This tuning may allow better estimation of continued ice-sheet melt in the late Holocene, contested by the different groups of geophysical modellers.

Table 6.3: Details of geophysical models which give predictions of Holocene sea-level change, compared to empirical data from in North Queensland in this study.

Model authors	Empirical data used previously to test model	Earth model parameters	Ice models and eustatic contribution in late Holocene	Predicted nature of high stand in North Queensland
Nakada and Lambeck 1989, Lambeck and Nakada 1990.	Data from around Australia including North Queensland micro atolls	Lithosphere thickness - 50 km, Upper mantle viscosity (to a depth of 670 km) 2×10^{20} Pa/s, Lower mantle viscosity (to the core-mantle boundary) 10^{22} Pa/s.	ARC3 and ANT3B ice models, no Laurentide melt after 6800 cal years BP, 3 m of Antarctic melt between 6800 cal yrs BP and present.	Pronounced high stand after 6800 cal years BP and steady fall to present levels
Chappell <i>et al.</i> 1982	Data from North Queensland micro atolls only	Lithosphere thickness 96 km, other parameters unknown	No eustatic melt after 5000 cal years BP	High stand peak at 6300 cal years BP, steady fall to present levels
Milne <i>et al.</i> 2005	None in far field after 7800 cal years BP (the end of the Barbados record (Fairbanks, 1989)	Lithosphere thickness between 96-120 km, Upper mantle viscosity between 5×10^{20} and 10^{21} Pa/s, Lower mantle viscosity between 10^{21} and 10×10^{22} Pa/s.	ICE-3G with modifications – tuned to Barbados and other far-field records during Meltwater Pulse 1A (Bassett <i>et al.</i> , 2005). Antarctic melt slows between 7000-5000 cal years BP with no melt after 5000 cal years BP	High stand with pronounced peak but significant period during late Holocene with sea level above present

Nakada and Lambeck (1989) model

Nakada and Lambeck's 1989 geophysical model of sea-level change along the North Queensland coastline (Table 6.3, Figure 6.8 B-D and red line on Figure 6.5) suggests relative sea level first reached its present value around 7200 cal years BP in Cleveland Bay, with the peak of the high stand at 2.2 m above present at 6800 cal years BP, and steady fall to present during the late Holocene. This model assumes 3 m of continued Antarctic ice melting until recently.

Chappell et al. (1982) model

Chappell's geophysical model predictions start at what his model predicts as the peak of the high stand at ~6300 cal years BP in Cleveland Bay, with sea level 1.2 m above present and linear fall to present (Table 6.3, Figure 6.8 A and black dotted line on

Figure 6.5). This model is similar to those from the 'Durham School' in that it assumes no ice melt after 5000 cal years BP.

Before this study micro atoll data from Cleveland and Halifax Bays fitted both Chappell and Nakada and Lambeck's models, with the peak of the high stand between 6800-6000 cal years BP at 1.1-1.8 m above present with steady fall from this peak to present. However, my new data redresses a lack of late Holocene sea-level index points and adds definition to the late Holocene sea-level curve, suggesting an alternative sea-level scenario. This data suggests the peak of the high stand was later and possibly higher than predicted by either model (~1-2.8 m above present between 6700-3000 cal years BP), indicating a prolonged period (~3700 years) in the late Holocene when sea level was relatively stable above present. With new data the shape of the sea-level curve for Cleveland and Halifax Bays fits more closely with Zone II of Lambeck and Nakada's model of mid/late Holocene sea-level curves across the continental shelf in North Queensland than the isoline for Zone I which is geographically closer to Cleveland Bay (Figure 6.8 D).

Mis-fit between both model predictions and sea-level data suggests alterations to Antarctic melting in the mid-late Holocene are required by both models. Lambeck acknowledges that if melting stops at 6800 cal years BP, the high stand in his model always occurs at the time of cessation of melting regardless of distance from ice loading, but with melting continuing into the late Holocene the high stand is later and is broader (Lambeck, 2002). However, the Nakada and Lambeck (1989) model, which assumes continued melting during the late Holocene does not predict a high stand sufficiently broad and late to fit with sea-level data from Cleveland and Halifax Bays (Figure 6.5). Further melting after 6800 cal years BP is required to fit both Nakada and Lambeck's (1989) and Chappell *et al.*'s (1982) models to the sea-level data available.

The only sea-level data in North Queensland used to tune either model (and subsequent models from the ANU school – see Table 6.2) is from micro atolls (Chappell *et al.*, 1983; Nakada and Lambeck, 1988; Nakada and Lambeck, 1989; Lambeck and Nakada, 1990; Fleming *et al.*, 1998; Lambeck, 2002). Because vertical error terms on micro atolls may be underestimated, conclusions made about late Holocene melting based on this data may be incorrect.

Milne et al. (2005) models

This model has seven iterations varying differing parameters in the earth model (Table 6.4). By altering earth parameters I can test whether the model is capable of replicating sea-level data without modification to the ice model. The ice model is based on the ICE-3G deglaciation history (Tushingham and Peltier, 1991), with a glaciation phase added to create a glaciation period of ~100 ka years and the model is tuned to fit Barbados and other far-field sea-level records during the lateglacial period, especially during meltwater pulse 1A (14500-13500 cal BP) (Bassett *et al.*, 2005). The earth and ice models are improved including corrections for migrating shorelines, perturbations in Earth rotation and water loading in near-field regions during ice retreat (Milne *et al.*, 1999; Mitrovica and Milne, 2002; Horton *et al.*, 2005a). The Antarctic component is also revised to produce rapid melt of 7-8 mm/yr in the early Holocene slowing down to ~0.5 mm/yr between 7000 and 5000 cal BP with zero melt after 5000 cal BP (Table 6.3).

Table 6.4: Model iterations from the ‘Durham school’ model compared to empirical data in this study.

Model name/identifier	Lithospheric thickness (km)	Upper mantle viscosity (Pa/s)	Lower mantle viscosity (Pa/s)
Reference (solid black)	96	5×10^{20}	10^{22}
Thin Lithosphere (grey dashed)	71	5×10^{20}	10^{22}
Thick Lithosphere (black dashed)	120	5×10^{20}	10^{22}
Less viscous upper mantle (low UMV - grey dotted)	96	10^{20}	10^{22}
More viscous upper mantle (high UMV - black dotted)	96	10^{21}	10^{22}
Less viscous lower mantle (low LMV - grey dot dash)	96	5×10^{20}	10^{21}
More viscous lower mantle (high LMV - black dot dash)	96	5×10^{20}	5×10^{22}

Figure 6.9 (A) shows each of the earth models in Table 6.4 with the sea-level data from Cleveland and Halifax Bays. All of the models over-predict the height of the mid Holocene high stand compared to the sea-level data. The high lower mantle viscosity model predicts the closest sea-level curve to the observations (Figure 6.9 A). In a recent study comparing these earth models to relative sea-level data from South America (Table 6.2), low or high upper/lower mantle viscosity models do not accurately

predict Holocene sea-level changes, and the thin lithosphere model performs best overall in comparison to sea-level data (Milne *et al.*, 2005). The same thin lithosphere model (grey dashed line on Figure 6.9 A) accurately predicts sea level in Cleveland and Halifax Bays during the past 3000 years, but over-predicts the height of the mid Holocene high stand by 2.8 m (Figure 6.9 A).

All the model predictions in Figure 6.9 (A) give a similar shape to the mid/late Holocene sea-level curve for Cleveland Bay, with a distinct high stand peak and relatively linear sea-level fall in the late Holocene (Figure 6.9 A). Each earth model shows extremely rapid sea-level rise until 7000 cal BP (~7.5 mm/yr), a slight slow down between 7000-6000 cal BP (~4.3 mm/yr) and the peak of the mid Holocene high stand at 6000 cal BP. Nakada and Lambeck’s model fits the sea-level data from Cleveland and Halifax Bays better than any of Milne *et al.*’s (2005) models (Figure 6.9 A). Varying earth model parameters only changes the height of the high stand and sea-level elevation during the late Holocene, does not fundamentally change the shape of the sea-level curve or the timing of inflections in the rate of change. This suggests adjusting the amount and rate of ice melting in the mid/late Holocene will better fit Milne *et al.*’s (2005) geophysical model to sea-level data from Cleveland and Halifax Bays.

The youngest far-field tuning point in Milne *et al.*’s (2005) global ice model is from the Barbados record at 7800 cal years BP (Fairbanks, 1989), so it is no surprise that the ice model fails to predict accurately mid/late Holocene sea-level changes in northeast Australia. Although this model predicts mid/late Holocene sea-level change in South America (Milne *et al.*, 2005), Shennan *et al.* (2006) suggest decreasing meltwater input between 7000-3000 cal years BP by between 0.2-2 m to improve fit to Holocene sea-level data from the UK (Tables 6.2 and 6.5).

Table 6.5: Modifications to the ICE-3G model (globally averaged ice melt) which bring model predicted sea-level elevation closer to empirical data from Cleveland and Halifax Bays.

Time period (ka cal BP)	Shennan <i>et al.</i> (2006) modifications (meltwater reduction in ICE-3G model)
7	-1 m
6	-2 m

Time period (ka cal BP)	Shennan <i>et al.</i> (2006) modifications (meltwater reduction in ICE-3G model)
5	-1 m
4	-0.5 m
3	-0.2 m

Lowering the meltwater signal by up to 3 m at 6000 cal BP and 0.4 m at 3000 cal BP changes the shape of the sea-level curve and amplitude of the high stand in Cleveland and Halifax Bays and fits most earth models better to the observations, although the degree to which the high stand is lowered by meltwater modifications depends on the earth model used (Figure 6.9 B). The earth model with a high lower mantle viscosity and meltwater modifications suggested by Shennan *et al.* (2006), which fit near-field sea-level data from the UK also provide the best fit of Milne *et al.*'s (2005) models to sea-level data from Cleveland and Halifax Bays (black dot dash on Figure 6.9 B). However, further analysis is required to explore whether a higher temporal resolution would bring observations and predictions closer together during the period when sea level first rose above present, and whether the ice model needs further modification to predict the long period of relatively stable sea level during the late Holocene suggested by the empirical data (Figure 6.9 B).

Summary

New and recalibrated sea-level index points from Cleveland and Halifax Bays add definition to the shape and amplitude of the mid Holocene high stand, supporting the theory of continued ice melt through the late Holocene, possibly from Antarctica. Before tuning, Milne *et al.*'s (2005) ice model over-estimates the volume of melt through the mid Holocene, but the final solution with ice melt ending at 5000 cal BP does not predict fully relatively stable sea-level above present in the late Holocene shown by the data. Nakada and Lambeck's 1989 model underestimates the volume of melt, and increased melt during the last 4000 years may bring this model closest to the empirical data.

6.2.5 Holocene history of the other parts of the North Queensland coast

Recalibrating sea-level index points from the whole of North Queensland through the Holocene allows comparison of Holocene relative sea-level change along this long

coastline (Figure 6.2). However, despite the apparent amount of data available (Tables 2 and 3 in Volume 2), much of it is not precise, and there are gaps in the record at crucial times through the mid/late Holocene (Figure 6.2).

In the northern part from Torres Strait to Cairns (approximately 1400 km) sea-level index points are either from coral cores or coral micro atolls. There are only 40 re-calibrated index points available from this whole region, which reflects its remoteness (Figure 6.2 A). Cored coral has poor precision and I rely on 19 coral micro atoll index points to deduce the mid/late Holocene sea-level curve (there is no reliable sea-level data available before 6900 cal years BP) (McLean *et al.*, 1978; Chappell *et al.*, 1982; Chappell *et al.*, 1983). Micro atoll data shows sea level was already 0.5-1.2 m above present between 6900-6700 cal BP, reaching a peak of ~1.5 m above present around 5000 cal BP. Sea level remained between 0.5-1.5 m above present until at least 1000 cal years BP before falling to present. Nakada and Lambeck's 1989 model (red line on Figure 6.2 A) predicts sea level reached 2 m above present between 6900-6700 cal years BP and Chappell's model predicts maximum sea level at 1.2 m above present around 6300 cal years BP (black line on Figure 6.2 A). The empirical data indicate the peak of the high stand was slightly lower and later, at ~1.5 m above present around 5000 cal years BP, with a prolonged period in the late Holocene with sea level relatively stable above present. Nakada and Lambeck's model predicts the shape of the sea-level curve closer to Zone II than Zone I (Figure 6.8 D), which fits closer to the sea-level data, but Chappell's model suggests linear decline in sea level after the high stand.

The central area from Cairns to Mackay covers a coastline 742 km long, with the vast majority of relatively precise sea-level information in North Queensland. However, there are few precise index points during the early/mid Holocene, especially between 8000-6500 cal BP when sea level first rose above present (Figure 6.2 B). The regional sea-level curve for central North Queensland is similar to that for Cleveland and Halifax bays described in Section 6.2.2.

The southern area from Mackay to Bundaberg (656 km) has very few index points, all derived from cored coral (Figure 6.2 C). They give a gross indication of sea-level change since 7900 cal years BP, indicating that sea level likely rose to ~4 m above present between 8000-7000 cal years BP, remaining above present until at least 1250 cal years BP. This is a tentative interpretation given the vertical error bars on each index point (Figure 6.2 C). Nakada and Lambeck's model suggests the highest high

stand in Queensland in this region, at up to 3 m above present at 6800 cal years BP, followed by near linear fall to present. I cannot test this model with empirical data due to the large error bars on sea-level reconstructions (Figure 6.2 C).

Geophysical model predictions (Chappell *et al.*, 1982; Nakada and Lambeck, 1989; Lambeck and Nakada, 1990; Lambeck, 2002) infer that sea-level histories along the North Queensland coastline should be relatively similar, with more variation across the continental shelf than along the coastline through the mid/late Holocene, which is backed up by the available sea-level data. All outer shelf index points are based on cored coral with poor precision (± 5 m at best – see section 6.2.1). This makes them ineffective sea-level indicators during the mid/late Holocene when sea-level change across the shelf was less than ~ 3 m. Establishing sea-level histories across the shelf is difficult, therefore it is not possible to precisely examine crustal levering across the shelf through the mid/late Holocene.

6.3 GENERAL ISSUES WITH SEA-LEVEL RECONSTRUCTIONS IN CLEVELAND BAY

6.3.1 *Precision of sea-level reconstructions*

The summary band on Figure 6.5 is relatively imprecise during the late Holocene because of differences in elevation estimates between indicators and between sea-level index points created from single cores (e.g., up to 1.5 m height difference over 35 years in Cocoa Creek Core 14 and up to 1 m height difference between similar aged samples at Cocoa and Alligator Creeks (Figure 6.5)). Some authors suggest episodic late Holocene sea-level change occurred along the east coast of Australia (Baker and Haworth, 2000b; Baker and Haworth, 2000a), but even where there are relatively large elevation differences within and between-cores, vertical error bars overlap and there are no positive tendencies in reconstructions after 5400 cal years BP. Lambeck's (2002) geophysical model predicts no rapid or abrupt changes in sea level (of more than 0.5 m) during the past 6800 cal years around the Australian coastline, and I believe vertical fluctuations over short time periods are not evidence of rapid sea-level change. I infer from the summary curve relatively stable sea level between 5400-3000 cal years BP with relatively slow sea-level fall from the peak starting prior to 3000 cal years BP.

In the central North Queensland coastline as a whole, sea-level index points developed from mangrove indicators (Belperio, 1979; Grindrod and Rhodes, 1984; Pye and

Rhodes, 1985; Larcombe *et al.*, 1995; Larcombe and Carter, 1998) show consistently lower elevation during the mid/late Holocene than other indicators (Figure 6.2 B). All models of late Holocene sea-level change on this coastline infer relative sea level above present between at least 6000-2000 cal years BP, but some mangrove indicators suggest sea level below present during this period (Chappell *et al.*, 1982; Nakada and Lambeck, 1989; Lambeck and Nakada, 1990; Lambeck, 2002) (dark blue index points on Figure 6.2 B). This may be due to poor elevation control (e.g., levelling to national datum), but consistently lower elevations by different studies in a range of locations suggest compaction as the overarching cause of lower sea-level estimates from mangrove sediments. This may account for the large scatter in sea-level index points based on buried mangrove facies in Cleveland Bay between 10200-7200 cal years BP (Figure 6.5).

Studies in other parts of northern Australia find a similar elevation disparity between sea-level indicators based on mangrove and other indicators (e.g., between raised beach and mangrove indicators in Northern Territory (Nott, 1996), and between coral micro atolls and mangrove deposits in Princess Charlotte Bay, North Queensland (Chappell, 1987)). Compaction may explain the lack of mangrove evidence in Bowling Green Bay for sea level more than 1 m above present during the late Holocene (Belperio, 1979), which has been presented as 'negative evidence' for a mid Holocene high stand. This study caused controversy because at the time coral and micro atoll evidence from adjacent islands showed sea level at least 1 m above present between 3800-3200 years BP (Hopley, 1980), and today there is overwhelming evidence for a mid-late Holocene high stand. This may have implications for new reconstructions where there are mangrove muds beneath minerogenic sediments in the stratigraphic sequence. However, this is only the case at Cocoa Creek, and reconstructions from minerogenic sediments stratigraphically above mangrove muds are not consistently lower than from other cores or proxies (Figure 6.5).

6.3.2 Sediment reworking

A problem found with all cores is out of sequence radiocarbon dates in the bottom half of each sedimentary sequence. However combining information from a range of sources, including radiocarbon dated foraminifera, foraminifera-based sea-level reconstructions and lithostratigraphy gives an enhanced picture of environmental change through the Holocene in Cleveland Bay.

Figure 6.10 shows sea-level index points from Cleveland and Halifax Bays, but I also add sea-level index points from each core based on the lithostratigraphic contact between organic-rich and minerogenic sediments (starred on Figures 5.16-5.19). I infer the indicative meaning of this contact as approximately -0.18 m AHD (+/- 0.4 m) from modern environments in Cleveland Bay (Figures 4.1 and 4.2), and assume a linear sedimentation rate between the lowest/highest radiocarbon date and the contact. Table 6.6 explains the evidence for reworking, erosion or changes in sedimentation rate in each core inferred by lithostratigraphic index points and their position on the sea-level curve for Cleveland/Halifax Bays (Figure 6.10).

Table 6.6: Evaluation and interpretation of evidence from lithostratigraphic index points from cores at Cocoa and Alligator Creeks.

Core	Base or top of sequence?	Evidence	Possible interpretations
Cocoa Creek Cores 7 and 14 (Figures 5.16 and 5.17)	Upper limit of lower organic unit	Elevation of index points do not fit with general curve of sea-level change (Figure 6.10)	1. Whole of lower part of sequences were reworked post deposition. 2. Erosion occurred between contacts and basal dates (no visual evidence for this in lithostratigraphy) 3. Sedimentation rate between the top of the organic units and the bottom dates may be much slower than assumed, so index point provides minimum age for the contact
Cocoa Creek Cores 7 and 14 and Alligator Creek core 10 (Figures 5.16, 5.17 and 5.19)	Lower limit of upper organic unit	Elevation of index points do not fit with general curve of sea-level change (Figure 6.10)	1. Erosion of upper shell-rich minerogenic horizons prior to mangrove development 2. Sedimentation rate between the top dates and the bottom of the organic units may be much slower than assumed, so index point provides maximum age for the contact
Alligator Creek Core 1 (Figure 5.18)	Lower limit of upper organic unit	Elevation is slightly low but within the error terms of the reconstructions (Figure 6.10)	1. No erosion occurred through the regressive sequence prior to mangrove development 2. Sedimentation rate between top date and bottom of organic unit is correctly inferred by a linear rate upwards from this date

Evidence in Table 6.6 suggests the minerogenic lower intertidal/shallow subtidal material in all cores from Cleveland Bay may not represent sedimentation through the whole mid/late Holocene. At Alligator Creek, organic material is absent from the base of both cores. If minerogenic sediments in these cores represent environmental change from the exposed Pleistocene surface through the mid Holocene transgression and regression, I would expect a unit of mangrove-derived organic silt on top of the Pleistocene surface before minerogenic sedimentation started (as seen in Cocoa

Creek cores). Its absence suggests erosion of organic material may have occurred during transgression, which fits with a young age at the base of Alligator Creek Core 10 (3350-3470 cal years BP), although the basal age in Alligator Creek Core 1 (6730-6890 cal years BP) fits better with the transgressive sea-level curve in Figure 6.5.

Although lithostratigraphic index points suggest changes in sedimentation rate, erosion, or reworking in basal and upper sections of sediment cores, a more significant problem is out of sequence radiocarbon dates in the middle minerogenic part of core sequences. Out of sequence radiocarbon dates may be due to large-scale reworking of low intertidal/shallow subtidal sediments (suggested in Table 6.6). Alternatively they may arise if the foraminifera in the sediments which are used to extract sea level and age information are reworked. I try to address the issue of potential foraminifera movement within sediments in Section 5.3 using paired samples of foraminifera and bivalve shells. Unfortunately the experiment is flawed because I do not know the life habitat of the bivalve shells dated, which are unarticulated and may be reworked or live infaunally. Therefore I cannot test whether foraminifera give the true age of a sediment body even where large-scale reworking is unlikely (despite this problem other studies use foraminifera as sea-level height and age indicators (Edgecombe *et al.*, 1999; Horton *et al.*, 2000)).

A potential mechanism for large-scale reworking is due to wave-base migration during the early/mid Holocene transgression. Alternatively, episodic reworking may be due to isolated high impact cyclone events, as the Cleveland Bay chenier plain provides sedimentary evidence of a series of cyclones during the mid/late Holocene (Figure 5.3 and 6.7). Figure 6.11 shows conceptually how large-scale reworking may occur during transgression as the wave base moves progressively shorewards if intertidal/shallow subtidal sediments are not quickly submerged beneath marine sediments (Demarest and Kraft, 1987; Larcombe and Carter, 1998). This sediment body is buried during regression under intertidal and shallow subtidal sediments which are not reworked by wave-base erosion. Both reworked (transgressive) and non-reworked (regressive) sediment bodies will be similar in terms of particle size and foraminiferal distribution as they are formed in similar environments. The process of transgression may have reworked low intertidal and shallow subtidal sediments in Cleveland Bay into 'bay-fill sediments' during rising sea level in the mid Holocene. However, some out of sequence radiocarbon ages are during the period of relatively stable sea level at 1-2.8 m above present, as recently as ~2900 cal years BP (Alligator Creek Core 1 (Figure 5.18)) when transgression-induced wave-base erosion would not have occurred. This

suggests that both mechanisms suggested above and potentially others not considered may have caused reworking in sediment cores.

This problem does not occur in other transfer function studies because reconstructions are generally limited to upper intertidal environments above MTL, which are less likely to be affected by wave-induced sediment mixing or the effects of tropical cyclones. If there were visual signs of reworking in the minerogenic horizons of cores from Cleveland Bay I would have avoided these sections when deciding on environments and sections of core to reconstruct sea-level change from. Reworking is not obvious from particle size distributions or qualitative examination of foraminiferal assemblages in these horizons (Figures 5.6-5.9), and is only shown by radiocarbon dating. This highlights a limitation of using minerogenic low intertidal/shallow subtidal sediments for sea-level reconstructions.

6.4 ISSUES WITH USING FORAMINIFERA AS PROXY INDICATORS IN THIS LOCATION

6.4.1 *Disappearance of agglutinated foraminifera down core*

Rapid disappearance of agglutinated foraminifera below the top 1 cm slice of mangrove sediment is documented by several authors working in tropical and sub tropical mangrove environments (Puerto Rica, Culver, 1990; South Georgia, USA, Goldstein and Watkins, 1999; Northern Territory, Australia, Wang and Chappell, 2001; French Guiana, Debenay *et al.*, 2002; Debenay *et al.*, 2004; southeastern USA, Tobin *et al.*, 2005), although agglutinated foraminifera from a sub-tropical mangrove environment are preserved in pre-Holocene sediments in Trinidad (Saunders, 1958). Agglutinated foraminiferal tests are made up of grains cemented by an organic tectin or acid mucopolysaccharide cement, which is soluble in hydrogen peroxide or sodium hydrochlorite (Lipps, 1973). However there are few investigations into how and why this organic cement also dissolves beneath the surface of many tropical mangrove sediments. Tobin *et al.* (2005) suggest that aerobic rather than anaerobic conditions combined with raised temperature in mangrove sediments causes bacterial oxidation and degradation of this organic cement. They suggest two possible scenarios causing aerobic conditions in mangrove sediments: 1.) bioturbation by fiddler crabs 2.) relative sea-level transgression and regression 6000-4000 years ago exposing mangrove sediments to the air (theory developed in response to sea-level changes on the eastern seaboard of the USA).

In cores taken from Cleveland Bay both upper and lower organic units contain no agglutinated foraminifera (Figures 5.6 and 5.7). Scenario 2 may be a mechanism to explain absence of agglutinated foraminifera in upper organic units (between 60-100 cm below the surface) as late Holocene regression exposed mangrove deposits before burial by modern salt pan sediments. However, this does not explain why the lower organic sections of cores do not contain agglutinated foraminifera. More plausible is scenario 1 that fiddler crabs promote bacterial oxidation below the sediment surface, as modern fringing mangroves within Cleveland Bay are home to millions of fiddler crabs which disturb the sediment surface and are known to burrow to at least 30 cm deep in mangrove environments (Grindrod, 1988) (Figure 6.12 shows photographs of the effect of fiddler crabs on the sediment surface in different mangrove zones at Cocoa Creek). However species of fiddler crab also live in intertidal areas as far as 40° N and S where agglutinated foraminifera are preserved below the sediment surface (Culver and Horton, 2005; Tobin *et al.*, 2005). It is likely that agglutinated foraminifera disappear in tropical mangrove environments due to a number of interrelated factors including burrowing by fiddler crabs and molluscs, increased air and water temperature, biological turnover and predation (Sen Gupta, 1999).

I cannot investigate in this study how and why agglutinated foraminifera disappear from mangrove sediments in Cleveland Bay. However, the impact of this process means that all my fossil cores contain no agglutinated foraminifera. This is a fundamental limitation of using foraminifera to reconstruct sea-level change in this tropical environment. Most recent studies in temperate areas use high marsh foraminifera faunas with narrow zonation in transfer functions to reconstruct relative sea-level change with small error terms (see Table 6.3). However, I must use calcareous assemblages which exist from ~MTL downwards to reconstruct sea-level change.

6.4.2 Environmental parameters affecting intertidal and subtidal foraminiferal assemblages

Studies using fossil foraminifera from environments below MTL are rare (e.g. Hardbattle, 2004), largely because tidal current and wave transport of tests occurring in unvegetated intertidal and shallow subtidal environments is thought to give each assemblage a broader elevation zonation than in vegetated upper intertidal environments (Hayward *et al.*, 2004b), and also because agglutinated upper intertidal foraminifera are well preserved in fossil sediments from temperate locations. Subtidal foraminiferal assemblages respond to a range of environmental variables including availability of light, nutrients and temperature, not investigated in this study (Sen Gupta,

1999). There is also the issue of mixing by waves and currents, especially in estuaries where exotic marine species are introduced in suspension, and are often very small, thin walled species which are distinct from larger indigenous species (Wang and Murray, 1983).

The percentage of variance in foraminiferal assemblages explained by elevation from two sites in Cleveland Bay is low (12.5 %) and total variance explained is 61 %, compared to a study of foraminiferal distributions between MTL and HAT around the UK where 32 % of total variance is explained by elevation, and all environmental variables investigated account for 76 % of total variation (Horton and Edwards, 2006) (Figure 6.13). If only samples above -0.2 m AHD (30 cm below MTL – 13 samples) in Cleveland Bay are included the percentage variance explained by elevation increases to 17 % and the total variance explained decreases to 59 %, which are still low compared to figures from the UK (Figure 6.13). This shows that in this tropical mangrove environment there must be more factors (some of which are not quantified in this study) controlling foraminiferal distribution than in temperate salt marshes studied in the UK, and elevation alone controls less variance. However, Pearson's correlation coefficient between environmental variables shows elevation is positively correlated to LOI, % clay fraction and salinity (Table 4.1), which explains some of the 24-37 % of intercorrelation between variables (Figure 6.13). Although the unique contribution of elevation in explaining variance is lower than in temperate locations, it is still the single most important sampled environmental variable governing foraminiferal distribution.

Unexplained variance is the same whether using a long environmental gradient (whole data set – 69 samples) or a short one (samples above -0.2 m AHD only – 13 samples), which infers that environmental factors not investigated in this study affect tropical foraminiferal distributions throughout the elevation range from upper intertidal to subtidal environments, and the total effect of unexplored environmental factors does not increase with decreased elevation. Unexplored environmental variables may include temperature, nutrient availability, oxygen conditions, degree of mixing, seasonal or small scale spatial variations in foraminiferal assemblages or random variation (Scott and Medioli, 1980a; Jennings *et al.*, 1995; Sen Gupta, 1999; Horton and Murray, 2006).

Temperature may be an important variable in the tropical intertidal zone where ponded water and sediments exposed during low tide are heated by the sun, whilst dissolved oxygen conditions fluctuate in the intertidal zone during each tidal cycle (Sen Gupta,

1999; Debenay *et al.*, 2002). Over a longer timescale the living population varies substantially in mid-high temperate intertidal environments through the year due to seasonal variation in reproduction of individual species (Scott *et al.*, 2001; Horton and Edwards, 2003), although I try to account for this by taking modern samples at the same time during the year and using dead assemblages which most closely represent fossil populations found in cores (Murray, 2000). Scott and Medioli (1980a) show local spatial variability occurs but does not exceed the difference between assemblages in distinct environments in temperate salt marshes. Alternatively, the unexplained variance could be due to natural random variation in the foraminiferal species populations. However, most of these variables also exist in temperate marshes where unexplained variance is ~24 % (Figure 6.13) (Horton and Edwards, 2006). The most likely cause of unexplained variance is sediment and water temperature variations caused by tropical climate, which also affects nutrient availability (Debenay, 2002).

A study by Hardbattle (2004) investigates foraminiferal assemblages between -4.2 and -48 m AHD in and around Cleveland and Bowling Green Bays, showing a distinct change around -10 m AHD between estuarine and shelf benthic species and an assemblage dominated by larger rotaliid foraminifera which inhabit a wide depth range in warm, clear, nutrient deficient seas (Sen Gupta, 1999). This distinct change in assemblage may represent the lowest elevation where foraminifera respond to environmental variables such as elevation, pH, loss on ignition, salinity and particle size variations. Beyond this depth larger foraminifera, which tolerate depth ranges of 10s of metres become dominant (Hardbattle, 2004).

6.4.3 *Matching between modern and fossil foraminiferal assemblages*

The relationship between modern and fossil foraminiferal assemblages, assessed using MAT is relatively poor compared to other studies of foraminiferal assemblages in temperate environments (33 % of fossil samples have poor modern analogues (Table 6.7)). However, none of these other studies have out of sequence radiocarbon dates within the sediment cores used for fossil foraminiferal analysis. When I exclude fossil samples from horizons interpreted as reworked, the percentage of fossil samples with poor modern analogues falls to 14 %. This is similar to the number of samples with poor analogues in some other studies and means reconstructions in this study are equally valid as those from other studies (Table 6.7). There is also a degree of correlation between reworking (identified by out of sequence radiocarbon ages) and a high MAT-predicted dissimilarity coefficient, but this is not a general rule that can be used to indicate reworking.

Table 6.7: Comparison of percentage of fossil samples with good analogues between this and other foraminifera-based studies in temperate locations.

Authors and location	Number of samples in modern training set	% of fossil samples with poor modern analogues
This study	62 modern samples	33 % of all samples, 14 % if excluding samples in reworked horizons
(Horton and Edwards 2005) North Norfolk, UK.	Local training set – 47 samples Regional training set (UK wide) – 160 samples	Local training set – 60 % Regional training set – 0 %
(Edwards and Horton, 2000) Poole Harbour, UK.	Regional training set (UK wide) – 160 samples Regional training set with calcareous taxa grouped together as 'dissolved' – 160 samples	Regional training set – 36 % Regional 'dissolved calcareous' training set – 12 %
(Edwards <i>et al.</i> , 2004b), Connecticut, USA.	Regional training set – 91 samples	0 %

Identifying modern environments to sample in order to improve analogue matching is not easy. Two issues are important; 1.) collecting material from a sufficiently long environmental gradient to incorporate the full range of environments each species inhabits, 2.) Ensuring the modern training set represents the majority of local spatial variability within that range. It is difficult to define the lower end of the environmental gradient represented by foraminifera in fossil cores because many species are present in modern samples from MTL to at least -5 m LAT, and there is no lithological distinction between intertidal and subtidal environments from core material. I took modern samples down to -7.16 m AHD (5.3 m below LAT), stopping here due to logistical issues and because I did not expect mid/late Holocene sediments to contain foraminifera from subtidal environments below -7 m AHD. Since it was not possible to sample to the ends of the environmental gradient represented by the foraminiferal assemblages found in fossil cores I had to use a degree of *a priori* knowledge of the environments likely to be found in fossil cores as there was no other objective criteria to limit sampling elevation.

My training set is relatively small compared to those in other studies where analogue matching is good (Table 6.7). Reconstructed palaeo-surface elevations for fossil samples without modern analogues are well within the elevation range of the modern training set and fit together within general trends from samples with modern analogues (Figures 5.16-5.19). Therefore, samples without modern analogues appear to represent natural spatial variability I did not have time to sample within the modern elevation range. If I were to increase the size of the modern training set, the percentage of fossil samples with good modern analogues would likely increase.

6.4.4 Elevation errors in foraminifera-based reconstructions

Total elevation errors are relatively large compared to foraminifera-based studies in temperate locations (Horton *et al.*, 1999b; Horton *et al.*, 2000; Gehrels *et al.*, 2001; Edwards *et al.*, 2004a; Edwards *et al.*, 2004b; Gehrels *et al.*, 2005), but errors are comparable to those of other indicators used in North Queensland (Table 6.1). This is because diversity and vertical range of foraminiferal populations increases as the environment attains greater stability (i.e. more oceanic) in low intertidal and shallow subtidal environments (Scott *et al.*, 2001). When comparing RMSEP error between this and other foraminiferal studies it is important to note that only one other study is from a tropical mangrove environment but my present study covers by far the largest elevation range (Table 6.8). Comparing the 2 σ RMSEP error (rarely quoted in papers on developing transfer functions) to the vertical range of the modern training set indicates the RMSEP error in this study is relatively low given the length of the environmental gradient (Table 6.8). This study shows that transfer function reconstructions are possible from low intertidal and shallow subtidal tropical environments, and their error terms are not proportionately larger than using the same technique in upper intertidal, temperate locations.

Table 6.8: Transfer function errors from this and other foraminiferal studies

Authors and location	Notes on environment and vertical range	Transfer function method	Vertical range of environmental gradient	RMSEP error (2 σ) (+/- m)	RMSEP error as % of vertical range
This study	Agglutinated and calcareous foraminifera between -3.94 m LAT and MHWST	WA PLS	8.31 m	0.81	9.7%
(Horton <i>et al.</i> , 2003) North Queensland,	Mainly agglutinated foraminifera	WA PLS	2.11 m	0.14	6.6 %

Authors and location	Notes on environment and vertical range	Transfer function method	Vertical range of environmental gradient	RMSEP error (2 σ) (+/- m)	RMSEP error as % of vertical range
Australia.	between MLWNT and just below HAT				
(Horton <i>et al.</i> , 1999b; Horton <i>et al.</i> , 2000) various sites in the UK.	Agglutinated and calcareous foraminifera between MTL and HAT	Weighted Averaging	4.11 m	0.59	14.4%
(Gehrels <i>et al.</i> , 2001) various sites in the UK.	Agglutinated and calcareous foraminifera between MHWNT and HAT	Partial Least Squares	3.2 m	0.16	5 %
(Edwards <i>et al.</i> , 2004a; Edwards <i>et al.</i> , 2004b) Connecticut, USA.	Agglutinated foraminifera between MHWST and HAT	WA PLS	0.80 m	0.26	32.5 %
(Gehrels <i>et al.</i> , 2005) Nova Scotia, Canada.	Agglutinated foraminifera from 0.58 to 0.86 m above MTL	WA Tolerance downweighted	0.28 m	0.11	39.2 %

6.4.5 Age errors and the marine reservoir effect

Abundant in situ calcareous foraminifera make good AMS radiocarbon dating material for new reconstructions. However, it is difficult to know whether foraminifera are in situ because assemblages and particle size distributions may not change when reworked. I picked between 500-1000 clean, whole foraminifera from sediments at each 1 cm thick level dated, avoiding any abraded or broken specimens. Counting multiple species and foraminiferal sizes (including juvenile and adult specimens) allows an average date estimation from each layer. Duplicated dates from different foraminiferal samples from the same layer indicate this method is acceptable (see results in Section 5.3). An AMS date on between 500-1000 foraminifera from a 1 cm thick slice (with an assemblage which appears to be in situ within the lithology of the core) may be less likely to be reworked by bioturbation (crabs and molluscs in the intertidal/shallow subtidal zone) than a date on a single bivalve shell with an unknown modern distribution, however I have not proved this conclusively in this study. If large scale reworking of sediment occurs both bivalve shells and foraminifera are likely to be reworked.

Because it is not clear from particle size data or foraminiferal assemblages that foraminifera in the reworked horizons are mixed, this is a potential limitation of using calcareous foraminifera as dating material. However, once a pattern of reworking is identified in several cores by age reversals this may indicate horizons of other cores where radiocarbon dating would be unproductive. AMS radiocarbon dating of *in situ* foraminifera does provide a reliable chronology for the majority of sediments with sea-level reconstructions in this study, despite the limitations outlined above.

Dated marine shells and foraminifera are usually calibrated to atmospheric ^{14}C levels using a marine reservoir correction factor (Stuiver *et al.*, 1998). The deep oceans are depleted in ^{14}C relative to the atmosphere, but the surface ocean has a ^{14}C level intermediate between these two reservoirs. This intermediate level is caused by variable mixing in the surface ocean of much older ^{14}C from deep ocean water masses (where radioactive decay has occurred) with modern ^{14}C from the atmosphere. The result is an 'apparent' age for marine organisms (compared with terrestrial organisms) which varies around the world, depending on the proximity to areas of deep ocean water upwelling and local oceanographic factors (Stuiver *et al.*, 1998).

The commonly used correction factor for open Australian waters is 450 $\pm$ 35 years (Gillespie and Polach, 1979), with more recently a correction for Queensland waters of 410 years $\pm$ 7 years (Ulm, 2002). However, intertidal and shallow subtidal foraminifera and marine shells may not be exposed to the same level of mixing with deep ocean water masses as open water (deeply-subtidal) foraminifera or shells. Northeast Australia has a broad, shallow continental shelf which mitigates the influence of ^{14}C -depleted deep ocean upwelling by ensuring mixing through wave and current action (Ulm, 2002). Therefore, shallow subtidal foraminifera and shells on the Great Barrier Reef shelf may not exchange with deep ocean reservoirs and may not require the full oceanic water correction. Also of concern is marine reservoir correction of intertidal foraminifera which are exposed during part of the tidal cycle, and are likely to have a ^{14}C age closer to the expected coeval terrestrial sample age. For both shallow subtidal and intertidal foraminifera and shells in northeast Australia the marine reservoir correction factor of 410 years may be invalid.

Past studies elsewhere in the tropics (where there is no broad, shallow continental shelf) have used coral which exist at and below Mean Low Water of Spring Tides (MLWST) to calculate local and regional marine reservoir effects (e.g. Cocos Keeling Islands, Indian Ocean, Hua *et al.*, 2004). This work implies that organisms living up to

MLWST take up carbon from old sources at the same rate as open ocean organisms. However, few studies have investigated the effect of old carbon on organisms which live subtidally on the shallow Great Barrier Reef continental shelf or higher in the tidal frame. Calcareous foraminifera and bivalves live up to Mean Tide Level but are often classified as 'marine', and are corrected for old carbon accordingly. Sea-level studies often apply an open water marine reservoir correction factor to radiocarbon-dated intertidal foraminifera (e.g. Horton *et al.*, 2000; Horton and Edwards, 2005). This is potentially overestimating its effect. Although this is an issue which needs to be addressed because the marine reservoir correction adds a potentially large error estimate to sea-level reconstructions (Edwards and Horton, 2006), given the enormity of the task it is beyond the scope of this study. I have therefore decided not to correct any radiocarbon dates from intertidal or shallow subtidal material for the marine reservoir effect, and error bars on radiocarbon dates do not reflect this uncertainty. This means the calibrated age of all sea-level index points using intertidal calcareous material for dating may be underestimated by up to 410 years. This is a topic for future investigation which is becoming increasingly important as transfer functions allow reconstructions in environments where calcareous foraminifera are the only reliable in-situ material for dating.

6.5 TRANSFER FUNCTION METHODOLOGICAL CONSIDERATIONS

6.5.1 *Removing samples from the modern training set*

Training set screening removes samples or species that have the potential to produce erroneous reconstructions. It is inevitable that some samples in a large training set show a poor statistical relationship with elevation, due to the influence of other environmental variables, taphonomic issues, natural variability or human error. Modern samples poorly related to elevation can decrease the ability of the transfer function to estimate species coefficients and affects reconstructions (Gasse *et al.*, 1995). It is common to remove samples with an absolute residual (observed minus predicted) greater than the standard deviation of elevation in the training set (Jones and Juggins, 1995; Horton and Edwards, 2006), or those with an absolute residual greater than one quarter of the total range of the elevation gradient (Gasse *et al.*, 1995).

Figure 6.14 shows the final transfer function model used to reconstruct sea level in this study. One sample is an outlier, with a residual value of 1.677 m. In Section 5.4.2 I

decide to leave this outlier in the training set because it may reflect natural variability in foraminiferal assemblages. Its residual is very close to 1 standard deviation of the elevation gradient (1.673 m) and one quarter of the elevation gradient (1.679 m). Because there is only one outlier and it is close to the threshold I could take it out of the training set, resulting in a 4 cm decrease in RMSEP and slight increase in r^2 value (Table 6.9). Although transfer function error constitutes the majority of total error in transfer function reconstructions (see Section 5.5.2), artificially dampening what may be natural variability in the modern training set would be wrong, giving an over-optimistic estimate of the transfer function model's predictive power. As this outlier is not beyond the thresholds used by others I cannot justify removing it. However, this does raise the issue of over-estimating the predictive power of transfer functions by removing modern training set samples. Only where ecological information indicates outliers are influenced by other processes (e.g., disturbance and human activity in upper salt marsh samples (Edwards *et al.*, 2004b)) can those samples be removed. Some authors justify removing outlying low intertidal/shallow subtidal samples because they may be more susceptible to reworking and disturbance by biological activity (Edwards *et al.*, 2004b; Horton and Edwards, 2006). However, it is difficult to prove that outliers from low intertidal/subtidal environments are due to reworking or taphonomic processes and not natural variability in these environments, where foraminifera still respond to elevation but have wider environmental tolerances. For this reason it is unwise to remove outlying training set samples from the environments where reconstructions may occur.

Table 6.9: WA-PLS model performance measures for two models of foraminiferal assemblage composition: reduced all data model and reduced all data model with 1 outlier removed. Components highlighted in yellow give the minimal adequate models.

Model	Component number	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias
Reduced all data model All agglutinated and calcareous foraminifera with samples below - 5.8 m AHD removed (62 samples) Gradient length 3.05 SD units	1	0.70	0.94	1.88	-0.02
	2	0.93	0.48	0.61	0.01
	3	0.95	0.41	0.51	0.01
	4	0.95	0.43	0.44	0.02
	5	0.95	0.43	0.44	0.02

Model	Component number	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias
Reduced all data model with 1 outlier removed All agglutinated and calcareous foraminifera with samples below - 5.8 m AHD (61 samples) Gradient length 3.05 SD units	1	0.72	0.91	2.02	-0.02
	2	0.94	0.43	0.65	0.01
	3	0.96	0.37	0.43	0.02
	4	0.96	0.38	0.45	0.02
	5	0.96	0.40	0.45	0.04

6.5.2 Assessing transfer function reliability

Statistical measures and Modern Analogue Technique (MAT) give a good indication of the internal consistency and reliability of reconstructions using a transfer function model. However, it is also useful to gauge reconstruction reliability by examining the extent results are reproduced by different methods or independent models. In the absence of other modern training sets or replicate cores from close to those in this study one way I can assess reliability is to compare results using an independent transfer function method, as well as investigating alternative cut-offs (other than MAT minimum dissimilarity coefficient) to assess matching between modern and fossil assemblages.

Reconstructions using the Maximum Likelihood transfer function method

Theoretically, Maximum Likelihood (ML) regression and calibration provides the most statistically rigorous transfer function approach for environmental reconstruction (Birks, 1995). Unimodal response curves fitted for each species using logistic regression determine jointly what biological composition and occurrences are expected at each elevation. This models disjoints in the distribution of each species along the elevation gradient as smooth unimodal curves, then calculates the probability of each elevation occurring with a given biological assemblage over the range of possible elevation values (pers comm. Juggins, 2005). The elevation with the highest probability is the ML estimate (Birks, 1995). This approach fits symmetric unimodal curves to each species but some species in my modern training set have skewed or stepped distributions along the elevation gradient (Figure 4.13).

Table 6.10: Maximum Likelihood and Weighted Averaging Partial Least Squares performance measures for a model of foraminiferal assemblage composition with agglutinated and calcareous foraminifera and all samples below -5.8 m AHD excluded.

Model/Method	Boot-Strapped r^2	RMSEP (m error)	Maximum Bias	Average Bias
Maximum Likelihood Reduced all data model	0.92	0.52	0.71	0.09
Component 3 WA PLS Reduced all data model	0.95	0.41	0.51	0.01

Performance measures show ML performs slightly poorer than WA PLS using the reduced all data model (Table 6.10). Calibrated transfer function results for each core using ML compared to WA PLS (Figure 6.15) show general agreement of reconstructions between methods in each core. There is no systematic offset between reconstructions apart from in Alligator Creek Core 10, where ML reconstructions are always at a higher elevation than using WA PLS. Most ML reconstructions are within the 1σ transfer function error term using WA PLS (Figure 6.15). These results give increased confidence that reconstructed palaeo-surface elevations using WA PLS are accurate, but in the same way that WA PLS always produces a result, ML does not indicate whether fossil samples have modern analogues and whether reconstructions are a true reflection of assemblage composition.

Modern Analogue Technique

Modern Analogue Technique is a technique for reconstructing a past environmental variable from modern microfossil assemblages, but in this study its main aim is to provide a statistical cut off for assessing a good match between modern and fossil foraminiferal assemblages and, therefore, reliability of transfer function reconstructions (see sections 3.3.4, 4.3.2 and 5.5.1). Since the cut off is calculated using dissimilarities between all samples in the modern training set, removing samples (e.g., those dominated by agglutinated taxa in the dissolution and reduced dissolution models) may decrease the value of the largest minimum dissimilarity, reducing the number of fossil samples with modern analogues. In Table 6.11 I compare minimum dissimilarity values using each model with data from Cocoa Creek Core 14, as this is the largest single core data set available. There are no agglutinated foraminifera in Cocoa Creek core 14 so I would expect the number of fossil samples with modern analogues not to change whether using the all data or dissolution model. However, Table 6.11 shows the number of samples with modern analogues actually decreases. When I remove samples from the base of the elevation gradient (in reduced all data and reduced

dissolution models), the largest minimum dissimilarity coefficient in the modern data and the number of fossil samples with modern analogues stays the same, indicating that removing samples from the base of the elevation gradient does not decrease the noise within the modern foraminiferal data. Using MAT to assess the validity of reconstructions may be influenced by the number of samples in the modern training set as well as the closeness of fit between modern and fossil samples.

Table 6.11: Modern Analogue Technique minimum dissimilarity coefficient results for each of the 4 modern data models explored in Chapters 4 and 5.

Model	Number of samples in modern data set	Largest Minimum dissimilarity coefficient in the modern data set	Number of samples in Cocoa Creek Core 14 within the largest minimum dissimilarity coefficient
All data	69	49.27	32
Reduced all data	62	49.27	32
Dissolution	62	38.70	21
Reduced dissolution	58	38.70	21

MAT is widely used to assess the match between modern and fossil samples because it is independent of WA PLS and ML and provides a statistically valid cut off to indicate similarity between modern and fossil samples, but it does have this limitation. Therefore, assessing whether MAT accurately estimates similarity between modern and fossil foraminiferal assemblages can only be tested by comparing results to other techniques described below which compare modern and fossil assemblages independent of MAT.

Bootstrapped sample specific errors (RMSE_S1)

Bootstrapped errors produced during each transfer function reconstruction consist of 2 parts; bootstrapped sample error, unique to each fossil sample (RMSE_s1). Calculated as standard error in estimating taxon coefficients (Birks, 1998) and bootstrapped transfer function model error (RMSE_s2).

The bootstrapped sample error (RMSE_s1) gives an indication of reconstruction reliability. Standard error in estimating coefficients for species in each fossil sample increases if species do not have modern analogues or if the analogues are not present in a large proportion of the modern training set. This error term is used in estimating

total reconstruction error (Section 5.5.2). However, it does not have an explicit method to determine a cut off error value for an acceptable reconstruction.

Goodness of fit measures

Birks (1998) suggests two simple measures of reconstruction reliability which are independent of all transfer function methods and are simple to compute:

- 1. Percentage of the total fossil assemblage that consists of taxa not represented in the training set.
- 2. Percentage of the total fossil assemblage that consists of taxa that are poorly represented (e.g., <10 % or <5 % occurrences) in the training set.

If many taxa in the fossil assemblage are not in the modern training set, or are present in very low numbers, the transfer function reconstruction is likely to be invalid because species coefficients of rare taxa are poorly estimated by the transfer function and result in high standard errors (Birks, 1998). Unlike MAT the techniques mentioned above also do not have an explicit method to determine a cut off value for an acceptable match and a reliable reconstruction. Goodness of fit results from all cores show virtually every taxa in fossil samples is present in the modern training set, but many fossil species are poorly represented in the modern training set (Table 6.12). This infers some samples will have unreliable elevation estimates.

Table 6.12: Goodness of fit measures for all fossil cores from Cleveland Bay.

Fossil core	(1) Maximum % of fossil sample not in training set	(2a) Maximum % of fossil sample poorly represented in training set (10 % occurrences)	(2b) Maximum % of fossil sample poorly represented in training set (5 % occurrences)
Cocoa Creek Core 7	6.7	58	29
Cocoa Creek Core 14	3.5	61	15
Alligator Creek Core 1	0.0	66	13
Alligator Creek Core 10	4.3	46	7

Comparing the three methods of assessing similarity described above shows some correlation between the techniques (Figure 6.16), but there is a relatively high level of disagreement between RMSE_s1 error and the goodness of fit measure (Figure 6.16 a). This confirms that assigning a cut off value using any technique and rejecting samples with a value above that cut off value is inappropriate. Each technique only

provides a general guide to the relative similarities between fossil and modern data which should be used in conjunction with other lithostratigraphic and ecological data to reject reconstructions which appear 'unreasonable'. This is an important result because until now the only widely used method of assessing dissimilarity and reliability of transfer function reconstructions is to use a percentile cut off value in MAT (Hamilton and Shennan, 2005; Horton and Edwards, 2005).

6.5.3 *Improving transfer function error estimates*

Total error of new sea-level reconstructions in this study is dominated by transfer function error (Table 5.17), which includes the sample specific bootstrapped error (RMSE_s1) and the bootstrapped transfer function model error (RMSE_s2). The bootstrapped transfer function model error (RMSE_s2) produced by the C2 program is a single error term, regardless of varying levels of scatter and precision in model reconstructions at different parts of the elevation gradient. In this study there are variations in reconstruction residuals with more scatter in predictions at lower elevations (Figure 5.13 and 6.14). This may be due to several factors; smaller number of samples in the training set at lower elevations, species with wider tolerances at lower elevations with poorly estimated coefficients and the edge effect of truncation of species responses within the model at low and high elevations. Therefore, I investigate here a method of splitting the elevation gradient up so that the model error term incorporated into total error for each fossil sample more accurately reflects true model error at the part of the elevation gradient where the fossil sample is reconstructed.

To maximise precision in reconstructions I use a running mean of residuals from 10 adjacent modern samples to calculate changing transfer function model error term along the elevation gradient (Figure 6.17 B). The model error term for each fossil sample can then be related to its position on a linear regression line through these mean error terms along the elevation gradient (Figure 6.17 B). I calculate a revised total transfer function error using bootstrapped sample errors generated by the transfer function (described in Section 4.11.1) and the new model error term, determined by predicted elevation using the equation of the regression line (Figure 6.17 B). Total reconstruction error of sea-level index points from Cocoa and Alligator Creeks generally decreases using a revised transfer model error term, by a maximum of +/- 22 cm (1350 and 1421 cal years BP in Alligator Creek Core 1 on Figure 6.18). This is because reconstructed elevations are in the top half of the elevation gradient (Figure 6.17 B). The C2 program overestimates model error for most reconstructions above - 3.01 m AHD (shown by the dashed red line on Figure 6.17 B for WA-PLS component 3

using the reduced all data model). However, regardless of improving transfer function error estimates the general curve of sea-level change inferred by the whole record from Cleveland and Halifax Bays does not change (Figure 6.5 and 6.18).

6.6 CHAPTER SUMMARY, RESEARCH QUESTIONS AND HYPOTHESES

In this chapter I compare relative sea-level change during the past 10,000 calibrated years from sediment cores and other sources in Cleveland and Halifax Bay, and re-evaluate sea-level change evidence from other parts of North Queensland. I also investigate the Holocene geomorphological history of Cleveland Bay, showing how the landscape differed from today during the Holocene high sea-level stand. This information allows me to answer below research questions set out in Chapter 1.8, which are the main research objectives of this study. In addition I evaluate the usefulness of calcareous foraminifera as proxy sea-level indicators and evaluate the foraminifera-based transfer function methodology used to create relative sea-level reconstructions. I suggest alternative ways of validating transfer function results and reducing transfer function error terms which may enhance the usefulness and precision of this technique.

Research Question 1: What indicators can be used in reconstructing relative sea-level change in North Queensland?

Research Question 1 a. Is it possible to define age, elevation and error terms for each type of indicator used in reconstructing relative sea level in this region (Coral, micro-atolls, encrusting oysters, sediments with and without microfossils)?

It is possible to define age, elevation and error terms for the range of proxy sea-level indicators used in north Queensland, despite limitations with individual proxies and the issue of the marine reservoir effect discussed in Sections 6.2.1 and 6.4.5. Re-calibrating sea-level data gives a more accurate but less precise estimate of Holocene sea-level history on this coast, taking into account true age and elevation errors of each indicator used. Coral micro-atolls are by far the most accurate and precise indicator used on this coast. They provide reconstructions from northern and central areas covering isolated episodes during the period from 7000 cal yrs BP to present. Encrusting oysters are also relatively precise indicators which provide excellent relative sea-level reconstructions where they are preserved. Foraminifera-based reconstructions are less precise than either coral micro-atolls or encrusting oysters, but

there is greater potential to create reconstructions from a range of coastal locations where micro-atolls or oysters may not be present or preserved.

Research Question 1 b. Are microfossils abundant and readily preserved?

Foraminifera are abundant in surface and shallow fossil sediments in Cleveland Bay. Calcareous foraminifera are readily preserved, showing little difference in assemblages between surface and shallow fossil assemblages, but agglutinated foraminifera are removed from sediments beneath the surface and are absent from fossil cores collected in Cleveland Bay.

Research Question 1 c. Are microfossil assemblages controlled by elevation?

Elevation is not the only controlling variable on foraminiferal assemblages in Cleveland Bay, but it is the most important variable measured.

Research Question 1 d. Is there a good relationship between modern and fossil microfossil assemblages?

There is a good relationship between modern and fossil foraminiferal assemblages, which is comparable to that found in other foraminifera-based studies in temperate locations (see Table 6.7).

Research Question 1 e. Can fossil sedimentary sequences provide quantitative reconstructions of sea-level change?

Fossil sedimentary sequences provide quantitative reconstructions of mid/late Holocene sea-level change in Cleveland Bay, with error terms not proportionately larger than in upper intertidal, temperate locations, given the length of the environmental gradient (Table 6.8). However there are poorly understood issues with sediment reworking, only identified by radiocarbon dating which limit the environments where quantitative sea-level reconstructions can occur.

Research Question 1 f. Is there suitable in situ material for AMS radiocarbon dating to create an age model for reconstructions?

AMS dating of calcareous foraminifera provides an accurate age model of the late Holocene period only for sea-level reconstructions. Out of sequence radiocarbon dates in mid Holocene minerogenic sediments highlights problems with reworking, which is not obvious from analysis of foraminiferal assemblages at and around dated horizons. This is a limitation with using calcareous foraminifera to create an age model. However

in these sediments only calcareous foraminifera and individual unarticulated bivalve shells (with even greater potential to be reworked) are available for dating.

Research Question 2: What is the pattern of Holocene relative sea-level change in North Queensland?

Research Questions 2 a, b and c:

- a. When did relative sea level first reach its current value?*
- b. What was the amplitude and timing of the peak of the mid Holocene high stand?*
- c. What was the nature of relative sea-level fall through the late Holocene?*

The general form of the sea-level record from Cleveland Bay is sea level rising above its present value prior to 6700 cal years BP, relatively stable sea level at an elevation of 1-2.3 m above present between 6700-5000 cal years BP, and between 1-2.8 m above present between 5000 cal years BP and 3000 cal years BP. This is followed by sea-level fall to between 0.4-0.8 m above present until 1200 cal years BP, with subsequent slow fall to present. The high stand was a prolonged period (~3700 years) in the late Holocene with sea level relatively stable 1-~2.8 m above present.

6.2.3 Research Question 3: Does application of sea-level index point analysis in sediments help to define the mid Holocene high stand?

Research Question 3 a. Do observed sea-level tendencies through the mid-late Holocene correlate at site and regional scales?

On a local scale not all tendencies correlate, as reconstructions from Cocoa Creek Core 7 between 4700-4000 cal years BP infer negative tendency while reconstructions from Core 14 in this period infer stable sea level (Figure 6.6). On a regional scale within Cleveland Bay, tendency information suggests sea level was relatively stable above present from 6700 cal years BP, with negative tendency from 3500 cal years BP.

Research Question 3 b. Does index point analysis help to understand the nature of the mid Holocene high stand (e.g., duration, single or multiple maxima)?

Index point analysis helps to define the nature of sea-level change through the mid/late Holocene, adding definition to the shape and amplitude of the mid Holocene high stand. The sea-level data suggests the high stand is a long period of relatively stable sea level 1-2.8 m above present between 6700-3000 cal years BP, falling to present in the past 1200 cal years. Prior to this work sand flat, micro atoll, mangrove and

encrusting oyster indicators in Cleveland and Halifax Bays provided reconstructions with little or no indication of tendencies of sea-level movement and inconsistent error terms, suggesting gradual sea-level fall from a peak of 1-1.8 m around 6200 cal years BP. New reconstructions question the elevation accuracy of sand facies from Cocoa Creek. Together with micro atoll and encrusting oyster index points my work increases the body of evidence which indicates that sea-level was relatively stable above present through much of the late Holocene. This may form the basis for future geophysical model testing in North Queensland.

Research Question 4: Is the resolution of sea-level data sufficient to differentiate between models of mid-Holocene sea level high stand duration and amplitude?

New and recalibrated sea-level index points from Cleveland and Halifax Bays support the theory of continued ice melt through the late Holocene, possibly from Antarctica. Before tuning with Cleveland and Halifax Bay sea-level data, Milne *et al*'s (2005) ice model over-estimates the volume of melt through the mid Holocene, but the final solution with ice melt ending at 5000 cal BP does not predict fully relatively stable sea-level above present in the late Holocene shown by the data. Nakada and Lambeck's 1989 model and Chappell *et al*'s 1982 model underestimate the volume of melt during the late Holocene, but increased melt during the last 4000 years may bring Nakada and Lambeck's 1989 model closest to the empirical data.

CHAPTER SEVEN: CONCLUSIONS

7.1 PROJECT SUMMARY

This study is a first attempt to create a record of mid/late Holocene sea-level changes from North Queensland using a foraminifera-based transfer function approach. This technique is used frequently to reconstruct Holocene sea-level changes in temperate locations in North America and Europe, but it has never been thoroughly tested in a tropical environment. I chose North Queensland as a study area because sea-level reconstructions give important information for geophysical modelling, and some existing Holocene sea-level index points in North Queensland have problems with variable precision, different indicative meanings applied to the same indicator and inconsistencies with radiocarbon date calibration. The coastal geomorphology of North Queensland provides the ideal environment of low energy, shallow intercalated muds for a microfossil-based sedimentary study of mid-late Holocene sea-level change.

Calcareous foraminifera from intertidal and shallow subtidal environments create a good transfer function model, able to reconstruct sea level with a comparable level of precision to some other proxy indicators on this coastline. Despite relatively large absolute error terms, they are comparable in relative terms to those of transfer functions in temperate environments, given the length of the environmental gradient.

By creating new sea-level index points and re-calibrating existing ones from other indicators I infer the general form of the mid/late Holocene sea-level record in Cleveland and Halifax Bays as sea level rising above its present value prior to 6700 cal years BP, with relatively stable sea level at an elevation of 1-2.3 m above present between 6700-5000 cal years BP, and between 1-2.8 m above present between 5000 cal years BP and 3000 cal years BP. This is followed by sea-level fall to between 0.4-0.8 m above present until 1200 cal years BP, with subsequent slow fall to present. Sea-level index point analysis, including tendency analysis extracts further information on the nature of the high stand. Tendency analysis confirms the hypothesis of relatively stable sea level above present between 6700-3500 cal years BP, and

indicates the inflection point between positive/stable and negative sea-level tendency (the end of the peak of the high stand) at or before approximately 3500 cal years BP.

These reconstructions allow me to evaluate 3 different geophysical models of late Holocene sea-level change in this region, and through model iterations test how the nature of the high stand is affected by earth and ice model parameters. Sea-level data support the theory of a gradual end to global ice sheet melt, with melting ending after 5000 cal years BP. Models by Chappell *et al.* (1983) and Nakada and Lambeck (1989) underestimate the volume of global ice melt during the late Holocene, and a model by Milne *et al.* (2005) over-estimates the volume of ice melt. The height of the high stand in Milne's model (likely in the others as well) is controlled primarily by earth model parameters, including lithospheric thickness, upper and lower mantle viscosity.

Evaluating geophysical models with sea-level data from far-field locations is a necessary step in increasing understanding of the nature of late Pleistocene ice sheets, the integrated melt signal from global ice sheets and glaciers and the viscosity structure of the solid earth. Increasing knowledge about the change in eustatic signal during the Holocene (evidenced by sea-level data from North Queensland) is particularly important in improving understanding of driving mechanisms for the change, and to understand how climate and sea level interacted during the mid Holocene when the rate of eustatic sea-level rise was similar to that being experienced today.

7.2 LIMITATIONS AND AREAS FOR FURTHER RESEARCH

This study highlights several issues and limitations of using a foraminifera-based transfer function approach in tropical environments. Firstly is the absence of agglutinated foraminifera in fossil sediments from Cleveland Bay. Rapid disappearance of agglutinated foraminifera on burial in mangrove sediments is noted by several authors in selected tropical locations, but no previous studies have investigated this in northern Queensland, and no study has yet come up with a definitive explanation for this phenomena. Creating a transfer function model using primarily calcareous foraminifera, which live over larger elevation ranges, is an acceptable alternative to using mainly agglutinated foraminifera, but it causes an inherent increase in reconstruction error. A second issue is reworking of lower intertidal/shallow subtidal sediments which is not obvious from visual, bio- or litho-stratigraphical analysis. Reworked horizons in my cores were not evident until I had the results of radiocarbon dating, which is costly way of identifying reworking. Without

a definitive explanation for reworking or an alternative method to identify it, future studies will have to use radiocarbon or another dating method to identify horizons where sea-level reconstructions are not valid.

A third issue is potential compaction of mangrove sediments through the mid/late Holocene, suggested by their generally lower reconstruction elevations than using other proxy indicators. I am unable to test this hypothesis by plotting intercalated and basal muds separately, since none of the publications detailing mangrove-based sea-level reconstructions give this information. This is an important area for future research.

A fourth issue, which is inherent to all marine proxy indicators used on this coastline (e.g., coral micro atolls and calcareous foraminifera) is the 'apparent' radiocarbon age of marine organisms (the marine reservoir effect). Little is known about the effect of old carbon on organisms which live in the tidal frame above MLWST, or subtidally where there is a broad shallow continental shelf. This is an important area for future research as transfer functions allow reconstructions in environments where calcareous foraminifera are the only reliable *in situ* material for dating.

Despite these limitations and issues this study is an important contribution to the study of Holocene sea-level change in Australia, increasing the body of evidence for gradual continued global ice melt during the mid/late Holocene. A future research direction is to collect new sea-level data from the southern Queensland coast, where the continental shelf narrows and geophysical models predict a different relative sea-level response through the mid/late Holocene. The technique developed in this study could be used to increase the precision of sea-level reconstructions, which are currently based solely on cored coral in this region. Comparison of sea-level reconstructions from South and North Queensland, between areas of wide and narrow continental shelf gives vital information on crustal levering during the mid/late Holocene, allowing further refinement of geophysical models of crustal response to current global sea-level rise.

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