Quantification of the indicative meaning of a range of Holocene sea-level index points from the western North Sea.

Volume One:

Main text, References and Tables

by

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"The formula two and two makes five is
not without its attractions"

Dostoevsky Fedar Milkallovich

Declaration

This thesis is the result of my own work. Data from other authors which are referred to in the thesis are acknowledged at the appropriate point in the text.

Abstract

One of the main aims of the LOIS Special Topic Project Number 316, of which this thesis is a part, is to develop and validate models of some of the major characteristics of the Holocene evolution of the western North Sea. Establishing sea-level change is important to this. To meet this aim, the **indicative meaning** must be defined. The indicative meaning of a coastal sample is the relationship of the local environment in which it accumulated to a contemporaneous reference tide level. This thesis provides a method of estimating the indicative meaning based upon the contemporary relationship among relative sea-level, environmental conditions and the succession and seasonal variations of foraminiferal assemblages.

Foraminiferal assemblages were collected over a period of twelve-months from the intertidal zone of four marshes along the margin of the western North Sea: Cowpen; Welwick; Thornham; and Brancaster marshes. Statistical analyses indicate that the foraminiferal distributions are controlled predominantly by altitude. The contemporary foraminiferal distributions of each marsh display a vertical zonation with respect to mean sea level, though, their zonation dimensions differ. The foraminiferal assemblages are classified by multivariate analyses into two zones: a high, middle and low marsh zone dominated by agglutinated species such as *Jadammina macrescens*, *Miliammina fusca* and *Trochammina inflata*; and a low marsh and tidal flat zone dominated by calcareous species such as *Elphidium williamsoni*, *Haynesina germanica* and *Quinqueloculina* spp.

The detailed foraminiferal data from each site has been combined to develop a quantitative reconstruction technique. This technique is used to estimate the indicative meanings of thirty-five sea-level index points which were chosen from specific locations and time periods during the Holocene. It is applicable to 'traditional' transgressive and regressive contacts, and more importantly, clastic sequences which have been previously ignored in the production of sea-level index points.

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Chapter One: Introduction

1.1 Preface

Palaeoenvironmental investigations of coastal lowlands provide chronological and altitudinal information regarding Holocene sea-level trends. Stratigraphical and micropalaeontological investigations of intercalated sequences of marine and terrestrial sediments may produce a series of **sea-level index points** (SLIs). Such index points use a wide variety of palaeoenvironmental data, although the potential vertical precision of terrestrial-marine (marine overlying terrestrial sediments: transgression) or marine-terrestrial (terrestrial overlying marine sediments: regression) contacts makes them the most widely studied types of index points within this thesis. Along low-energy coasts, SLIs can be based on sediment lithology, fossils and lithostratigraphic or biostratigraphic boundaries. These are employed to construct trends of relative sea-level where both the regional (eustatic, glacio-isostatic and hydro-isostatic) and the local (coastal morphology, sediment supply, tidal regime and terrestrial and fluvial input) factors may be identified.

The interpretation of SLIs is predominantly based upon the **indicative meaning** of a dated sample. The indicative meaning of a coastal sample is the relationship of a coastal sample to a tide level defined in terms of the **indicative range** and **reference water level**. The indicative range is a vertical range with regard to the reference water level, within which the coastal sample can occur and the reference water level is a tide level to which a coastal sample is assigned.

It is hoped that through detailed lithostratigraphical and biostratigraphical analyses of fossil and contemporary data the precision and definition of the indicative meaning of different sea-level indicators can be quantified.

1.2 Background

This thesis is a part of the Land-Ocean Interaction Study (LOIS) Special Topic Project Number 316 undertaken by the Environmental Research Centre (ERC), University of Durham and other LOIS partners. The LOIS project title is "Modelling the Holocene depositional regimes in the western North Sea at 1000 year time intervals". The main aim of this project is to develop and validate models of some of the major characteristics of the Holocene evolution of the western North Sea. The models of the Rivers, Atmosphere, Coastal and Estuarine Study (RACS) area (Berwick upon Tweed to North Norfolk), concentrate on the varying palaeogeographies of the coastline, bathymetries and tidal dispositions, and changing sediment fluxes. These will be obtained from a nested series of tide models, created by the Institute of Oceanographic Sciences (IOS), using reconstructions of Holocene palaeoenvironments at 1000 year time intervals.

One of the main inputs to the palaeotidal models is water depth. This is controlled by the complex interaction of eustatic changes (a result of fluctuating global ice volumes) and crustal movements (due to isostatic adjustments following deglaciation). The spatial variations of these effects will have to be modelled for each 1000 year time interval as an input to the final models. Onshore and offshore SLIs will be used in combination with crustal models developed by Lambeck (1993a, 1993b) to produce these data. SLIs from offshore areas are of particular relevance for two reasons. First, most of the evidence of early Holocene shorelines is offshore. Second, the continental shelf is remarkably flat in comparison to the land, therefore, the tilts produced by isostatic and neotectonic effect can be detected across the shelf.

Much of the onshore and offshore data existed before the project began. Extensive databases are held at the British Geological Society (BGS) and the ERC. ERC's radiocarbon databank of SLIs provides a good base to initialise and test the first runs of the models. Shennan (1982) and Tooley (1982b) collected 782 ^{14}C dates and verification of each date led to rejection of approximately half. The remainder were ^{14}C dates from peats showing similar indicative meanings and common reference water levels (approximately mean high water spring tides). Shennan (1989, 1992) and Long and Shennan (1993) used the dataset to show patterns of uplift and depression since deglaciation (Figure 1.1). Crustal movements were determined using two reconstructions of the 'eustatic sea-level' (Morner, 1984), first, the regional eustatic curve including oscillations as proposed by Morner (1984) and the second, a simpler curve with no oscillations which is similar to the 'equivalent sea-level' term used by Lambeck *et al.* (1990). Subtracting the fixed eustatic component from a relative sea-level value will give an estimate of net uplift or subsidence (glacio-isostatic, hydro-isostatic and tectonic constituents) combined with local-scale factors (sediment compaction, oceanographic and hydrological effects). The results from the analysis of Holocene geological data fit very well with the tide gauge data of twentieth century relative sea-level changes (Shennan and Woodworth, 1992). Shennan and Woodworth (1992) suggested that maximum rates of uplift ought to be recorded near the former centre of maximum Devensian ice thickness with rates of uplift diminishing with distance from this location. However, the temporal and spatial distribution of the index points was uneven. Furthermore, other factors such as sediment compaction, tidal range variations and gravitation effects were not quantified in the 1989 model. The sampling design of the current project, together with new data collected since 1989, will allow such factors to be quantified. The database has been enhanced by analysing the indicative meanings and reference water levels of all other index points both onshore and offshore. The sea-level indicators used are based upon the combination of lithostratigraphical (loss on ignition, grain size and chemical analyses) and biostratigraphical (diatom, foraminifera and pollen) evidence. The indicators range from those deposited at extreme high water or storm levels to sub-tidal levels, each with varying degrees of precision. The database has increased from 915 to 1574 data points since 1989, although validation is still required for some points.

In addition to the data that already exist, primary data will be collected from chosen locations within the RACS area and specific time periods during the Holocene. The new data will be used to calibrate initial crustal models to different parameters. For example, data from north-east England are valuable for testing the sensitivity of Lambeck's (1993a, 1993b) earth model parameters for upper mantle viscosity and lithospheric thickness. In contrast, sites in the south of the RACS area are less sensitive to changes in the mantle viscosity and lithospheric thickness parameters. However, they are essential to test the validity and robustness of the other parameters of the earth and ice models such as regional (onshore and continental) patterns of crustal movements.

The LOIS project "Modelling the Holocene depositional regimes in the western North Sea at 1000 year time intervals" will make a fundamental contribution to the Land-Ocean Evolution Perspective Study (LOEPS) element of LOIS. The project will reconstruct the changing land-ocean boundaries during the Holocene and aid in the identification of the critical geomorphological and ecological processes that determine the nature of that boundary. The database and graphical output is complementary to numerous projects within LOEPS studying coastal evolution. Two such projects are centred at the ERC: "Differential crustal movements within the RACS study site"; and "Holocene evolution of the Humber estuary".

The results from this thesis will be used to provide a comprehensive database to validate the final runs of the LOIS crustal model before inputting to the tidal model. The aims and objectives of this thesis will be incorporated within the database to improve the precision and definition of the SLIs.

1.3 Aims and objectives

1.3.1 Aims:

1. *Quantification of the precision and definition of the indicative meaning of a range of Holocene SLIs through the analysis of contemporary saltmarshes.* For sedimentary sequences to be used as SLIs their indicative meaning must be assessed. However, there has been a general lack of progress on the contemporary relationship between relative sea-level, environmental conditions and the succession and seasonal variations of plant and microfossil assemblages (Tooley, 1978a; French *et al.*, 1995). The understanding of the indicative meaning is a prerequisite for interpreting sea-level changes from fossil faunas. Therefore, the examination of the concept of the indicative meaning in more depth is crucial to the progression of sea-level research. At each contemporary site a range of lithostratigraphical and biostratigraphical techniques will be used to quantify the indicative meaning. These include diatom, foraminifera, pollen, vascular plants, organic content, grain size, pH and salinity analyses;
2. *Application of the contemporary results to produce new SLIs collected from the fossil cores.* If this proves successful the procedure will be repeated for index points collected by the ERC and other LOIS partners.

1.3.2 Objectives:

1. Specify contemporary coastal sites. The contemporary sites should exhibit a wide range of environments with the objective of ensuring that most fossil sites have a modern analogue;
2. Systematically study the contemporary intertidal zone using lithostratigraphical and biostratigraphical techniques. The number of transects and the frequency of sampling will depend upon the size of the intertidal zone and the resolution required;
3. Identify the environmental variable(s) which control contemporary microfossil distribution within the intertidal zone of each contemporary field site;
4. Compare the contrasting intertidal zones to identify general and site-specific trends in microfossil assemblages and environmental variables;
5. Employ a detailed study of contemporary microfossil assemblages along the intertidal zone to elucidate their elevational range with respect to a reference tide level and, therefore, constraining the accuracy of different sea-level indicators;
6. Identify fossil field sites along the margin of the western North Sea within the RACS study area;

7. Identify microfossil assemblages from fossil cores. Determine their altitudes (that can be related to former sea level), ages and indicative meanings to produce new SLIs.

1.4 Structure of Thesis

This thesis presents the results of a study of intertidal foraminifera from marshes along the margin of the western North Sea (Cowpen, Welwick, Thornham and Brancaster marshes), the development of quantitative techniques to reconstruct former sea levels and the application of these techniques to produce new sea-level index points (SLIs).

Chapter Two reviews the published literature and summarises the basic theory of sea-level change. Furthermore, the terminology used in sea-level studies and the methods of reconstructing former sea levels are described. Chapter Three discusses three microfossil groups: foraminifera; diatom; and pollen. To facilitate the evaluation of intertidal foraminifera as sea-level indicators an introduction is given of all aspects which might influence their modern distribution. In addition, post-depositional changes of foraminiferal assemblages are deliberated. Finally, this chapter develops a foraminiferal sampling design through a pilot study of Cowpen Marsh.

Chapter Four presents the results of a systematic study of the contemporary fauna, flora and sedimentary characteristics of Cowpen, Welwick, Thornham and Brancaster marshes. The chapter aims to elucidate the relationship of foraminiferal distributions versus a series of environmental variables and to identify the patterns of contemporary foraminiferal distributions across the intertidal zone. The chapter also aims to investigate seasonal variations of contemporary foraminiferal distributions and their possible implications for foraminifera as indicators of former sea levels.

Chapter Five describes the development of a quantitative palaeoenvironmental reconstruction technique. This chapter combines the foraminiferal and environmental data to create a training set containing a wide range of contemporary coastal environments, ensuring that most fossil sites have a modern analogue. This technique allows the indicative meaning of a range of Holocene SLIs to be reconstructed without the need of a local or seasonal surface study.

Chapter Six presents the lithostratigraphical, biostratigraphical and available radiocarbon (^{14}C) dating results from a range of fossil field sites along the margin of the western North Sea. The indicative meanings of SLIs are calculated and compared using the quantitative reconstruction technique developed in the previous chapter and the established technique of Shennan (1982, 1986).

The contemporary and fossil results of this thesis are summarised in Chapter Seven within the context of previous research. The final chapter concludes the thesis by considering to what extent the initial research aims and objectives stated in Section 1.3 have been met and proposes themes for future research.

Chapter Two: Sea-level Index Points

2.1 Introduction

A **sea-level index point** (SLI) is a datum that can be employed to show vertical movements of sea level when information about the geographical position, environment, indicative meaning, altitude and age are established. The concept was developed during the International Global Correlation Programme (IGCP) Projects 61 and 200, and is described in '*The Manual of Sea-level Research*' (van de Plassche, 1986) as well as a number of earlier papers (Preuss, 1979; van de Plassche, 1982; Shennan, 1982; Tooley, 1982a; Shennan *et al.*, 1983).

The aims and objectives of this chapter are as follows:

- Define and evaluate the indicative meaning;
- Introduce a series of lithostratigraphical and biostratigraphical sea-level indicators;
- Discuss the method of radiocarbon dating;
- Assess the errors involved in the production of SLIs;
- Review the techniques employed in the interpretation of SLIs.

2.2 Definition of sea level

The mean sea level (MSL) for the UK is referenced to the Newlyn Tide gauge (1915 - 1921). For any given location tide levels ranging from lowest astronomical tide (LAT) to highest astronomical tide (HAT) can be calculated using Newlyn as a reference (Table 2.1). Mean tide level (MTL) is calculated as the mid-point of the tidal range, depending upon the symmetry of the tide. Most tides in the world are asymmetrical due to the shallow water distortion of the tidal wave causing MSL to occur above or below MTL. The altitude of MSL indicators cannot be exactly determined because they do not leave a long term geological record in sediments or landforms. Therefore, sea-level curves using MSL are actually based upon MTL (Jardine, 1986).

		SUPRATIDAL ZONE
Highest Astronomical Tide	HAT	
Mean High Water Spring Tide	MHWST	
Mean High Water Neap Tide	MHWNT	
Mean Sea Level	MSL	
Mean Tide Level	MTL	INTERTIDAL ZONE
Mean Low Water Neap Tide	MLWNT	
Mean Low Water Spring Tide	MLWST	
Lowest Astronomical Tide	LAT	
		SUBTIDAL ZONE

Table 2.1 Tide levels within the intertidal zone.

The mean high water spring tide (MHWST) level is an ecologically more important reference level than MTL and is used more frequently (Tooley, 1978a; Kidson and Heyworth, 1979; Kidson, 1986; Long, 1992; Shennan, 1992; Zong 1992). This is because many sea-level indicators are derived from certain saltmarsh plants that normally accumulate around or above MHWST and are overlain or underlain by clastic sediments.

2.3 Interpretation of former sea levels

A SLI is typically composed of four components:

- A geographical location;
- An altitude that can be related to a former sea level;
- An age;
- A tendency of sea-level movement.

SLIs are produced from a wide variety of palaeoenvironmental data including morphological and archaeological data, palaeosols and other lithostratigraphic changes. For example, Pirazzoli (1986) analysed marine notches on limestone coasts; Roep (1986) employed barrier deposits in the western Netherlands; and Firth *et al.* (1995) correlated coarse clastic features and their ages to identify periods of relative sea-level (RSL) change. Despite the diverse range of evidence, the SLIs used in sea-level analysis in north-west Europe are overwhelmingly dominated by changes in lithology between terrestrial and marine deposits (Shennan, 1986; Long 1992; Long and Innes, 1995; Zong and Tooley, 1996).

The terms transgression and regression have been used in a wide variety of contexts and, as identified by Shennan (1980, 1982) and Tooley (1982b), inconsistencies in the use of the terms have led to much confusion. As a result it was difficult to correlate the results of different researchers. Accordingly, following Shennan (1980), they are to be used in a purely descriptive manner to describe changes in lithology from a semi-terrestrial to a brackish or marine deposit (transgressive overlap) and the replacement of a marine or brackish deposit by a semi-terrestrial deposit (regressive overlaps). Their usage does not imply the operation of any vertical movement of sea level. For example, a rising sea level will not cause a retreat of the coastline if the rate of sedimentation is higher than the rate of sea-level rise.

The tendency of sea-level movement describes whether the point records an increase or decrease in water level or salinity (Shennan, 1983). A tendency is interpreted to reflect the movement of marine water towards or away from a site but such movements are not necessarily synonymous with rises or falls in RSL (Nelson *et al.*, 1996). Transgressive contacts are commonly interpreted as indicating a positive tendency and regressive contacts a negative tendency, although study of fossil assemblages is usually required to confirm lithostratigraphic interpretations. Furthermore, fossil assemblages within a lithological homogeneous stratigraphic unit may also mark a tendency. For example, changes in foraminiferal assemblages in a peat from high marsh to low marsh would indicate a positive tendency of RSL. A positive tendency may be first recorded several centimetres below a transgressive contact possibly by biostratigraphic evidence of a gradual increase in salinity and/or water depth (Long, 1992; Nelson *et al.*, 1996). However, freshening of the depositional environment within a clastic unit below a regressive contact may reveal the onset of a negative tendency which may then continue across the contact into the overlying organic unit (Shennan *et al.*, 1995). The biostratigraphic recording of positive or negative tendencies within and/or across boundaries of dated units allows rates and the direction of changes in water depth and salinity to be estimated (Nelson *et al.*, 1996).

The correlation of numerous tendencies in a region through radiocarbon dating of index points can help establish the dominant tendency during particular time periods. Furthermore, where index points are constrained within an age-altitude band, evaluating the dominant regional tendency may identify regional oscillations of RSL.

2.4 The Indicative Meaning

For age/altitude analysis a SLI must have an **indicative meaning**. The indicative meaning of a coastal sample is the relationship of the local environment in which it accumulated to a contemporaneous reference tide level (van de Plassche, 1986). Since sea-level trends are seldom inferred from a single type of dated material, and to allow for comparisons between different areas, each sample is related to its own reference tide level. This reference tide level may not be constant and the interpretation must take into account the accuracy of the indicative range of the dated sample and the accuracy of the tide level to which it is referenced. Therefore, the indicative meaning can vary according to the type of evidence and it is commonly expressed in terms of an **indicative range** and a **reference water level**. The former is a vertical range within which the coastal sample can occur and the latter a waterlevel to which the assemblage is assigned, for example, MHWST, MTL, etc., (van de Plassche, 1986).

Furthermore, Shennan (1986) stressed that during the calculation of the indicative meaning the following points should be noted:

- The indicative meaning is dependent on the type of stratigraphic overlap under consideration;
- The reference water level should be given as a mathematical expression of tidal parameters rather than a single tide level ± a large constant factor since the constant factor will indicate quite different tidal inundation characteristics for areas of different tidal range;
- The indicative range can be reduced by dating the level at which microfossil and stratigraphic evidence suggests a change in sedimentary environment;
- The accuracy of reference tide level must be assessed.

The indicative meaning of indicators within saltmarsh sequences are complicated by ecological and habitat processes (Allen 1990a, 1990b).

There is a high interaction between physical processes such as RSL change and sediment supply, biological activity and a range of tide levels (Allen, 1993, 1996; French *et al.*, 1995). When RSL rise is sudden and of high magnitude such as the result of tectonic activity, the marsh surface may be 'drowned' (Reed, 1995). Various researchers have identified such events in the stratigraphic record as abrupt transgressive overlaps between non-adjacent lithofacies (Nelson, 1992; Long and Shennan, 1994; Nelson *et al.*, 1996). However, marsh submergence on passive coastal margins rarely occurs this rapidly. The overall response of marshes to RSL changes depends upon the relative importance of the inorganic and organic components of the marsh soil and the impact of increased hydroperoid on net sediment accumulation. The organic content varies within and between marshes with higher rates of vertical marsh sediment accretion in the low marsh and lower rates at higher elevations (Wood *et al.*, 1989; Nyman *et al.*, 1990; Nydick *et al.*, 1995). This variability causes problems when interpreting marsh statigraphies. Jennings *et al.* (1995) stated that the growth patterns of minerogenic marshes, irrespective of RSL rise, will favour the production of negative sea-level tendency stratigraphy. They noted that a change from minerogenic low marsh to organogenic high marsh (due to organogenic productivity matching RSL rise) will enhance this tendency. Moreover, Jennings *et al.* (1995) stated that a stratigraphy may be interpreted as a vertical oscillation rather than a single RSL rise if RSL rise results in marsh submergence (positive sea-level tendency) which is then shortly followed by renewed accretion, raising the marsh surface relative to the new tidal frame (negative sea-level tendency). Kidson and Heyworth (1982) argued that saltmarsh deposits were unsuitable as accurate indicators of former sea levels because marsh development can be driven by sediment supply to the marsh rather than by RSL change. Jennings *et al.* (1995) concluded that only mature marshes are reliable stratigraphic indicators of RSL change because their accretion rates are in equilibrium with RSL.

Allen (1995) used a zero-dimensional numerical model for the vertical growth of experimental tidal mudflats and marshes with tidal and sediment regimes similar to those of the Severn estuary. He concluded that, although fluctuations in sea level create intercalated semi-terrestrial and brackish or marine stratigraphies, they show a lagged response. The sensitivity of the tidal mudflats and marshes to forcing factors (e.g. sediment supply and tidal range), combined with the lag effect, cause substantial intrinsic uncertainties that far exceed observational errors that may be expected in the production of SLIs (Allen, 1995). Therefore, the transgressive and regressive overlaps infer sea-level changes of limited reliability in terms of chronology, amplitude of fluctuation and indicative meaning (Allen, 1995).

2.5 Sea-level Indicators

A sea-level indicator is a sample that may be employed to indicate former sea levels if its indicative meaning, indicative range and reference water level can be identified. The following lithostratigraphical and biostratigraphical techniques are commonly employed as sea-level indicators (Shennan *et al.* , 1996a).

2.5.1 Diatom analysis

Diatoms are usually the dominant microphyte in estuarine and marine littoral environments. In estuarine environments, epipelic diatoms (mainly pennates) are of particular importance (Admiraal, 1984). The ecological sensitivity of these organisms is well known with species composition depending upon competition, habitat availability, nutrient availability, salinity and turbidity. Diatom taxa thrive in water of particular salinity and become incorporated in coastal sediments through time. The resulting microfossil assemblages can be recovered and evaluated to reconstruct the environmental history (Palmer and Abbott, 1986). For sea-level studies the most useful historical reconstruction is one in which a substantial change is found in the proportions of sensitive fresh, brackish and marine diatoms (Zong and Tooley, 1996).

2.5.2 Foraminiferal analysis

Contemporary distributions of saltmarsh foraminifera have been related to fossil assemblages. The well-defined foraminiferal zones that subdivide the marsh increase the vertical resolution of the fossil deposits, providing accurate sea-level indicators (Scott and Medioli, 1978). Employing foraminifera to determine former sea levels requires that their contemporary distributions and controlling environmental variables are established (Thomas and Varekamp, 1991).

2.5.3 Pollen analysis

Pollen data can be used to aid reconstructions of former sea levels. Regressive and transgressive overlaps show high frequencies of saltmarsh indicators such as Chenopodiaceae, *Aster* type and *Plantago maritima* (Tooley, 1978a). Periods of prolonged subaerial exposure and peat growth may be characterised by high frequencies in tree pollen (e.g. *Corylus, Alnus* and *Quercus*) as carr develops. As sea level rises, the transition from terrestrial to saltmarsh to marine environments will be recorded. Using the pollen record, it is, therefore, possible to record the sequence of saltmarsh evolution and the development of subaerial environments, as well as vegetation responses to changing frequencies of inundation (Long, 1992).

2.5.4 Stratigraphical analysis

Periods of marine transgression are indicated by an upward transition from saltmarsh peats to estuarine clays and silts whilst a regression may lead to a change from estuarine silts and clays to saltmarsh peats. The precise nature and characteristics of transgressive or regressive processes are local and site dependent. Stratigraphical descriptions can allow basic mapping of the varying palaeogeographies of the coastline, bathymetries and tidal dispositions, and changing sediment fluxes (Shennan, 1994).

2.6 Radiocarbon dating

Radiocarbon (^{14}C) dating has been employed extensively in sea-level research as a means of establishing an absolute age for a SLI. Dating has focused on the transgressive and regressive contacts that have a known altitudinal relationship with sea level. Libby (1952) was the first to report the principles and methods of ^{14}C dating. He stated that ^{14}C is continually produced in the Earth's upper atmosphere and is taken up directly by plants during photosynthesis and indirectly by other life forms through the food chain. When the organism dies the carbon uptake ceases and the ^{14}C isotope begins to decay. Therefore, given the standard of ^{14}C activity and the half live (5570 ± 30 ^{14}C years) of the isotope, an age can be calculated by measuring the ^{14}C of the sample. The process of measuring ^{14}C activity is described by Bowen (1978).

The development of the Accelerator Mass Spectrometry (AMS) technique for radiocarbon dating in the 1980's greatly increased the range of datable sedimentary deposits (Hajdas *et al.*, 1995; Jiang *et al.*, 1997). For example, it is impossible to determine the age of calcareous assemblages (foraminifera, molluscs, ostracods) in clastic deposits by 'conventional' ^{14}C dating. However, AMS dating allows sparse samples with a low carbon content to be dated. Therefore, if there are sufficient numbers, the calcareous material can be used for dating. Previous studies have employed molluscs and planktic foraminifera for AMS dates (Bard *et al.*, 1990; Austin *et al.*, 1995; Heier-Nielsen *et al.*, 1995; Kristensen *et al.*, 1995). AMS dating provides reliable ^{14}C ages with only 1 mg of carbon which enables direct assignments of precise ages of monospecific foraminiferal samples younger than about 44 ka. However, to compare the marine ^{14}C ages with the continental chronologies, all ^{14}C dates obtained on foraminifera have to be corrected because of the slow ocean turnover of ^{14}C. This is known as the 'marine reservoir age effect' (Jones *et al.,* 1989). The correction is in the order of 300 to 400 years at low latitudes rising to 1200 years at higher latitudes in the southern oceans and North Pacific

(Austin *et al.*, 1995). Marine samples from British waters suggest a correction factor of 405 ± 40 years (Harkness, 1983).

AMS dating has further advantages over 'conventional' ^{14}C. It is possible using the AMS technique to differentiate between different biological species (foraminifera, molluscs, plant remains) or between different chemical fractions (peat: humin; humic acid; and fulvic acid; bone: collagen; and amino acids). However, various researchers (Hedges, 1991; Shore *et al.*, 1995) suggested that as a technique, AMS dating may not be as precise as 'conventional' ^{14}C dating. Shore *et al.* (1995) stated that the smaller the sample dated the greater the effect of contamination. Heier-Nielsen (1995) argued that this statement is only true if the contamination comprises absolute amounts of foreign material added to the sample. Heier-Nielsen (1995) concluded that dividing a large sample into smaller sub-samples and AMS dating them separately provides much more information than 'conventional' ^{14}C dating of the bulk sample. Any foreign component will reveal itself as an outlier among the results. One final point worth noting is that AMS dating is more expensive than 'conventional' ^{14}C dating and, therefore, needs additional justification.

2.7 Source of error

The value of samples as indicators of former sea levels can only be assessed following the consideration of errors affecting the calculation of SLIs. Significant errors are possible in the estimation of the altitude and age of SLIs. It is important to state clearly the extent of such errors because they may equal or exceed the trends in RSL and, therefore, produce invalid interpretations. The major sources of error are discussed below.

2.7.1 Levelling the altitude of stratigraphic boundaries

Shennan (1980, 1982, 1986) identified three sources of altitudinal error when levelling the altitude of stratigraphic boundaries: measurement of depth of a borehole; levelling of the site to an Ordnance Survey (OS) benchmark; and accuracy of the benchmark to Ordnance Datum (OD) Newlyn.

A number of largely unavoidable altitudinal errors occur during the measurement of depth of a borehole when hand coring. These include the identification of boundaries, the curvature of sampling rods, the measurement of depth, the angle of the borehole and compaction. More serious errors occur with the use of a piston corer because of sediment compaction during extrusion, or over sampling in the field.

Altitudinal errors occur during the levelling of a site to an OS benchmark due to equipment failure, incorrect benchmark data and levelling errors. To combat this care should be taken to set up the equipment correctly. Furthermore, all benchmarks employed should be on solid rock or boulder-clay surfaces and not in areas of unconsolidated sediments where subsidence could have altered the true benchmark height.

Shennan (1986) noted that the accuracy of the OS benchmark is dependent on the length of the survey line from Newlyn and varies with the order of benchmark and levelling. For local comparisons, the errors of benchmarks are ± 0.01 m relative to each other. However, for inter-regional comparisons the error increases. Shennan (1986) estimated this to be ± 0.15 m for England and Wales and ± 0.20 m for Scotland relative to OD. A further important point to note is that the accuracy of the estimated altitude of a stratigraphic boundary is dependent on the sampling density and the local stratigraphic surface roughness (Makarovic, 1973). Shennan (1986) stated that to avoid altitudinal errors of the magnitude of ± 0.30 m, a borehole density equal to a 30 m grid may be required. A summary of the errors and their approximate ranges is provided in Table 2.2.

Identification of boundary	± 0.01m
Measurement of depth - hand coring	± 0.01m
Measurement of depth - commercial U4	± 0.05 m
Measurement of depth - commercial (disturbed)	± 0.25 m
Compaction and extrusion of piston cores	up to 0.06 m
Duits gouge sampler (not for ^{14}C samples)	up to - 0.20 m
Angle of borehole	up to 0.04 m
Levelling to benchmark	up to ± 0.02 m
Accuracy of benchmark to OD	± 0.15 m
Sampling density - 1 borehole per 2 m^2	± 0.06 m
Sampling density - 1 borehole per 5400 m^2	± 0.14 m
95 % limits =	± 0.30 m

Table 2.2 Errors affecting the measured altitude of stratigraphic boundaries based on data from the Fenland (Source: Shennan, 1982).

2.7.2 Indicative meaning

Interpretation of past or fossil sea-level indicators based upon modern tidal levels may be inaccurate. The precision with which former sea levels can be estimated is limited by temporal and spatial tidal distortions (Redfield, 1972; Kidson and Heyworth, 1979; van de Plassche, 1986, 1991; de Rijk and Troelstra, 1997; van der Molen, 1997). Temporal tidal variations complicate the establishment of valid present local tide levels, for example HAT and LAT (van der Molen, 1997). Furthermore, van der Molen (1997) stated that spatial differences in local tide levels must be taken into account when former sea levels are calculated. Van der Molen (1997) calculated that MHWST at the landward limit of the intertidal zone was up to 0.55 m lower than the simultaneous MHWST on the tidal flat which was in turn approximately 0.10 m higher than MHWST in the inlet. Similarly, Redfield (1972) showed MHWST was not uniform across the Great Marshes, Massachusetts. Spatial differences may explain some of the contrariety among indicative meanings for different sites.

Furthermore, some indicators do not have a consistent indicative meaning as illustrated by the transition between fenwood and reedswamp. For example, Godwin (1940) stated that fenwood peat will start to form at MHWST in a coastal fen. However, in a backswamp area the groundwater level may be the controlling factor and approximates to MTL (Godwin, 1940). This effect is important in the assessment of the relationship between RSL movements and the variations in the initiation of basal peats. Furthermore, there are difficulties not only in establishing the level of the local water table relative to the indicator but also in determining the relationship between the local water table and sea level. Errors are most likely on coasts with large tidal ranges, or where there are significant spatial variations in tidal level, for example, within estuaries (Kidson, 1982, 1986; Shennan, 1986).

2.7.3 Tidal Range

Shennan (1980) stated that during the calculation of the indicative meaning a constant relative tidal regime is assumed. Furthermore, the absolute tidal regime is assumed to relate to present conditions. Shennan (1980) acknowledged that by making these assumptions the value of the indicative meaning is reduced but it is necessary whenever index points with different indicative meanings are used.

Gehrels *et al.* (1995) demonstrated that if the tidal range has not remained constant through time, sea-level chronologies based upon high tide level indicators will differ from the 'true'

MTL curve (Figure 2.1). Woodworth *et al.* (1991) indicated that there could be long-term changes in the tidal regime of the north-west European continental shelf as the result of changes in the deep ocean tides bordering the shelf. These may stem from long-term changes in the tidal potential arising from variations in the orbital elements of the Sun and Moon from long-term changes in the shape or depth of the major ocean basins, or from the rate of global tidal dissipation. Furthermore, various researchers have noted that tidal range is strongly influenced by shelf width and basin configuration (Redfield, 1958; Jardine, 1975; Cram, 1979; Woodworth *et al.*, 1991). Coastlines which are fronted by a wide shallow shelf or by a semi-enclosed sea (e.g. North Sea) are most susceptible to tidal range changes (Gehrels *et al.*, 1995). Temporal changes in the shelf width or basin configuration may be the consequences of either anthropogenic effects including dredging of rivers and other shallow areas (such work causes a reduction in tidal friction and an increased mean tidal range) or natural processes including long-term changes in RSL and sediment supply (Woodworth *et al.*, 1991).

Previous studies which identify changes in tidal range through time fall into the categories of sedimentary analysis and modelling. Palaeotidal range was estimated by comparing the thickness of units in the sedimentary sequence with those formed under present-day tidal conditions from pits along the barrier shoreline of the western Netherlands (Roep *et al.*, 1975; Roep, 1986; Roep and Beets, 1988). Alternatively, Scott and Greenberg (1983) indicated through numerical tidal modelling that tidal range in the Bay of Fundy increased on average by 1.2 % per 1 m rise in sea level between 7000 and 2500 cal. yrs. BP. Austin (1991) used numerical tidal models with sea level lowered as a plane surface by amounts indicated by eustatic sea-level curves to simulate the tidal development of the north-west European continental shelf. Hinton (1992, 1995) combined the palaeogeographic evidence with numerical modelling to simulate palaeotidal development for the Wash. Gehrels *et al.* (1995) developed a three-dimensional model of M_2 tidal component for the Gulf of Maine, based upon contemporary bathymetry and published sea-level curves for the area. Their results showed that the M_2 tidal range at 5000 cal. yrs. BP was 73 % of the contemporary value. However, simulations of palaeotidal development are limited by the accuracy of the palaeogeographic reconstructions and the tidal models employed.

Identifying changes in tidal range through time is beyond the scope of this thesis but is one of the specific objectives of LOIS.

2.7.4 Sediment compaction

The majority of sediments employed as SLIs have been subjected to post-depositional displacement in altitude largely due to compaction of the underlying peats, clays and silts. Jelgersma (1961) has reviewed some of the literature on this topic and stressed that compaction of deposits with a high sand fraction is very low whilst compaction of peat may be as high as 90 % by volume. Compaction of unconsolidated sediments is the result of many factors that vary over time: drainage and load (either under their own weight or from overlying sediments) (Tooley, 1978a); composition (Jelgersma, 1961); structure; and mineralogy (Skempton, 1970).

The variability in the compaction of sediments means that correction factors are rarely applied. Kidson and Heyworth (1973) applied Skempton's correction factors based upon site-specific geotechnical data in the Somerset Levels. However, Shennan (1986) stated that there is significant variability in applying Skempton's correction factors to sequences that contain clays with a high carbonate or organic content, and interleaved peat layers. Kidson (1982) concluded that only a recognition of altitudinal error due to compaction can be attempted. Furthermore, Zong (1993) has suggested that, until more empirical studies are carried out for a wide range of lithological successions, all assessments should be regarded as tentative and approximate if misinterpretation of the data is to be avoided.

An alternative approach to reduce the problem of sediment compaction is to date sequences of basal peats (van Straaten, 1954; Jelgersma, 1961, 1966; van de Plassche 1979, 1980, 1991, 1995; Smith, 1985; Denys and Baeteman, 1995; Kiden, 1995). The basal peats are compaction-free because the underlying Pleistocene sands are practically unaffected by compaction (Jelgersma, 1961). This approach is flexible enough to allow correlation with compaction susceptible samples of intercalated peats and clays (van de Plassche, 1991). However, there are criticisms surrounding the interpretation and indicative meaning of samples from the base of basal peats. Jelgersma (1961) considered the process of basal formation to be a product of distance to the shoreline, tidal range and permeability of the underlying sandy subsoil. For correct interpretation it is important to distinguish whether sea level or local groundwater level changes initiate the formation of basal peats. For example, Kiden (1995) noted that sea-level data collected by Jelgersma (1961) from south-west Netherlands showed an anomalously high age/altitude position relative to sea-level curves for the rest of the Netherlands. Kiden (1995) concluded that this was the result of early peat growth above contemporaneous MSL which was primarily due to groundwater-gradient effects on the gently inclined Pleistocene subsoil. Van de Plassche (1979) concluded that basal peat samples could only be employed in sea-level reconstructions after a detailed study of the relief of the underlying Pleistocene sands. As a result, van de Plassche (1979) only took samples where there was a sufficient slope on the Pleistocene surface to avoid this groundwater-gradient effect.

The problem of compaction of sediments within sea-level research has not been fully resolved. The variability in the compaction of sediments means that correction factors are rarely applied. However, if sea-level research is limited to using compaction-free basal peats whose underlying strata can be determined to have a sufficient slope, this would severely limit the presently available database. Furthermore, there are problems in defining the indicative meaning for samples from the base of basal peats. Although samples from the top of basal peats will have a well-defined indicative meaning, they are themselves subject to some compaction.

2.7.5 Dating of sea-level index points

One of the fundamental assumptions of both AMS and 'conventional' ^{14}C dating is that the production of atmospheric ^{14}C has remained constant in time and space. However, Vries (1958) showed that wood samples collected in the seventeenth century contained greater than expected levels of ^{14}C. Suess (1970, 1978, 1980) confirmed that ^{14}C production has fluctuated through time by dendrochronological cross-matching with the Bristlecone-pine tree-ring record. Superimposed on the calibration curve are 'Suess wiggles'. These are non-random changes in atmospheric ^{14}C on an approximate 100 year timescale (Suess 1980, 1986; Stuiver *et al.*, 1991; Stuiver and Braziunas, 1993). The impact of variations in atmospheric ^{14}C production, particularly medium term 'Suess wiggles', on the interpretation of ^{14}C data is considerable. Van de Plassche (1986) noted that the plateaux in Suess's calibration curve can cause spurious clustering of SLIs. Accordingly, ^{14}C dates in this thesis are calibrated to sidereal years using the CALIB 3.0 program (Stuiver and Reimer, 1993). There is a general tendency for radiocarbon ages to be younger than calibrated ages during most of the past 20 ka (Figure 2.2). Moreover, the age range of one or two standard error calculations for calibrated ^{14}C dates is generally double that of the ^{14}C timescale (Bartlein *et al.*, 1995). The standard deviations indicate the precision of the measurement of the sample's radioactivity and the likelihood that the level of radioactivity represents a particular age.

Further problems with ^{14}C dating are associated with isotopic fractionation. During photosynthesis ^{12}C is preferentially absorbed by plants relative to ^{14}C (van de Plassche, 1986; Twiddy, 1997) and, therefore, the plants are deficient in ^{14}C compared to the atmosphere (Bowen, 1978; Olsson, 1979, 1986). The problem is corrected through laboratory analysis of the ^{13}C isotope. The known ^{14}C:^{12}C ratio is approximately twice that of ^{13}C:^{12}C ratio. Therefore, if ^{13}C is calculated, then isotopic fractionation can be corrected.

The known ^{14}C:^{12}C can be diluted by the 'hard water error' which is unique to areas of carbonate rock. In these areas groundwater is enriched in dissolved inorganic carbon that will be absorbed during photosynthesis. The amount absorbed is variable, although in extreme cases it could be up to 50 % of the total carbon (Hedges, 1991). This carbon is older than the atmospheric ^{14}C and dilutes the ^{14}C:^{12}C ratio. Hedges (1991) and Olsson (1986) stated that different plants absorb ^{14}C at different rates. Therefore, AMS dating of selective plant remains is one method of reducing the hard water error.

Additional errors are largely the result of contamination. Contamination of a ^{14}C sample occurs as the result of incorporation of either older carbon during sediment accumulation or younger carbon after deposition. Old carbon, such as the dissolved inorganic carbon of the hard water error, is an allochthonous component. Contamination by younger carbon occurs as the result of root penetration or downward movement of humic acids. Careful screening procedures can remove some contaminants. AMS dating has an obvious advantage due to the smaller mass of material needed, although the smaller the sample the greater the possible effect of contamination (Shore *et al.*, 1995).

2.8 Interpretation of Sea-level Index Points

There are two established techniques in sea-level research that are used to interpret SLIs: age/altitude analysis; and tendency analysis.

Age/altitude analysis attempts to determine how sea level has varied by plotting data points on a scatter plot with altitude as the dependent variable. Initially this scatter was summarised by a single line. One of the earliest such diagrams was completed by Godwin (1940). He applied pollen analysis to sea-level research as a method to relatively date sediments but was aware of the possible errors. Following the advent of ^{14}C dating (Libby, 1952) an absolute date could be assigned to samples of known altitude and indicative meaning. Subsequently numerous sea-level curves were produced on global, regional and local scales under the guidelines of IGCP Project 61 whose stated aim was to establish regional MSL curves (Bloom, 1977). Excluding sea-level curves from formerly glaciated regions where isostatic uplift has been more dominant than eustatic rise of sea level, all remaining curves showed similar trends characterised by a decreasing rate of sea-level rise through the Holocene, especially after *ca.* 5000 cal. yrs. BP.

However, a major conflict surrounded the nature of this rise and the possible existence of former periods during the Holocene when sea level was higher than the present.

Evidence for higher sea levels came mainly from raised shorelines in the tropics, particularly in Australia (Daley, 1934; Fairbridge, 1961). The controversy that such shorelines are not typically found in other parts of the world has been resolved following the results of crustal modelling (Clark *et al.*, 1978; Peltier, 1980). These suggested that raised shorelines should be expected in locations remote from the centres of ice loading, following the adjustment of the earth to a redistribution of the ice and water load. Chappel (1974) has shown how hydro-isostatic processes can lead to outer shelf subsidence and inner shelf uplift and, therefore, relict raised shorelines.

As to the nature of Holocene sea-level rise, there were two 'schools of thought'. Some researchers accept the ideas initiated by Fairbridge (1961) who suggested sea-level rise is composed of a series of transgressions separated by regressive phases (Morner, 1969; Tooley 1974, 1978a). While they accept that some of the alternations of peats and marine clays may be explained in local terms by, for example, the breaching of beach barriers, they nevertheless interpret many of the intercalating layers of terrestrial and marine sediments to actual changes in sea level. Other researchers suggest sea-level rise took the form of a smooth exponential decay curve (Jelgersma, 1961; Shephard, 1963; Kidson and Heyworth, 1973, 1979; Kidson, 1977). They interpret alternations of marine and terrestrial sediments in terms of local geomorphic changes and as consequences of differential rates of sea-level rise, sedimentation and isostatic rebound.

Tooley (1978a), whose work in north-west England belongs to the first 'school of thought', identified ten distinct marine transgressions during the Holocene (Figure 2.3). The transgressions were interpreted from clays, silts and sands deposited under brackish-water or full marine conditions. These are separated by biogenic sediments of limnic or terrestrial origin. ^{14}C dates on biogenic material which intercalate the marine sediments provide a chronology for the transgressive sequence. These were compared with sequences established in England and Wales and north-west Europe. Subsequently, Tooley (1978a) proposed a correlation of marine episodes in north-west Europe. The establishment of a synchronism of marine episodes, irrespective of local and regional factors, would permit conclusions to be made about eustatic and palaeoclimatic oscillations.

In contrast, Kidson and Heyworth's (1978) sea-level curve for the Somerset Levels showed a smooth almost exponential rise in sea level with no evidence of minor regressions or renewed transgressions (Figure 2.4). They regarded Holocene sequences of intercalating peats and clays as responses to minor variations in the relative rates of sedimentation and sea-level rise. Godwin (1956) interpreted the thicker marine clays found on the coastal fringes of the Somerset Levels in terms of a renewed transgression in the late Holocene. However, Kidson and Heyworth (1978) did not accept this interpretation and suggested that the cumulative effect of occasional high sea levels caused by large storms, storm surges and long period of tides account for all the evidence put forward by Godwin (1956). Kidson and Heyworth (1978) stated that there is no evidence in the Somerset Levels of Holocene sea levels being higher than that of the present.

The two 'schools of thought' suppressed relevant information and stagnated sea-level research. Harvey (1969) stated that one school may regard the explanation offered by another as unacceptable and unreasonable. This amounts to choosing what Kuhn (1962) terms a 'paradigm'. In seeking a paradigm, the controversy between the two schools of thought could be rejected and research could then be concentrated on how to evaluate past altitudes of relative and absolute land-level and sea-level. Shennan (1982, 1986) believed the way forward was the development of standard methodologies for lithostratigraphical and biostratigraphical analyses. Shennan (1983) produced a flow diagram of research methods based upon continual assessment of errors (Figure 2.5). SLIs plotted on an age/altitude graph should be shown as transgressive or regressive overlaps with an error box that demonstrates the range of the indicative meaning and a full assessment of altitudinal and age errors (van Straaten, 1954; Kidson and Heyworth, 1979; Streif, 1979; Shennan, 1982; Tooley, 1982b). However, Shennan *et al.* (1983) noted that it is difficult to evaluate the accuracy of chronological correlation schemes based on a comparison of sea-level curves from a broad sea-level band. For example, two SLIs, one transgressive and the other regressive from the same borehole, separated by 20 cm of marine clay, will have error boxes that will greatly overlap. If these index points are plotted on a sea-level band they will be smoothed and will not indicate their differing tendencies.

Tendency analysis offers an alternative approach based on direct investigation of the timing of changes in marine influence (Morrison, 1976). This method uses only age and tendency of index points, ignoring altitude altogether (Curray, 1964; Geyh, 1971; Roeleveld; 1974; Griede, 1978). Furthermore, it allows the application of statistical techniques in sea-level studies. Shennan *et al.* (1983) stated that the application of the tendency approach allows objective correlations between rising and subsiding areas. The method relies on consistent definition of terms, particularly the terms transgression and regression (Section 2.3). The relationship between transgressive and regressive overlaps and former sea levels has been questioned by Godwin (1975), Tooley (1978a) and Long (1991). For example, a change in sea-level movement from negative to positive will take place within the organic sediments and the actual lithological change from semi-terrestrial to a marine or brackish deposit will be a point within the continuous process of a positive tendency. Therefore, unless the method of definition is clearly stated then the correlation between different areas is meaningless. This is particularly important as the great advantage of the tendency approach is that it incorporates a range of SLIs from a variety of palaeoecological environments.

A valuable approach has been to archive SLIs in a central database with standardised entries and defined error margins that eliminate poor or unreliable data (Morrison 1976; Tooley 1982b, 1987; Shennan, 1982, 1989). This depends largely upon the methods of description, analysis, classification and presentation of data by the original authors. After rigorous screening, Morrison (1976) compiled a database for the western European seaboard of 700 ^{14}C dates. Following this method, Shennan (1982) and Tooley (1982b) collected 782 ^{14}C dates. Verification of each date led to rejection of approximately half. The remainder were ^{14}C dates from peats showing some relationship to sea level. This enabled the identification of local and regional tendencies of Holocene sea-level changes (Long, 1991). Tooley (1978a, 1982a, 1982b) showed the database as frequency histograms, which display the temporal pattern of dates, and as cumulative frequency histograms showing positive and negative sea-level tendencies. These diagrams show the unevenness in space and time of SLIs in the UK. The database has increased in size to 1574 data points since 1989 with approximately half rejected after verification (Shennan, 1995).

2.9 Summary

Understanding of former sea levels is based either on regular measurements of tide gauges or on the identification and interpretation of natural or artificial indicators that may have a vertical relationship with a reference water level (van de Plassche, 1986).

Sea-level indicators can be collected from a wide variety of palaeoenvironments. Typical sources include geological (lithostratigraphical) and palaeobiological (biostratigraphical) indicators. Extensive collection of corroborating data is needed to confirm the meaning of a particular sea-level indicator. Thus, a diverse range of analytical methods have been developed to obtain and evaluate relevant data in the production of SLIs (van de Plassche, 1986). Former sea levels may be examined with reference to transitions between marine and terrestrial sedimentation, although relationships are not always precise. For example, variations in past tidal regimes, wave climates and sediment supply mean that alternations between terrestrial and marine sedimentation are not always indicative of sea-level change.

Chapter Three: Saltmarsh microfossils

3.1 Introduction

Pollen assemblages are the most commonly used sea-level indicators. Pollen from saltmarsh and terrestrial taxa are frequently used to infer the palaeoenvironment. They may be complemented by diatom analysis which provides further information regarding the degree of marine influence. Although these indicators are employed in both North American and European studies, the use of foraminifera has become increasingly important. Scott and Medioli (1978, 1986) stated that assemblages of agglutinated saltmarsh foraminifera are the most accurate sea-level indicators on temperate coastlines and that the assemblages exhibit a strong correlation with elevation above MSL.

The aims and objectives of this chapter are as follows:

- Introduce a series of environmental variables that may influence the modern distribution of foraminifera;
- Discuss the preservation potential of intertidal foraminifera;
- Develop a foraminiferal sampling methodology to facilitate the evaluation of intertidal foraminifera as sea-level indicators;
- Summarise the methodology and taxonomy of diatom and pollen analyses.

3.2 Foraminiferal analysis

Foraminifera are classified as protozoans because they consist of a single cell which is made up of protoplasm with one or more nuclei. The soft tissue of the foraminiferal cell is largely enclosed within a shell (test) variously composed of secreted organic matter (tectin), secreted minerals (calcite, aragonite or silica) or agglutinated particles. Although foraminifera are known to live on the sea floor (benthic) and in suspension in the water column (planktic), it is only benthic species that live in brackish and nearshore areas such as saltmarshes. Planktic species have environmental requirements which are best met in oceanic areas.

Early studies of foraminifera were concerned with taxonomy (Montagu, 1808; Parker and Jones, 1859; Brady, 1884). Although this focus of research continues at present (Bronnimann and Whittaker 1988; Bronnimann *et al.*, 1989), ecological studies of foraminifera are gaining more importance. Most of the ecological studies have been carried out with the aim of providing a contemporary database with which fossil foraminifera can be compared and interpreted (Murray 1973, 1991; Boltovskoy and Wright, 1976).

In terms of foraminiferal distributions, the intertidal zone can be divided into two parts. First, an agglutinated assemblage that is restricted to the vegetated marsh. Second, a calcareous assemblage that dominates the mudflats and sandflats of the intertidal zone. The agglutinated assemblage is commonly employed as a sea-level indicator in the production of SLIs. Saltmarsh foraminiferal zonation is a significantly more accurate indicator of sea level than undifferentiated marsh deposits because well-defined zones subdividing the marsh increase the vertical resolution of the deposits (Scott and Medioli, 1978). Certain assemblages exhibit a higher accuracy (i.e. smaller vertical range) than others. For example, along the upper edge of Chezzetcook Marsh, Nova Scotia, Scott and Medioli (1978, 1980a) identified a 100 % *Jadammina macrescens* assemblage restricted to a 6 cm vertical range just below HAT. They claimed that the upper boundary of this zone is indicative of HAT with an accuracy of ± 5 cm.

Although calcareous foraminifera are often present within the contemporary marsh assemblages, they are largely ignored in the production of SLIs due to problems of preservation of the calcareous tests in fossil saltmarsh deposits (Scott and Medioli, 1980a; Scott and Leckie, 1990; Jennings and Nelson, 1992). Calcareous tests are rapidly destroyed after death through dissolution. Dissolution occurs near the sediment-water interface where a lowered pH associated with organic matter decomposition and sulphide-ammonia oxidation drives the reaction (Green *et al.*, 1993). However, Green *et al.* (1993) noted that calcareous foraminiferal preservation can occur within marsh deposits where the tests bypass the dissolution zone either through biogenic subduction or falling into tubes or burrows. Calcareous tests are rarely found within fossil saltmarsh deposits but they are found in abundance within the fossil mudflat and sandflat deposits.

3.2.1 Foraminifera and environmental variables

Employing foraminifera to determine former sea levels requires that their contemporary distributions and controlling environmental variables are established (de Rijk, 1995a) (Figure 3.1). This is particularly important because differences between rates of sea-level rise and sedimentation will cause shifts in the altitudinal and spatial distribution of foraminiferal zones (Thomas and Varekamp, 1991). With respect to each environmental variable there are five critical limits for foraminifera: lowest level for survival; lowest level for successful reproduction; optimum level; maximum level for reproduction; and maximum level for survival.

3.2.1.1 Elevation

The elevation relative to MSL has been isolated previously as a primary influence on foraminiferal distributions, and has been employed to produce vertical zonation within the intertidal zone (Scott and Medioli, 1980a). Contemporary foraminiferal assemblages commonly reflect the same major marsh zones indicated by the distribution of vascular plants, (Phelger and Walton, 1950; Murray, 1971; Scott and Medioli 1980a) although many local habitat factors influence the exact composition of individual foraminiferal assemblages. Scott *et al.* (1990) illustrated that foraminiferal assemblage zones in the northern hemisphere mirror those of the southern hemisphere. Moreover, studies from North America (Scott and Leckie, 1990), South America (Scott *et al.*, 1990; Jennings *et al.*, 1995) and Italy (Petrucci *et al.*, 1983) indicated that low and high marsh foraminiferal assemblage zones can be recognised world-wide. The high marsh zone is dominated by agglutinated species such as *J. macrescens* and *Trochammina inflata* whereas increased numbers of *Miliammina fusca* are found in low marsh zones.

Scott and Medioli (1980a) stated that the duration and frequency of tidal exposure are the most important variables controlling the distribution of foraminifera within the intertidal zone with salinity the next most significant variable. However, Jonasson and Patterson (1992) found that the effect of salinity is much more pronounced where there is considerable mixing with fresh water such as at the landward margins of a saltmarsh. Furthermore, foraminiferal assemblages may be controlled by a number of variables (e.g. salinity, temperature, dissolved oxygen, etc.) which may have no direct relationship to altitude in the tidal frame (Murray, 1971; Patterson, 1990; de Rijk, 1995a).

The depth of water overlying the foraminiferal habitat is a direct function of elevation. There have been many observations of the relationship between foraminiferal distributions and water depth (Bandy, 1960). Murray (1968) stated that the range of depths encountered in intertidal zones are too small to be significant.

3.2.1.2 Nutrition

Most foraminifera are detritus feeders that feed upon organic debris. Organic debris is abundant within the intertidal zone and is not considered to be a limiting factor (Murray, 1991). However, herbivore behaviour has been observed for some species such as *T. inflata* and *M. fusca* (Bender, 1989). Bender (1989) observed that *M. fusca* feeds on pennate diatoms and does not survive when other food is offered. Furthermore, the availability of food affects the morphology of foraminiferal tests (Boltovskoy *et al.*, 1991). Reduced nutrition may yield smaller tests and the overabundance of food restricts pseudopodial activity and inhibits test growth (Arnold, 1954).

3.2.1.3 Oxygen

Low dissolved oxygen conditions can be detrimental to foraminifera. Diurnal variations in the intertidal environment are greater than in any other marine environment (Bradshaw, 1968). The large diurnal variations are in sharp contrast to the constant dissolved oxygen values found in the open ocean. Prolonged exposure of *Ammonia beccarii* to oxygen saturation levels below 25 % causes dwarfed, thin walled and less ornamented tests (Bradshaw, 1968; Boltovskoy *et al.*, 1991). There was a similar detrimental effect when oxygen levels increased above 200 % saturation. The exclusion of open ocean species from the marsh habitat may be partly due to their inability to tolerate either high or low oxygen values (Bradshaw, 1968).

3.2.1.4 pH

The pH variations within the intertidal environment are greater than in any other marine environment (Bradshaw, 1968). The pH has an effect on both the protoplasm cell and the calcareous test of foraminifera. The cell must remain between relatively narrow pH limits for survival. Experiments have shown that *A. beccarii* cannot survive for more than 75 minutes at a pH of 2.0, or more than 37 hours at a pH of 9.5 (Bradshaw, 1968). Low pH creates a stress situation for calcareous foraminifera: specimens must spend considerable energy recalcifying their tests (Boltovskoy and Wright, 1976). Phelger (1970) found a high correlation between low pH and low foraminiferal abundance and diversity. Boltovskoy and Wright (1976) found evidence of dissolution (etching) of the calcium carbonate tests where the pH of the environment was below 7.8. Alve and Nagy (1986) reported dissolution of tests under a pH range of 6.5 to 7.2. Maximum dissolution occurs during winter when the solubility of calcium carbonate increases (Arnal, 1961).

3.2.1.5 Salinity

Salinity within the intertidal zone varies with time as a result of alternating periods of tidal inundation, desiccation, evaporation and heavy rain. The effect of continual increases and decreases in salinity upon foraminifera is unknown (Boltovskoy *et al.*, 1991). However, each foraminifera has specific limits of tolerance to salinity. The minimum and maximum salinity range for successful reproduction is small compared to those for survival (Bradshaw, 1968; Murray, 1968). Morphological variations will occur if a given species exists outside its salinity limits for growth. Numerous observations suggest that low salinities result in species becoming smaller and thin walled with their ornamentations decreased or absent (Boltovskoy *et al.*, 1991). Limited information is available on the effects of high salinities on test morphology. Scott and Medioli (1980a) suggested that the development of the two ecophenotypes of *T. macrescens* (forma *macrescens* and forma *polystoma*) are the result of differing salinities: forma *polystoma* develops at higher salinities (> 20 ‰); and forma *macrescens* at lower salinities.

3.2.1.6 Substrate

Foraminiferal species live in a variety of substrates with sediment being the most common. Some foraminifera live on the firm surfaces of plants. However, not all plants are suitable substrates, for example, *Codium* and *Fucus* rarely support foraminifera (Matera and Lee, 1972). Foraminifera can be subdivided into those that live on the substrate (epifaunal) and those that live within the sediment (infaunal) (Table 3.1). Furthermore, species can be free living and are able to move using their pseudopodia, or attached, either by their pseudopodia (clinging) or by cementation (sessile).

Previous observations of the relationship between sediment and foraminiferal distributions have concentrated on agglutinated species. Agglutinated foraminifera use specifically sized sediment particles (2 to 20 μm) for building their tests (de Rijk, 1995a), and, therefore, an absence of these may limit their distribution. However, much of the literature concerning the relationship between sediment and foraminiferal distributions is contradictory. For example, Jones and Ross (1979) and Dublin-Green (1992) found that sediments with silt-clay substrates supported the largest numbers of *M. fusca*. Conversely, no such relationship was observed in similar sediments by Murray (1968) in Christchurch Harbour, England or by de Rijk (1995a) in the Great Marshes, Massachusetts.

The influence of organic matter within the substrate on foraminiferal distributions is variable (Boltovskoy and Wright, 1976). High concentrations of organic matter can produce acidic conditions that are detrimental to foraminifera. Conversely, such high concentrations may enhance the nutritive content of the substrate and, therefore, favour survival, growth and reproduction (Boltovskoy and Wright, 1976).

	Epifaunal	Infaunal
Free	*Quinqueloculina*	*Ammonia*
	Triculina	*Cassidulina*
	Elphidium	*Elphidium*
		Uvigerina
Clinging	*Rosalina*	*Trochammina*
	Hanzawia	*Elphidium*
	Pararotalia	
	Elphidium	
Sessile	*Cibicides*	*Lepidodeuterammina*
	Rosalina	
	Nubecularia	

Table 3.1 The relationship between benthic foraminifera and substrate (Source: Murray, 1991).

3.2.1.7 Temperature

Air temperature directly affects intertidal foraminifera when large areas are exposed at low tide. At high tide, the temperature of the sediment is determined by the water temperature. Each foraminifera species will have its own temperature tolerances. Murray (1968) noted that the time of the year for reproduction varied according to the air and water temperature requirements of the species. Furthermore, in the winter when temperatures and salinities were low the foraminifera went into a state of near hibernation (Murray, 1968). The effect of temperature may be important in late glacial to early Holocene sites when there were large temporal changes in temperature.

3.2.1.8 Vegetation

Vegetation interacts chemically and physically with environmental variables. The interactions include: lower temperature ranges produced by shading beneath vegetation and algal mats; protection against desiccation; and creation of support so that micro-organisms can remain in an aerobic environment (Murray, 1991; Dublin-Green, 1992; de Rijk, 1995a).

3.2.2 Post-depositional changes of foraminiferal assemblages

A sample taken from a life assemblage can reveal information on the stages of growth and relative and absolute abundance of the individual species (Murray, 1991). The death assemblage can reveal similar information but differs from the life assemblage due to life processes and post-depositional changes (Figure 3.2).

Production is defined as the number of living tests per unit area per unit time. The rate of production depends upon initial size of the standing crop, the number of individuals that reproduce, frequency of reproduction and number of progeny. Reproduction results in the foraminifera cell vacating the test. Therefore, all empty tests, either from reproduction or death are added to the death assemblage. All life assemblages are subject to variations in production and the death assemblages are affected by its cumulative effects. The composition, diversity or density of death foraminiferal assemblages can be further altered by post-depositional changes. Post-depositional changes invariably function with the same intensity in all environments (Murray, 1991) and, therefore, in some environments the alteration may be insignificant whilst in others the change may completely alter the death assemblage. Jonasson and Patterson (1992) reported that post-depositional changes in sub-surface saltmarsh deposits of the Fraser River Delta, British Columbia, reduced the number of biofacies or assemblages that can be recognised compared to those present at the surface of the marsh. Jonasson and Patterson (1992) further noted that, although both agglutinated and calcareous foraminifera were present in the surface samples, only agglutinated forms were present in the sub-surface.

Post-depositional changes are the result of diagenetic processes. These include selective preservation of foraminifera, transportation of tests away from (loss) and into the assemblage (mixing), bioturbation, infaunal foraminifera and predation on foraminifera.

3.2.2.1 Selective preservation

The preservation of intertidal foraminifera depends on test composition and structure (de Rijk, 1995a). Agglutinated foraminifera are the most widespread marsh species due to their resistance to dissolution in the low pH conditions of marshes (Phelger, 1970; Boltovskoy and Wright, 1976; Alve and Nagy, 1986). However, certain agglutinated species are prone to disaggredation due to the oxidation of the organic lining of the test within surface sediments (Douglas *et al.*, 1980; Godwin, 1993; de Rijk, 1995a). For example, de Rijk (1995a) found that *Pseudothurammina limnetes* and *Polysaccammina ipohalyina* were present in surface samples but not in sub-surface samples. The tests of these species are formed by loose cementation of poorly sorted, coarse grains and are, thus, prone to disintegration. Other species have more robust tests (e.g. *J. macrescens*, *M. fusca* and *T. inflata*) and as a result, are well preserved in sub-surface samples (Goldstein and Harben, 1993; de Rijk, 1995a).

The tests of calcareous foraminifera are subject to dissolution due to the low pH of saltmarsh deposits. The rapid rate of dissolution of calcareous tests within contemporary marsh environments implies that they will be absent in fossil marsh sediments (Scott and Medioli, 1980a; Williams, 1989; Jonasson and Patterson, 1992, de Rijk; 1995a). These conclusions are based on the results of studies from North American saltmarshes. However, these marshes are subject to lower pH levels compared to European marshes due to the increased percentage of organic matter (Gehrels pers. comm., 1996). Therefore, the preservation potential of calcareous tests may increase in European fossil marsh sediments. Furthermore, calcareous foraminiferal preservation can occur within marsh deposits where the tests bypass the dissolution zone either through biogenic subduction or falling into tubes or burrows (Green *et al.*, 1993).

Compaction and drying of sediments can further influence the selective preservation of foraminifera. De Rijk (1995a) found that *J. macrescens* was sensitive to compaction and drying of sediments. Moreover, Specimens in sub-surface samples are often flattened with collapsed chambers (Lehmann and Rottger, 1997).

3.2.2.2 Transportation

A major problem in interpreting foraminiferal assemblages is distinguishing between autochthonous and allochthonous species (Coles and Funnell, 1981). Autochthonous foraminifera have existed at the place of deposition (in-situ) and indicate local environmental conditions whereas allochthonous species have been transported to the place of deposition and supply selective information about the regional environment. The known methods of transport of living and dead foraminifera are shown in Table 3.2.

Transportation by suspended load, bed load or wind (Murray, 1965; Nichols and Norton, 1969) is selective and depends on overall size and specific gravity of the foraminifera. Hence, all things being equal, smaller foraminifera will be subject to greater selective transport (Berger, 1970).

Living species	Living and dead species	Dead species
Species clinging to vegetation uprooted during storms	Bed load	Wind
	Ice	Sediment reworking
	Submarine sediment slides	
	Suspended load	
	Turbidity currents	

Table 3.2 Methods of transport of living and dead foraminifera (Source: Murray, 1991).

3.2.2.3 Bioturbation

Bioturbation commonly occurs in the top 4 cm of sediments below the ground surface with slower, more episodic, bioturbation below this depth. However, bioturbation can occur at depths greater than 12 cm (Aller and Cochran, 1976). The rate varies seasonally and is highest in summer (Green *et al.*, 1993). Bioturbation is critical in promoting the dissolution of calcareous foraminiferal tests as it prevents reaction product build-up and stimulates aerobic metabolites, iron sulphide oxidation and nitrification (Green *et al.*, 1993). Conversely, it can result in foraminifera bypassing the dissolution zone either through biogenic subduction or by falling into tubes or burrows (Green *et al.*, 1993).

3.2.2.4 Infaunal foraminifera

Infaunal foraminifera have been observed in many environments ranging from saltmarsh (Matera and Lee, 1972; Goldstein, 1988; Goldstein and Harben, 1993) to deep sea (Corliss and Emerson, 1990). The occurrence of infaunal foraminifera may significantly alter the species composition of sub-surface assemblages (Goldstein and Harben, 1993). Relative abundances of foraminiferal species that are infaunal and epifaunal may increase with depth compared to those species that are primarily epifaunal.

3.2.2.5 Predation

In sub-tidal environments foraminifera contribute 12 % to the live biomass (Gerlach, 1978). This provides a large potential food source for organisms such as gastropods, crustaceans, prosobranchs, fiddler crabs and some hermit crabs (Lipp and Valentine, 1970; Sliter, 1971). Predation can influence post-depositional changes when the foraminiferal tests are transported or destroyed.

3.3 Foraminiferal sampling

Processing methods can introduce an important source of errors in quantitative microfossil analysis (de Rijk, 1995a). Therefore, it is important to develop a foraminiferal sampling system that will facilitate the evaluation of intertidal foraminifera as sea-level indicators.

3.3.1 Collection and preparation of foraminiferal samples

3.3.1.1 Sample collection in the field

The collection of contemporary samples follows Scott and Medioli (1980a) and de Rijk (1995a). The standard sample volume is 10 cm^3 (10 cm^2 by 1 cm thick). Since the surface material is root bound and difficult to penetrate, a small hand-held corer with sharpened edges was developed following the guidelines of Scott and Medioli (1980a). The sampler is pushed into the surface of the intertidal zone and subsequently retrieved by pulling back while supporting the sample with a knife. The sampler is generally suitable for sampling cohesive sediments such as saltmarsh or mudflat deposits; it is less satisfactory for clean sands and gravels (Murray, 1991). Each sample is placed in buffered ethanol with the protein stain rose Bengal and is sealed in vials and refrigerated to prevent bacterial oxidation of the foraminiferal tests.

Rose Bengal is extensively used to differentiate living from dead foraminifera (Phelger and Walton, 1950; Walton, 1952; Scott and Medioli, 1980b; Murray, 1991). Protoplasm is stained bright red whereas test walls and organic lining are either unstained or lightly stained. It is assumed that tests containing protoplasm are living at the time of collection. However, Boltovskoy and Lena (1970) observed protoplasm in tests collected weeks and even month earlier. Furthermore, it is necessary to check that red staining is not caused by clusters of bacteria or other organisms using the test as a refuge (Murray, 1991). Nevertheless it is superior to other staining techniques such as heat saturated or heat acetylated Sudan black B. These techniques are hampered by similar problems and are more time consuming than the use of rose Bengal (Murray, 1991).

3.3.1.2 Sample preparation in the laboratory

A 2 cm^3 or 5 cm^3 sample volume is used for foraminiferal analysis of fossil samples. Centimetre slices are cut with a sharp knife at specific sampling intervals from augers, cores or monolith tins. The sampling interval used depends upon the lithostratigraphy, biostratigraphy, potential selective preservation, infaunal occurrence and reworking of foraminifera.

Conventional preparation techniques of contemporary and fossil foraminiferal samples are inadequate to isolate foraminifera in sediments with a high organic component (de Rijk, 1995a, 1995b; Lehmann and Rottger, 1997). A solid crust of fine organic material is produced when the sediment is washed, sieved and dried. The crust cannot be broken without the destruction of the tests. De Rijk (1995a) evaluated numerous other techniques and concluded that the use of a wetsplitter (Scott and Hermelin, 1993) provides the most reliable method for the preparation of foraminifera. Each sample is wet sieved through the 500 μm and 63 μm sieves and decanted. The greater than 500 μm and decanted fraction is examined before being discarded. The wetsplitter puts the remaining sample in suspension with approximately 2.5 litres of water which may then be divided into eight, sixteen or thirty-two equal parts. The wetsplitter has the following advantages: the procedure does not lose or damage foraminiferal tests; splitting the sample into representative parts reduces the number of specimens analysed; it increases the number of processed samples per day (Gehrels, 1994a); and the liquid medium makes the foraminiferal tests transparent, thus facilitating the detection of the rose Bengal stain (Scott and Medioli, 1980a; Lehmann and Rottger, 1997).

A pilot study was undertaken to test the accuracy of the wetsplitter (i.e. the similarity between aliquots) for sediments from Cowpen Marsh, Tees estuary.

- **Methods and Results**

A sample was collected and split into eight equal fractions (1 to 8) using the wetsplitter and counted (Table 3.3). Sample collection and preparation (Appendix One) followed Scott and Medioli (1980a) and de Rijk (1995a) and the taxonomy (Appendix Two) followed Murray (1971, 1979) and de Rijk (1995a).

Total foraminiferal percentages (living plus dead) between all splits remain relatively constant. This implies that the wetsplitter can be used to produce reliable results that are representative of the foraminiferal assemblages from a particular site.

Species	1	2	3	4	5	6	7	8	Mean	SD
Haplophragmoides spp.	3.2	1.2	2.0	1.3	1.3	1.0	1.5	1.0	1.6	0.7
Miliammina fusca	10.2	9.8	8.6	8.3	10.9	11.1	11.5	10.7	10.1	1.1
Jadammina macrescens	60.9	59.8	62	64.7	60.8	66.2	64.6	63.1	62.8	2.1
Trochammina inflata	15.1	15.6	15.0	14.1	15.6	14.5	13.9	15.3	14.9	0.6
Cibicides lobatulus	0.5	0.0	0.9	0.4	0.2	0.2	0.1	0.7	0.4	0.3
Elphidium williamsoni	5.4	5.1	4.7	5.5	4.9	3.7	3.5	4.1	4.6	0.7
Haynesina germanica	3.3	4.6	3.2	2.9	3.9	2.1	3.0	3.0	3.3	0.7
Quinqueloculina spp.	1.4	3.9	3.6	2.8	2.4	1.2	1.9	2.1	2.4	0.9
Total counted	212	232	207	251	206	211	232	216	220.5	

Table 3.3 Total foraminiferal percentages, mean and standard deviation (SD) of eight aliquots from a high marsh sample, Cowpen Marsh.

3.3.2 Determination of the life foraminiferal population

The most commonly collected sample for studies of the contemporary distribution of foraminifera is from 1 to 2 cm deep (Scott and Medioli, 1980a, 1980b; Scott and Leckie, 1990; Jennings and Nelson, 1992; Gehrels, 1994a, 1994b; de Rijk, 1995a, 1995b). This sampling procedure assumes that intertidal foraminifera are primarily epifaunal. However, infaunal foraminifera have been reported in a variety of saltmarshes. Infaunal occurrences may change the composition of death assemblages that accumulate in sub-surface sediments (Goldstein and Harben, 1993). Akers (1971) reported rose Bengal stained agglutinated foraminifera at depths of 30 to 35 cm in Beaufort saltmarsh, North Carolina. Goldstein (1988) further reported rose Bengal stained foraminifera in sub-surface sediments at depths of 8 cm. Goldstein and Harben (1993) found the infaunal *Arenoparrella mexicana* to be virtually absent in the surface sediments but abundant in sub-surface assemblages.

A pilot study was undertaken to test whether infaunal foraminifera alter the death assemblages of sub-surface sediments from Cowpen Marsh, Tees estuary.

- **Methods and Results**

Samples were collected at stratigraphic intervals from selected intertidal environments. Methods followed the guidelines set out in Section 3.3.1.2.

Ten living foraminifera have been identified from the three environments examined (high and low marsh and mudflat). Three agglutinated species (*J. macrescens*, *M. fusca* and *T. inflata*) and two calcareous species (*Elphidium williamsoni* and *Haynesina germanica*) dominate the life assemblage (Figure 3.3). The highest number of living foraminifera for each of these five species was observed in the surface sample (0 to 1 cm depth) which indicates that they are primarily epifaunal. In total, 75.2 % of all living foraminifera are found in the surface sample. However, 24.8 % are found below the surface sample, 7.6 % below 3 cm and 1.2 % below 6 cm. A small life assemblage of *Brizalina inflata* and *Cibicides lobatulus* is found at depths of 9 and 11 cm. This infaunal occurrence of living foraminifera may be due to either the creation of an 'oxygen oasis' around which living foraminifera may cluster (Goldstein and Harben, 1993) or bioturbation, whereby living foraminifera bypass the surface through biogenic subduction or by falling into tubes or burrows (Green *et al.*, 1993).

In summary, the intertidal foraminifera of Cowpen Marsh live primarily in epifaunal habitats. The silt substrate of Cowpen Marsh prevents significant penetration of the sub-surface and, thus, does not allow deep infaunal foraminifera. In contrast, the marshes of Larchmont Harbour, New York (Steinbeck and Bergstein, 1979) and Saplo Island, Georgia (Goldstein, 1988; Goldstein and Harben, 1993) have a more sandy substrate. Infaunal microhabitats can be expected because the oxygenated layer is deeper and the sediment is better aerated (Kitazato, 1994).

3.3.3 Life versus death versus total assemblage constituents

There is much debate about which assemblage constituents to use for foraminifera population studies. Published works on contemporary foraminifera report in terms of life (biocoenosis), death (thantocoenosis) or total (life plus death) assemblages. Many researchers state that the total assemblages most accurately represent general environmental conditions because they integrate seasonal and temporal fluctuations (Buzas, 1968; Scott and Medioli, 1980b; Scott and Leckie, 1990; Jennings *et al.*, 1995; de Rijk, 1995a). However, Murray (1982, 1991) suggested that the use of total assemblages disregards changes that will affect life assemblages after their death. Furthermore, they are sample dependent because the greater the vertical depth of a sample, the more important will be the death contribution. Murray (1973) stated that only life assemblages can be used to interpret environmental conditions. Nevertheless, only detailed observation of the assemblage over a considerable period of time can be used to determine all aspects of a population (Buzas, 1968).

Many of these studies have concentrated on agglutinated foraminiferal species occupying saltmarsh areas of the intertidal zone. However, this thesis is concerned with both agglutinated and calcareous foraminiferal species, occupying not only saltmarsh environments of the intertidal zone but also mudflat and sandflat environments.

A pilot study of seasonal and post-depositional analyses was undertaken to determine which assemblage constituents are most appropriate to identify the patterns of contemporary foraminiferal distribution across the intertidal zone from Cowpen Marsh, Tees estuary. The death, life and total foraminiferal assemblages were compared over a twelve-month period to determine their relationships.

- **Methods and Results**

Samples were collected at two-weekly intervals for a period of twelve-months from selected intertidal environments of Cowpen Marsh, Tees estuary. Methods followed the guidelines set out in Section 3.3.1.2

The foraminiferal death assemblage of Cowpen Marsh remains relatively stable during the twelve-month period. This is despite seasonal fluctuations in the life assemblage (Figure 3.4). The death assemblage ranges from 6215 in May 1995 to 10264 individuals in July 1995 with a coefficient of variance (V_c) of 0.13. In contrast, the life assemblage fluctuates between 1240 individuals in February 1996 and 7768 individuals in July 1995 with a V_c of 0.36. The total assemblage fluctuates between 9464 individuals in February 1996 and 18032 individuals in July 1995 with a V_c of 0.14.

Analyses of the relative abundance of six selected foraminiferal species from Cowpen Marsh reveal that the foraminiferal death assemblage remains relatively stable (Figure 3.5). The fluctuations of the life calcareous and agglutinated assemblage are more pronounced than for the dead foraminifera. For example, the relative abundance of living *H. germanica* ranges from 8 % in September 1995 to 30 % in July 1995 with a V_c of 0.31 and the relative abundance of total *H. germanica* ranges from 13 % in February 1996 to 28 % in May 1995 with a V_c of 0.20. The relative abundance of dead *H. germanica* ranges from 12 % in February 1996 to 26 % in June 1995 with a V_c of 0.19.

The pilot study was further extended to determine which modern assemblage constituents are the most appropriate for palaeoenvironmental reconstructions. Surface and sub-surface samples were collected from high, middle and low marsh and mudflat environments of Cowpen Marsh. Sub-surface samples were collected at a depth of 7 cm: virtually all infaunal activity within Cowpen Marsh occurred above this depth (Section 3.3.2).

The scatter plot (Figure 3.6) and Pearson's correlation coefficient (r = 0.84) show a positive linear correlation between sub-surface and death assemblages. The death assemblage fluctuates little between sub-surface and surface because the majority of calcareous species are minor contributors to death surface assemblages in intertidal environments. In contrast, the life and total assemblages in intertidal environments show non-linear relationships between the sub-surface and the surface. The life and total assemblages of the surface sample incorporate living calcareous species which can represent over 40 % of the assemblage. However, post-depositional changes result in calcareous species being removed and the sub-surface assemblage becomes dominated by agglutinated species. The scatter plots of sub-surface versus surface death and total assemblages show one anomalous data point associated with relatively high death and total percentages of *H. germanica* (57 % and 45 %, respectively) compared to the sub-surface value (24 %).

In summary, foraminiferal death assemblages differ from life assemblages through life processes and post-depositional changes. The twelve month study of death foraminifera assemblages described here indicates that the assemblage is in equilibrium with the depositional environment in which it is found. Death assemblages are removed from most seasonal fluctuations in life assemblages and, furthermore, sub-surface assemblages, that are the foci of palaeoenvironmental reconstructions, accurately represent the death surface assemblage.

3.4 Diatom analysis

Diatom analysis will be used together with foraminiferal and pollen analyses to confirm the meaning of a particular indicator. Furthermore, in the absence of suitable foraminiferal data, diatom analysis will be used to quantify the indicative meaning of SLIs. Diatom sample collection will follow the sampling system developed for foraminiferal analysis.

Diatoms are unicellular algae with chrysophyte-like photosynthetic pigments. The cell wall is silicified to form a frustule, comprising two valves. Diatoms have been recorded and classified for over 200 years. In the late 1890's the systematic and taxonomic investigations of contemporary and fossil diatoms began to be supported by studies of distributional ecology (Cleve, 1894-1895). However, it was not until the 1920's that diatom analysis was recognised as a valuable tool in reconstructing palaeoecological changes (Cleve-Euler, 1922; Lundqvist, 1924). In coastal sediments, diatoms are used to record environmental changes in salinity (Juggins, 1992) and tidal exposure (Denys, 1994; Hemphill-Haley, 1995a, 1995b). In freshwater sediments they provide information on the trophic state and pH (Cholnoky, 1968).

Round (1991) stated that diatoms preserved in sediments from continental margins will reveal a complex history of sea-level changes. Indeed, diatom analysis has been much more widely employed to reconstruct former sea levels than foraminiferal analysis (Tooley, 1978a; Palmer and Abbott, 1986). Diatom assemblages have been used to interpret changes in the degree of marine influence (Shennan *et al.*, 1996a; Zong and Tooley, 1996; Zong, 1997a) and as precise sea-level indicators (Shennan *et al.*, 1995, 1996b; Innes *et al.*, 1996; Zong, 1997b).

The study of the ecology of contemporary diatom distributions has shown salinity to be the dominant control (Hendey, 1964). Accordingly many species have been classified based upon their salinity (halobian) preference (Hustedt, 1927-1966; van der Werff and Huls, 1958-1974). Polyhalobian and mesohalobian classes represent marine conditions and oligohalobian forms indicate freshwater environments. Recently, Vos and de Wolf (1993) coded diatoms based upon the importance of life form (planktic, benthic and epiphytic), substrate preference, pH, nutrient content, temperature, duration and frequency of tidal exposure and salinity. Many of these factors are directly related to elevation. However, the complex ecology of diatom assemblages means that it is difficult to separate the role of each individual variable. Furthermore, laboratory studies show that for some variables the tolerances may be different from those found in field studies (Admiraal, 1977; Admiraal and Peletier, 1980).

Nelson and Kashima (1993) described the modern diatom assemblages along four intertidal transects in the Siuslaw, Coos and Coquille River estuaries in southern Oregon. They stated that the duration of supratidal exposure strongly influences factors such as salinity, sediment temperature, illumination and macrophyte communities in the intertidal zone. They compared the elevational distribution of contemporary diatom assemblages with downcore changes of fossil diatom assemblages. The contemporary assemblages indicate a three-part vertical zonation with a distinctive fresh-brackish water assemblage near the upper border of the marsh. However, the altitudinal range of this assemblage is large (0.7 m) and varies spatially according to the quantities of freshwater seepage and runoff into the marshes.

One of the most difficult problems in interpreting diatom assemblages from intertidal environments is distinguishing between autochthonous and allochthonous species (Brockmann, 1940; Beyens and Denys, 1982). Vos and de Wolf (1988) employed several diatom and non-diatom criteria for identifying whether diatoms are autochthonous or allochthonous (Table 3.4). Of particular importance is the use of other lithostratigraphical and biostratigraphical indicators as corroborating factors.

Diatom related criteria	Non-diatom criteria
Composition of different ecological groups. If two ecological groups do not overlap then one must be allochthonous.	Palaeogeographic location (e.g., marine diatoms are allochthonous in sediments formed in the hinterland of the coastal area).
Positive trends of different ecological groups within sedimentary sequences, especially benthic and epiphytic groups.	Lithology and sediment structure (e.g. epipsammic diatoms are allochthonous in heavy clays).
Occurrence of relatively rare taxa zones where diatoms of the same ecological taxa show a positive trend.	Other palaeoecological indicators such as foraminifera can be employed to confirm autochthonous diatom groups.
Degree of fragmentation of diatom frustrules. When most are unbroken this indicates they are autochthonous.	

Table 3.4 Diatom and non-diatom related criteria for the assessment of allochthonous and autochthonous diatom groups (Source: Vos and de Wolf, 1988).

3.5 Pollen analysis

Pollen analysis will be used in two ways: to support foraminiferal and diatom analyses to confirm the meaning of a particular indicator; and as a relative dating technique (Tooley, 1978a, 1978b). Pollen samples will be collected following the foraminiferal sampling system.

Pollen analysis relies on the fact that all flowering plants produce pollen and that ferns and mosses produce spores. The pollen and spores can be identified by their different structures and sculptures which often allows identification to proceed to species level (Moore *et al.*, 1991). The pollen and spores are more readily preserved within fossil deposits than many other parts of the plants due to their structural chemistry. Furthermore, they are found in sufficient numbers to provide an adequate statistical base for palaeoenvironmental interpretation (Moore and Webb, 1978). Changes in the absolute or relative abundance of different pollen types within a sediment sequence can be used to determine former vegetation and climatic history and, hence, local water levels by analogy with present-day examples (Pennington and Bonny, 1970; Godwin, 1975). Within sea-level studies, pollen analysis has been used to determine the nature of sedimentary changes associated with transgressive and regressive contacts and to provide evidence for changes in groundwater conditions during the accumulation of organic and inorganic sediments which may be related to sea-level changes (Long 1992; Bedlington 1994; Long and Innes, 1995; Shennan *et al.*, 1996a; Zong and Tooley, 1996). Pollen analysis can also provide information on gradual palaeoenvironmental changes within organic and inorganic sediments. Shennan (1994) and Innes *et al.* (1996) have used this information to produce models of sedimentary environments. Moreover, Shennan *et al.* (1995, 1996b) developed quantitative methods to establish the overall pattern of pollen assemblages and their relation to tide levels in order to interpret fossil assemblages. Pollen analysis is also employed as a relative dating technique and, in particular, to provide an independent test of ^{14}C dates.

3.6 Summary

The production of new SLIs within this thesis will concentrate on the analysis of foraminiferal microfossils. Foraminiferal analysis has been chosen in preference to other lithostratigraphical and biostratigraphical techniques because of its potential to quantify the indicative meaning of a range of Holocene SLIs. Contemporary distributions of saltmarsh foraminifera have been related to fossil assemblages (Scott and Medioli, 1980a). Scott and Medioli (1978, 1986) stated that assemblages of agglutinated saltmarsh foraminifera are the most accurate sea-level indicators on temperate coastlines and that the assemblages exhibit a strong correlation with elevation above MSL. Furthermore, the assemblages are well preserved, easily detectable in fossil deposits and occur in high numbers (100 to 200 per cm^3), thereby providing a good statistical base for palaeoenvironmental interpretations. However, the use of foraminifera to determine former sea levels requires the establishment of their contemporary distributions, controlling environmental variables and post-depositional changes.

Lithostratigraphical and biostratigraphical (diatom and pollen) data will be used to corroborate the foraminiferal data to confirm the meaning of a particular indicator. Furthermore, in the absence of suitable foraminiferal data, they will be used to quantify the indicative meaning of an index point.

A series of pilot studies from Cowpen Marsh produced three results that are incorporated in the foraminiferal sampling system of this thesis:

- Preparation techniques of contemporary and fossil foraminiferal samples (Appendix One), following Scott and Medioli (1980a) and de Rijk (1995a), proved adequate to isolate foraminifera in sediments with a high organic component. The data show that the wetsplitter can be used to produce reliable results that are representative of the foraminiferal assemblages from a particular site;

- The intertidal foraminifera of Cowpen Marsh live primarily in epifaunal habitats.
- A long-term study of foraminiferal death assemblages provides the most reliable dataset for studying patterns of foraminifera distributions. Death assemblages are removed from most seasonal fluctuations found in life assemblages and, furthermore, sub-surface assemblages, the foci of palaeoenvironmental reconstructions, accurately represent the death surface assemblages.

Chapter Four: Contemporary intertidal environments

4.1 Introduction

Coastal saltmarshes are complex bio-sedimentary systems occurring within the intertidal zone and are best developed along temperate coasts with low wave energy (Allen, 1993, 1995, 1996; French *et al.*, 1995). They support varied and normally dense stands of halophytic plants. These communities grade seaward into mudflats or sandflats, to which they are genetically related and from which they are often separated by either a ramp or a cliff. Furthermore, saltmarshes may grade upwards to a supratidal zone composed of freshwater marshes and coastal woodland communities. Saltmarshes exhibit a distinct plant zonation that has been variously interpreted as representing successional stages in land-building processes (Steers, 1934, 1960; Chapman, 1940, 1960) or as plant response to environmental stress gradients (Chapman, 1977; Jacobson and Jacobson, 1989). At low tide the marsh is exposed to the atmosphere with variable temperatures, periods of desiccation and periods of precipitation. At high tide it is submerged beneath tidal waters that vary less in temperature but more in salinity, pH and dissolved oxygen. The topography of marshes undulates with local highs representing former channel levees and shallow pools representing unfilled former tidal channels and creeks. These differing elevations have a profound effect on the distribution of flora and fauna of saltmarshes.

Research on the operation of saltmarsh systems has provided considerable insights into their hydrodynamics, ecosystem structure and interaction with other coastal sedimentary and ecological systems. The interaction of biogeographic, climatic, tectonic and tidal factors results in a diversity of saltmarsh forms. While early studies concentrated on the ecology of specific sites (Marsh, 1915; Cozens-Hardy, 1925), later studies have sought to establish general principles of marsh formation and, thus, identified a number of characteristic types. In Britain, Chapman (1941) distinguished between south, east and west coast marshes on the basis of ecological and physiographic differences. Adam (1978) further sub-divided British saltmarshes according to their dominant vegetation types. The east coast marshes have a greater species diversity than either the *Spartina* marshes of the south coast or the *Puccinella/Festuca* marshes of the west coast. Beeftink (1976) and Allen and Pye (1992) devised a genetic classification, segregating marshes into five characteristic forms developed under different conditions of tidal range, salinity and shoreline configuration: open coast; back-barrier; estuarine fringing embayment; and loch or fjord-headed marshes. Tidal range is particularly important as it controls the flux of water, sediment and nutrients to and from the marsh (French *et al.*, 1995).

Four contemporary intertidal environments were selected from the margin of the western North Sea within the RACS area to quantify the indicative meaning of a range of Holocene index points (Figure 4.1). They exhibit a wide range of environments (tidal range, salinity and shoreline configuration) ensuring that most fossil sites anticipated within the LOIS programme have a contemporary analogue (Table 4.1).

Site	Environment	Tidal Range
Cowpen Marsh	Estuarine	Meso-tidal range (6.0 m)
Welwick Marsh	Estuarine	Macro-tidal range (7.9 m)
Thornham Marsh	Open coast	Macro-tidal range (8.0 m)
Brancaster Marsh	Back-barrier	Macro-tidal range (8.0 m)

Table 4.1 Contemporary sites from the western margin of the North Sea.

The aims and objectives of the investigations at each contemporary field site are as follows:

- Systematically study the contemporary fauna, flora and sedimentary characteristics of the intertidal zone using lithostratigraphical and biological techniques;
- Elucidate the relationship between contemporary foraminiferal distributions and a series of environmental variables (altitude, pH, salinity, substrate and vegetation cover);
- Identify the patterns of contemporary foraminiferal distribution across the intertidal zone over an annual cycle;
- Determine the magnitude of seasonal variations in the foraminiferal assemblages;
- Compare the contrasting intertidal zones to identify general and site-specific trends in foraminiferal assemblages and environmental variables;

4.2 Cowpen Marsh

Cowpen Marsh is the principal contemporary site of this thesis. It lies in close proximity to the University of Durham and is, therefore, an ideal site for a time-intensive investigation of seasonal influences. A detailed procedure has been developed for data analysis and interpretation from this site which provides a deductive framework for the subsequent research at Welwick, Thornham and Brancaster marshes.

4.2.1 Environmental setting

The Tees estuary is located on the north-east coast of England with a meso-tidal range (Table 4.2.1) and forms a large proportion of the Tees lowlands which lie between the higher areas of south-east Durham and the North York Moors. The present estuary (Figure 4.2.1) is a small remnant of a once extensive area of tidal flats and shifting channels that have been reduced by successive reclamation phases. Reclamation has had two functions: to improve the navigability of the river; and to provide land for industrial development. The most significant example of these reclamation works was the construction of the breakwaters at the mouth of the Tees in 1882 which profoundly affected sedimentation in the lower estuary. The construction of the new British Steel complex at Redcar in the 1970's completed the development of the southern bank of the River Tees which began in the nineteenth century. On the northern bank development was hampered by an area of tidal flats at Seal Sands. Economic pressures in the 1960's and 1970's led to rapid reclamation of much of the remaining intertidal area to accommodate oil refineries and chemical works. The cumulative effect of over two centuries of human interference is that little of the estuary remains in its natural state. The Tees estuary is for the most part enclosed on its landward side by industrial development, except for the marshes of Cowpen Marsh (Sproxton, 1989).

Cowpen Marsh lies on the north side of the Tees estuary between Greatham Creek and the A178 road. The marsh is a remnant of a once more extensive area of tidal flat. Encroachment on the natural environment began in this area during the early part of the eighteenth century. The building of a seawall in 1740 effectively converted 85% of Cowpen Marsh into freshwater marsh with only the north-eastern corner remaining tidal (Sproxton, 1989). The reclaimed area south of Greatham Creek, formally common land, was acquired by Imperial Chemicals (ICI) in 1921 and was farmed under stint holders from Cowpen Bewley until 1978, and thereafter by ICI. In 1965, 170 acres including all of the saltmarsh area of the creek, was designated as a Site of Special Scientific Interest (SSSI) by the Nature Conservancy Council. Grazing has been halted in the area and Cowpen Marsh has become one of the most important wildlife sites in the Tees estuary.

Lowest Astronomical Tide (LAT)	Mean Low Water Spring Tide (MLWST)	Mean Low Water Neap Tide (MLWNT)	Mean Sea Level (MSL)	Mean High Water Neap Tide (MHWNT)	Mean High Water Spring Tide (MHWST)	Highest Astronomical Tide (HAT)
-2.85 m OD	-1.95 m OD	-0.85 m OD	0.32 m OD	1.45 m OD	2.65 m OD	3.15 m OD

Table 4.2.1 Tide levels for Cowpen Marsh (Source: Admiralty Tide Tables, 1997).

Cowpen Marsh can be divided into high, middle and low marsh on the basis of the vascular flora (Figure 4.2.2). Approximately 90 % of the marsh area is high and middle marsh. The high marsh has the greatest number of floral species and is dominated by *Elytrigia atherica*, *Festuca ovina*, *Limonium vulgare*, *Atriplex* spp., *Plantago maritima* and *Suaeda maritima*. The number of species decreases at the transition between high and middle marsh (2.45 m OD) with the latter dominated by *Aster tripolium*, *F. ovina*, *Salicornia europaea* and *Suaeda maritima*. The transition to the low marsh (2.12 m OD) is marked by a further decrease in number with only *F. ovina* and *Salicornia europaea* remaining.

An assessment of the human influence on the foraminifera of the Cowpen Marsh is possible by comparing the foraminiferal assemblages of the pilot study (Section 3.3) versus Brady's (1870) foraminiferal study of the River Tees. Brady's foraminiferal samples taken from Cowpen Marsh and the Tees estuary are dominated by agglutinated species *Haplophragmoides wilberti*, *Jadammina macrescens*, *Miliammina fusca* and *Trochammina inflata* and calcareous species *Ammonia beccarii*, *Cibicides lobatulus*, *Elphidium williamsoni* and *Haynesina germanica*. Brady's (1870) assemblage compares favourably with the pilot study assemblage, although no quantitative data are presented. Nevertheless, this indicates that there has been little change in the foraminiferal assemblages of Cowpen Marsh during the latter part of the nineteenth century and the twentieth century.

4.2.2 Geological history

The Tees estuary is underlain by a succession of sedimentary rocks of Triassic (Mercia Mudstone and Sherwood Sandstone) and Jurassic (Lower Lias Shales) age which dip gently towards the south-east (Barne, *et al.*, 1995). Outcrops of the bedrock are rare because they are obscured by unconsolidated deposits of Quaternary age. Borings reveal the presence of a broad shallow valley in the solid geology. This proto-Tees valley has been over-deepened to a depth of -30 m OD possibly by ice impinging on the area from the north (Radge, 1939).

Glacial tills, thought to be entirely of Devensian age (Smith and Francis, 1967), infill the proto-Tees valley and cover much of the area to a maximum thickness of 30 m. Overlying the glacial tills is a late glacial lacustrine deposit, the Laminated Clays. Agar (1954) interpreted these as being deposited in a body of freshwater impounded by the receding Devensian ice sheet.

The final ice retreat drained the late glacial lake and allowed free drainage of the postglacial River Tees to a predicted contemporary sea level between - 50 m and - 75 m OD at *ca.* 12000 cal. yrs. BP (Lambeck, 1995). During this process of readjustment the Tees cut a gorge to a depth of - 25 m OD through the Laminated Clays and glacial till and 6 m into the underlying Mercia Mudstone (Agar, 1954). Further incision was halted by Holocene relative sea-level rise which resulted in the infilling of gorges occupied by the Tees and its lower tributaries (Tooley, 1979).

Relative sea-level changes in the Tees estuary area are interpreted from sequences of intercalated peat and clastic sediments of middle Holocene age which are now exposed in the intertidal zone on the open coast at Hartlepool Bay, just north of the mouth of the Tees (Tooley 1978a, 1979). Data from within the estuary come from Thornaby and Cowpen marshes (Shennan, 1992). A thin basal peat formed on pre-Holocene sediments is dated to *ca.* 7000 cal. yrs. BP. Diatom and pollen data indicate that the transitional contact to the overlying intertidal clastic sediments represents a positive sea-level tendency. The regressive contact between these clastic sediments and an overlying intercalated peat bed, interpreted as a negative sea-level tendency from lithostratigraphical and biostratigraphical data, is dated at *ca.* 5250 cal. yrs. BP. This is overlain by further intertidal sediments and the microfossil data confirm the interpretation of a positive sea-level tendency for the transgressive contact which is dated *ca.* 3450 cal. yrs. BP. Relative-sea level has been approximately the same as present since *ca.* 2900 cal. yrs. BP. Any subsequent variations in relative sea-level are not preserved within the stratigraphic record because they are too close to the present ground surface and are, therefore, disturbed by agricultural activities (Plater and Shennan, 1992).

4.2.3 Materials and methods

Thirty-one stations were established along a transect from high marsh to mudflat and they covered the intertidal zone from HAT to below MTL. The stations were placed at marked changes in topography and encompass a wide variety of ecological communities. All stations were levelled to OD using an automatic level and staff. Samples were collected at approximately two-weekly intervals for a twelve-month period. Each sampling date coincided with a spring tide and timing of collection was standardised to approximately six hours after high tide. Three samples were taken from each station: a standardised 10 cm^3 volume (10 cm^2 surface sample by 1 cm thick); an approximate 5 cm^3 volume (5 cm^2 surface sample by 1 cm thick); and an approximate 30 cm^3 volume (30 cm^2 surface sample by 1 cm thick). The standardised sample was employed for foraminiferal analysis. This volume allowed comparison with similar studies (Scott and Medioli, 1980a; Scott and Leckie, 1990; de Rijk, 1995a). It was stored in ethanol, sealed in vials and refrigerated to prevent bacterial oxidation of the foraminifera tests. The other samples were wrapped in plastic and refrigerated for diatom and lithological analyses.

4.2.3.1 Foraminifera analysis

The sample collection and preparation (Appendix One) followed Scott and Medioli (1980a) and de Rijk (1995a) and the taxonomy (Appendix Two) followed Murray (1971, 1979) and de Rijk (1995a). The foraminiferal samples were analysed at two-weekly intervals during the twelve-month period from stations 1 to 31. The preservation of foraminifera was variable with the number of tests counted fluctuating from 0 to 2304 individuals/10 cm^3 sample.

Foraminiferal death assemblages are used for the analysis because, as discussed previously, they are removed from most seasonal fluctuations in life assemblages. Furthermore, the sub-surface assemblages which are the foci of palaeoenvironmental reconstructions accurately represent death surface assemblages (Section 3.3.3).

4.2.3.2 Diatom analysis

Sample collection and preparation (Appendix One) followed Palmer and Abbott (1986). Diatom samples from Cowpen Marsh were analysed once during the twelve-month period from stations 1 to 30 by Dr Y. Zong, Lecturer in Geography at the University of Durham. The 1 cm thick surface samples were collected and mixed in order to remove seasonal variations. Preservation of diatoms was variable but a minimum count of 200 valves was possible for most samples.

Diatom species were identified with reference to Hendey (1964) and van der Werff and Huls (1958-1966), and were grouped according to their salinity tolerance (Palmer and Abbott, 1986). Polyhalobian (salinity > 30 %) and mesohalobian (salinity 0.2 to 30 %) classes represent marine conditions. Oligohalobian (salinity < 0.2 %) forms reflect freshwater environments and may be subdivided as halophilous, indifferent and halophobous taxa. Terminology followed Hartley (1986) and the salinity classes were obtained from de Wolf (1982) and Vos and de Wolf (1993).

4.2.3.3 Environmental variables

Five environmental variables were recorded (altitude, pH, salinity, substrate and vegetation cover). The influences of these variables on contemporary distributions of foraminifera have been discussed previously in Section 3.2.1. It suffices here to note the following:

- Altitude is a surrogate for flooding frequency. Flooding frequency depends upon the elevation above MSL and the surface morphology. It governs the intertidal ecology as it determines porewater salinity and provides a source of nutrients and clastic material for the intertidal zone;
- A low pH creates a stress situation for calcareous foraminifera and may limit their distribution;
- Salinity of the sediment porewater (largely the foraminiferal habitat) is determined by evaporation and infiltration of seawater, precipitation, surface water runoff and seepage of fresh ground water;
- The surface substrate of Cowpen Marsh consists of saltmarsh peat with clay and silt. To characterise the foraminiferal substrate, grain size and loss on ignition were measured;
- Vegetation interacts chemically and physically with environmental variables. Therefore, the composition and density of vegetation can influence foraminiferal occurrence and was also measured.

The environmental variables were recorded four times during the twelve-month period (once every three months) from alternate sites on the transect from stations 1 to 31. Porewater salinity, loss on ignition and grain size analyses were performed following the methods proposed by Lambert *et al.* (1949), Ball (1964) and Folk (1965), respectively (Appendix One). Analysis of pH was completed in the field using litmus paper. The relative abundances of each floral species and total cover (%) were recorded at two weekly intervals from a 4 m^2 area around each sampling station. Vascular flora were identified with reference to Burd (1994).

4.2.4 Foraminiferal assemblages

Fifty-three dead foraminiferal species have been identified from the twelve-month study of surface samples from the intertidal zone of Cowpen Marsh (Figure 4.2.3). The maximum number of species per sample is 24 and the mean sample foraminiferal abundance is 412 individuals/10 cm^3. The Shannon-Weaver (H(S)) and Fisher indices (α) of diversity show an increase in species diversity along the transect from high marsh to mudflat (Figure 4.2.4). The H(S) index increases from 0.0 at station 1 to 2.33 at station 24. Similarly, the α index increases from 0.1 at station 1 to 3.9 at station 22. The α index is more variable than H(S) because there is a tendency for α to increase with sample number (Murray, 1968; Buzas, 1969b; Peet, 1974).

The foraminiferal death assemblages between stations 1 and 31 are dominated by three agglutinated species (*J. macrescens*, *M. fusca* and *T. inflata*) and three calcareous species (*E. williamsoni*, *H. germanica* and *Quinqueloculina* spp.) (Figure 4.2.5). *J. macrescens* and *T. inflata* dominate the high and middle marshes (stations 1 to 10) with a monospecific *J. macrescens* assemblage at the landward limit of the high marsh (station 1). The transition between the middle and low marsh (defined by vascular plant distributions) corresponds to a decrease in the relative abundance of *J. macrescens* and *T. inflata* and an increase in *M. fusca*.

The transition between low marsh and mudflat corresponds to a decrease in mean foraminiferal concentration to 176 dead individuals/10 cm^3 at station 17. The agglutinated species are replaced by the more diverse calcareous species, dominated by *E. williamsoni*, *H. germanica* and *Q.* spp. The maximum abundance of *E. williamsoni* (24 %) and *Q.* spp. (16 %) occurs at the landward limit of the mudflat zone (stations 17 and 19, respectively). *H. germanica* dominates the mudflat zone (stations 17 to 31) with a maximum of 53 % total death foraminifera at station 27.

4.2.5 Diatom assemblages

Seventy-five diatom taxa have been identified from the study of Cowpen Marsh (Figure 4.2.6). The samples from all stations are rich in diatoms except for those from stations 21 and 22 where only 14 and 32 valves are counted, respectively.

The dominant diatoms from high marsh stations are oligohalobous taxa such as *Navicula mutica*, *Nitzschia dubia* and *Achnanthes minutisima* with some mesohalobians (for example, *Navicula halophila*) and halophobes. In addition, a few polyhalobous taxa such as *Paralia sulcata* are found. *Navicula mutica* dominates the landward limit of the high marsh with a maximum abundance of 49 %.

The middle marsh stations are dominated by mesohalobians and oligohalobians such as *Achnanthes delicatula*, *Navicula digito-radiata*, *Navicula halophila*, *Navicula cari* var. *cincta*, *Trybionella hungarica* and *Achnanthes lanceolata*. The maximum abundance of *Navicula halophila* (54 %) occurs at station 9.

The diatom assemblages from low marsh stations are dominated by mesohalobous taxa such as *Achnanthes delicatula*, *Amphora salina*, *Navicula cryptocephala* and *Navicula halophila*. The maximum percentage of *Achnanthes delicatula* (30 %) occurs at station 16.

The dominant diatoms from mudflat stations are polyhalobous and mesohalobous taxa such as *Paralia sulcata*, *Navicula peregrina* and *Navicula phyllepta* with some oligohalobians like *Trybionella hungarica* and *Nitzschia fonticola*. Low diatom valve counts are observed at stations 21 and 22 and correspond with anomalously high abundances of *Paralia sulcata* (64 % and 47 %, respectively).

4.2.6 Environmental variables

Mean porewater salinity increases from a minimum of 8.6 ‰ at the landward limit of the high marsh (station 1) to a maximum of 23.6 ‰ at station 13 (Figure 4.2.7). The transition between low marsh and mudflat coincides with a rapid decrease in salinity values to 11.5 ‰ at station 23. The salinity values from station 2 to 13 (the majority of the high, middle and low marsh) are associated with large standard errors. This variability probably reflects changes in the balance among desiccation, precipitation and tidal inundation across the intertidal zone.

The pH values are relatively constant throughout the year and show small standard errors. Mean pH increases between the high marsh and mudflat with two distinct thresholds: the first between station 1 and 2 where pH increases from 5.4 to 6.0; and the second between stations 7 and 9 (the transition between middle and low marsh) where pH increases from 6.1 to 6.8.

The grain size distribution of Cowpen Marsh is dominated by material from the clay and silt size classes. The clay fraction decreases from high marsh to mudflat. Standard errors for the clay fraction measurements are small indicating little seasonal variability across the intertidal zone. Similarly, loss on ignition (LOI) remains relatively constant between seasonal measurements. The mean values for LOI decrease from a maximum of 56.1 % at station 1 to 12.4% at station 25. The percentage vegetation cover declines across the intertidal zone with pronounced falls at the transitions between middle and low marsh, and low marsh and mudflat.

The scatter plot matrix and Pearson's correlation coefficients (*r*) among all environmental variables are shown in Figure 4.2.8. The scatter plots indicate strong non-linear relationships of altitude versus LOI, grain size, pH, salinity and vegetation cover. The correlation coefficients are only a measure of the strength and direction of a linear relationship between two variables and do not on their own imply any causal relationship. Since nearly all scatter graphs show non-linear relationships among the environmental variables of Cowpen Marsh (e.g. altitude versus salinity), correlation coefficients are disregarded and, subsequently, are not used further.

4.2.7 Relationships between foraminifera and environmental variables

The annual averages of the five environmental variables (LOI, grain size, pH, salinity and vegetation cover) and altitude were related to the annual average of the six most important dead foraminifera found on the intertidal zone. The objective is to determine if any variable, within the ranges observed (e.g. altitudinal values from 3.24 m OD to - 0.35 m OD), appears to control foraminiferal distributions.

4.2.7.1 Foraminifera and altitude

The scatter plot of *J. macrescens* versus altitude (Figure 4.2.9) shows a strong positive non-linear relationship. The taxa's relative abundance increases at altitudes exceeding 2.04 m OD indicating dominance in more elevated environments such as the high and middle marsh. Conversely, the relative abundance of *H. germanica* increases below 2.04 m OD suggesting dominance in low altitude environments with increased flooding frequency such as the mudflat. The scatter plots of *M. fusca, T. inflata* and *Q.* spp show unimodal relationships. The scatter plot for *E. williamsoni* shows a weak relationship with altitude.

4.2.7.2 Foraminifera and LOI

The scatter plot of *J. macrescens* versus LOI (Figure 4.2.10) shows a strong positive non-linear relationship indicating a dominance in environments with organic substrates such as the high and middle marsh. *M. fusca* and *T. inflata* show unimodal relationships with LOI, respectively.

The scatter plot of *H. germanica* shows a rapid decrease in relative abundance at the same LOI values as the increases in *J. macrescens*. *E. williamsoni* and *Q.* spp. show weak relationships with altitude.

4.2.7.3 Foraminifera and grain size

There is a positive relationship (Figure 4.2.11) of *J. macrescens* versus percentage clay fraction which indicates a dominance in environments with a high clay content such as the high and middle marsh. Relatively high abundances of *H. germanica* are restricted to clay fractions below 27 %. *T. inflata, M. fusca, E. williamsoni* and *Q.* spp. show weak relationships with percentage clay fraction.

4.2.7.4 Foraminifera and pH

The scatter plots of the six foraminiferal species versus pH (Figure 4.2.12) show two clusters of points associated with the two distinct thresholds of pH values observed across the intertidal zone. Relatively high abundances of *J. macrescens* and *T. inflata* predominantly cluster between pH values of 5.9 and 6.1 and relatively low abundances cluster above a pH of 6.5. Conversely, the scatter plots of *H. germanica, E. williamsoni* and *Q.* spp. show a cluster of data points with a wide range of abundance at pH values above 6.5 and very low abundances below 6.5. *M. fusca* shows no relationship with pH.

4.2.7.5 Foraminifera and salinity

The scatter plots of foraminiferal abundance versus porewater salinity show that only *J. macrescens* is present when salinities are below 11.5 ‰ (Figure 4.2.13). *H. germanica* shows a clustering of data points with a wide range of abundance between salinity values of 11.0 and 16.0 ‰ with very low abundances outside this cluster. The scatter plots for the other four species show weak relationships with salinity.

4.2.7.6 Foraminifera and vegetation cover

The scatter plot (Figure 4.2.14) of *J. macrescens* versus vegetation cover shows a strong positive non-linear relationship indicating a dominance in environments with dense vegetation cover such as the high and middle marsh. The scatter plots of *H. germanica, E. williamsoni* and *Q.* spp. show high relative abundance at low vegetation cover values. The pattern of the three species varies: the abundance of *H. germanica* reaches a maximum when there is 0 %

vegetation cover suggesting dominance in barren environments such as the mudflat; and the abundances of *E. williamsoni* and *Q.* spp. reach a maximum at the low marsh fringe where vegetation cover is sparse. The scatter plots of *T. inflata* and *M. fusca* show weak relationships with vegetation cover.

4.2.7.7 Synopsis

The scatter plots of six foraminiferal species versus environmental variables show strong relationships with altitude. Moreover, LOI, grain size, pH, salinity and vegetation cover further influence the distribution and abundance of species. However, the scatter plot matrix (Figure 4.2.8) shows that these variables change along the altitudinal gradient of the intertidal zone.

4.2.8 Multivariate analysis of contemporary foraminifera

Two multivariate methods were employed to detect, describe and classify patterns within the Cowpen Marsh foraminiferal dataset: unconstrained cluster analysis; and detrended correspondence analysis (DCA).

Unconstrained cluster analysis was used to classify contemporary samples into more-or-less homogeneous groups (clusters): unconstrained means that clusters do not have to consist of contiguous samples. Cluster analysis produces a nested series of clusters represented as a hierarchy or dendrogram (Prentice, 1986; van Tongeren, 1987). Boxplots of maximum, minimum, median and interquartile altitudes of each station within the cluster were analysed to determine a vertical zonation of the intertidal zone of Cowpen Marsh.

DCA is a frequently used ordination technique which was applied to represent samples as points in a multi-dimensional space. Similar samples are located together and dissimilar samples apart. Birks (1986, 1992) stressed the complementarity of the cluster analysis and ordination. Cluster analysis is effective in classifying the samples according to their foraminiferal assemblage but DCA gives further information about the pattern of variation within and between groups. This is important as the precise boundaries between clusters can be arbitrary (Prentice, 1986).

Cluster analysis and DCA were performed on average monthly and average annual foraminiferal death assemblages (%) from the twelve-month study period (the annual assemblages may suppress monthly variations). Two variants of cluster analysis were used: unweighted Euclidean distance (no transformation or standardisation of the data); and unweighted Chord distance (foraminiferal abundances (%) were replaced by their square root during the analysis). The former variant detects clusters based upon frequencies of dominant taxa whereas the latter places more importance upon the minor taxa when classifying the data. Therefore, comparisons between the two variants indicated whether results were reliable (i.e. essentially the same result whichever option was used). The multivariate analyses were based on computations made with the TILIA program of Grimm, release 2.0 b.0.5, 1991-1993. Only samples with counts greater than 40 individuals and species that reach 5 % of the total sum were included (following Gehrels, 1994a; Shennan *et al.*, 1996b).

4.2.8.1 Cluster analysis

Cluster analysis of **unweighted Euclidean distance of monthly clusters** detects three cluster zones (Figure 4.2.15):

- Zone MEJM is dominated by *J. macrescens* and *T. inflata* with low frequencies of *M. fusca*. The altitudes range from 3.24 m OD to 2.14 m OD (1.1 m) (Figure 4.2.16). However, the upper quartile range is high (0.67 m) because of the incorporation of samples at the landward limit of the high marsh that have a monospecific (*J. macrescens*) assemblage;
- Zone MEMF is dominated by *M. fusca* and *J. macrescens* with low frequencies of *Haplophragmoides* spp., *T. inflata*, *H. germanica*, *E. williamsoni* and *Q.* spp. It is distinct from other zones by having the highest percentages of *M. fusca*. Zone MEMF ranges from 2.38 m OD to 1.94 m OD (0.44 m) with a small interquartile range of 0.09 m (2.18 m OD to 2.09 m OD);
- Zone MEHG is dominated by calcareous species such as *H. germanica*, *E. williamsoni* and *Q.* spp. The zone ranges from 2.09 m OD to - 0.35 m OD (2.44 m) with an interquartile range of 1.61 m (1.88 m OD to 0.27 m OD).

Cluster analysis of **unweighted Euclidean distance of annual assemblages** detects three cluster zones: AEJM; AEMF; and AEHG. (Figure 4.2.17). The zones correspond with the equivalent monthly clusters based on Euclidean distance in terms of sample and species composition (Figure 4.2.18). However, the altitudinal range of annual Zone AEMF is 0.26 m smaller than monthly Zone MEMF.

The second variant, **unweighted Chord distance of monthly assemblages** (Figure 4.2.19) classifies the data into three zones: MCJM; MCMF; and MCHG. The sample and species composition of each zone are comparable with the equivalent monthly clusters based on Euclidean distance. Furthermore, the altitudes of Chord Zones MCJM and MCHG are comparable with Euclidean Zones MEJM and MEHG, respectively. However, the altitudinal range of Chord zone MCMF is 0.20 m larger than Euclidean Zone MEMF (Figure 4.2.20). The three zones produced by Cluster analysis of **unweighted Chord distance of annual assemblages** correspond with the monthly clusters based on Chord distance in terms of sample and species composition (Figure 4.2.21 and 4.2.22). Furthermore, they are identical to the three annual clusters based on Euclidean distance.

To summarise, the various methods of cluster analyses produce essentially the same clusters in terms of sample and species composition and altitudinal range. This implies that the results are statistically reliable.

4.2.8.2 DCA

The first two DCA axes of **monthly assemblages** account for 68 % and 16 % of the total variance of species data (84 % in all) (Figure 4.2.23a, 4.2.23b). Axis One, whose eigenvalue is 0.82, has high positive loadings for minor calcareous species found within the low marsh and mudflat (e.g. *Bulimina gibba*, *Fissurina lucida*, *Oolina hexagona* and *Rosalina williamsoni*) and low positive or negative loadings for agglutinated species found within the high and middle marsh (e.g. *T. inflata, J. macrescens*, *H.* spp. and *M. fusca*) (Table 4.2.2). DCA Axis One scores versus altitude show a strong negative sigmoid correlation (Figure 4.2.23c). Axis One scores from 0.8 to 2.4 show relatively small altitudinal variations whilst the largest altitudinal variations occur with scores greater than 2.4. These scores identify with samples that are dominated by *M. fusca* and *H. germanica*, respectively. Therefore, the species loading and Axis One scores imply that Axis One reflects an altitudinal gradient from high and middle marsh through low marsh to mudflat. In contrast, the loadings and scores of Axis Two (eigenvalue 0.20) do not reflect any major environmental gradient.

The zonations produced by cluster analysis of unweighted Euclidean and Chord distance of monthly assemblages correspond to distinct regions in the ordination diagram. The Euclidean Zones lie on Axis One: MEJM and MEMF are tightly constrained on the ordination diagram; and MEHG is widely scattered (Figure 4.2.23a). Furthermore, the distribution of Zones MEJM and MEMF, and MEMF and MEHG overlap, whereas MEJM and MEHG are exclusive. The Chord Zones (MCJM, MCMF and MCHG) show a comparable arrangement (Figure 4.2.23b).

Species	Axis One	Axis Two	Axis Three
Haplophragmoides spp.	0.75	1.21	0.70
Jadammina macrescens	0.74	1.22	0.48
Miliammina fusca	1.62	0.78	2.44
Tiphotrocha comprimata	1.77	2.24	2.66
Trochammina inflata	-0.50	1.32	1.79
Ammonia beccarii var. *batavus*	4.26	1.51	-0.33
Ammonia beccarii var. *limnetes*	3.48	2.18	1.66
Ammonia beccarii var. *tepida*	4.87	1.56	1.09
Brizalina variabilis	4.38	2.11	0.86
Bulimina gibba	4.62	-1.26	2.16
Cibicides lobatulus	4.09	-0.90	1.76
Elphidium earlandi	2.87	0.35	0.21
Elphidium excavatum	4.26	0.13	0.88
Elphidium incertum	4.08	2.11	1.22
Elphidium magellanicum	4.14	-1.34	2.02
Elphidium williamsoni	2.60	-0.86	-0.30
Fissurina lucida	4.65	0.63	1.92
Fissurina marginta	4.68	-0.96	1.90
Fursenkoina fusiformis	4.55	0.34	0.38
Globigerina quinqueloba	4.14	0.03	2.89
Haynesina germanica	3.12	0.55	1.16
Lagena clavata	4.18	-1.86	1.79
Lagena sulcata	4.45	2.55	-1.50
Oolina hexagona	5.45	2.38	-.83
Quinqueloculina spp.	2.50	2.96	1.79
Rosalina williamsoni	5.24	-1.31	3.91
Variance (eigenvalues)	0.82	0.20	0.11
Percent total variance	68	16	9
Cumulative percent of total variance	68	84	93

Table 4.2.2 Loading and percentages of variance explained by the first three detrended correspondence axes from monthly foraminiferal death assemblages of Cowpen Marsh.

Species	Axis One	Axis Two	Axis Three
Haplophragmoides spp.	-0.05	0.21	1.36
Jadammina macrescens	0.26	0.68	0.00
Miliammina fusca	0.93	0.17	1.20
Tiphotrocha comprimata	-0.5	-0.02	3.79
Trochammina inflata	-0.69	0.62	1.34
Ammonia beccarii var. *batavus*	3.24	0.09	0.38
Ammonia beccarii var. *limnetes*	3.11	1.84	0.47
Ammonia beccarii var. *tepida*	3.33	2.74	0.53
Brizalina variabilis	3.22	-0.38	0.40
Bulimina gibba	3.35	-2.65	0.27
Cibicides lobatulus	3.14	1.42	0.37
Elphidium earlandi	2.41	-0.08	0.44
Elphidium excavatum	3.19	1.06	0.44
Elphidium incertum	3.16	-1.79	0.27
Elphidium magellanicum	3.24	2.71	0.62
Elphidium williamsoni	2.16	-0.89	0.48
Fissurina lucida	3.36	-0.39	0.31
Fissurina marginta	3.41	-3.12	0.34
Fursenkoina fusiformis	3.23	-0.70	0.44
Globigerina quinqueloba	3.28	0.98	0.41
Haynesina germanica	2.75	0.05	0.43
Lagena clavata	3.39	-1.09	0.49
Lagena sulcata	3.19	1.53	0.67
Oolina hexagona	3.33	-2.36	0.20
Quinqueloculina spp.	2.24	2.55	0.44
Rosalina williamsoni	3.53	-2.45	0.56
Variance (eigenvalues)	0.79	0.06	0.03
Percent total variance	87	7	4
Cumulative percent of total variance	87	94	98

Table 4.2.3 Loading and percentages of variance explained by the first three detrended correspondence axes from annual foraminiferal death assemblages of Cowpen Marsh.

DCA of **annual assemblages** produces an ordination diagram controlled by Axis One (Figure 4.2.24a). Axis One (eigenvalue 0.79) accounts for 87 % of the total variation of species data. The species loadings (Table 4.2.3) and the scatter plot of Axis One scores versus altitude (4.2.24b) are comparable with the results from DCA of monthly assemblages. Furthermore, the zonations produced by cluster analysis of unweighted Euclidean and Chord distance of annual assemblages shows each zone lying on Axis One and occupying a particular region in the diagram: Zones AEJM/ACJM, AEHG/ACHG and AEMF/ACMF are mutually exclusive; and Zones AEHG/ACHG show the widest scatter (Figure 4.2.24a).

4.2.8.3 Synopsis

The dendrograms obtained by monthly and annual cluster analyses based on unweighted Euclidean and Chord distance each classify the contemporary foraminiferal death assemblages of Cowpen Marsh into three zones: Zone CIa dominated by *J. macrescens* and *T. inflata*; Zone CIb dominated by *M. fusca* and *J. macrescens*; and Zone CII dominated by calcareous species, notably, *H. germanica*. The similarities between the variants of monthly and annual cluster analyses are further shown in the stacked bar comparisons (Figure 4.2.25). The distribution of monthly Euclidean and Chord zones across the intertidal zone are comparable both in terms of the number and proportion of samples. For example, Euclidean Zones MEMF and Chord Zones MCMF dominate stations 11 to 16. However, the only identical relationship to exist between the two variants is shown for annual Euclidean and Chord cluster zones (Figure 4.2.25c).

Zone	Dominant species	Altitudinal Range (m OD)
CIa	*Jadammina macrescens*	3.24 to 2.22
	Trochammina inflata	
CIb	*Jadammina macrescens*	2.22 to 2.04
	Miliammina fusca	
CII	*Haynesina germanica*	1.99 to - 0.35

Table 4.2.4 Foraminiferal zones of Cowpen Marsh derived from annual clusters based on either unweighted Euclidean or Chord distance.

Therefore, the exact sample and species composition and altitudinal range (Table 4.2.4) of each zone are determined from annual rather than monthly clusters (CIa, CIb and CII are comparable to clusters AEJM/ACJM, AEMF/ACMF and AEHG/AEHG, respectively). The annual constituents are preferred because they are removed from monthly variations and, therefore, can provide more accurate sea-level indicators. This inference is supported by evidence from DCA. The ordination diagrams show that comparable monthly cluster zones overlap whilst annual cluster zones are mutually exclusive. Therefore, the precise boundaries among the former are arbitrary whereas the latter are reliable (Prentice, 1986).

4.2.9 Seasonality

Seasonal variations in foraminiferal populations have been documented in many studies (Buzas, 1965; Jones and Ross, 1979; Scott and Medioli 1980b; Alve and Murray, 1995). Buzas (1965) examined seasonal distribution and abundance of foraminifera in Long Island Sound. He observed that the total number of living individuals was greater in June than in any other sampling month and that this correlated with maximum temperature and abundance of zooplankton and phytoplankton.

However, before starting a seasonality study of foraminifera, careful consideration must be given to the goal of such research. If emphasis is placed purely on biological aspects, the analysis should include important parameters such as life, death and total assemblages and reproductive behaviour. However, the objective of this study is to evaluate the use of dead foraminifera as a tool for reconstructing former sea levels. Therefore, seasonal patterns of contemporary foraminiferal death distributions across the intertidal zone were analysed over an annual cycle.

4.2.9.1 Monthly variations in foraminiferal death assemblages

The death foraminiferal population of Cowpen Marsh remains relatively stable during the twelve-month period compared to the life population (Section 3.3.3). However, the death assemblage ranges from 6215 in May 1995 to 10264 individuals in July 1995 with a standard deviation of 1081 (Figure 4.2.26a). Furthermore, species diversity varies seasonally during the 12 month period. Both the Shannon-Weaver (H(S)) and Fisher indices of diversity reach a maximum during the summer and a minimum during with winter (Figure 4.2.26b). This pattern is related to increases and decreases in the number of calcareous species present. Many species such as *Brizalina pseudopuncta, Lagena laevis* and *Patellina corrugata* are only found at Cowpen Marsh in the summer season.

Seasonal foraminiferal variations may have important implications for multivariate analysis. For example, Figure 4.2.27a shows seasonal variations of the altitudes of three cluster zones detected by monthly cluster analysis of unweighted Euclidean distance. The majority of the variation of the upper boundary of Zone MEJM and the lower boundary of MEHG is due to the absence of certain stations in the cluster analysis (stations 1 to 5: altitudes 3.24 to 2.47 m OD; stations 28 to 31: altitudes 0.17 to - 0.35). However, the altitudinal ranges of the lower boundary of MEJM and the upper boundary of MEHG remain relatively constant during the 12 month period. For example, the lower boundary of MEJM fluctuates from 2.27 m OD to 2.14 m OD. Similarly, the upper and lower boundaries of MEMF remain constant, although MEMF shows two anomalous altitudinal ranges (October 1995 and January 1996). A comparable relationship is observed for seasonal variations in the altitudes of three cluster zones detected by monthly cluster analysis of unweighted Chord distance (Figure 4.2.27b).

The maximum and minimum values can be used to produce monthly error bars for the upper and lower boundaries of each Euclidean and Chord zone (Table 4.2.5). Certain boundaries exhibit higher consistencies than others and, thus, smaller altitudinal ranges. The smallest monthly altitudinal range is observed for lower boundaries of Zone MEJM (± 6.5 cm). Moreover, the monthly error bars for Euclidean zones are less than or equal to the comparable Chord zones, implying that cluster analysis based upon Euclidean distance is less susceptible to seasonal variations. This inference is supported by the maximum under-estimation and over-estimation of equivalent annual zones based on Euclidean and Chord distance.

Method	Monthly zone	Upper boundary (m OD)	Lower boundary (m OD)	Annual zone	Maximum under-estimation	Maximum over-estimation
Euclidean	MEJM	2.855 ± 0.385*	2.205 ± 0.065	CIa	0.82 m*	0.08 m
	MEMF	2.275 ± 0.105	2.015 ± 0.075	CIb	0.26 m	0.10 m
	MEHG	2.015 ± 0.075	0.005 ± 0.355*	CII	0.76 m*	0.10 m
Chord	MCJM	2.83 ± 0.41*	2.18 ± 0.09	CIa	0.87 m*	0.13 m
	MCMF	2.275 ± 0.105	1.995 ± 0.215	CIb	0.46 m	0.18 m
	MCHG	1.805 ± 0.285	0.005 ± 0.355*	CII	1.18 m*	0.10 m

Table 4.2.5 The errors of the upper and lower boundaries of monthly cluster zones and maximum under-estimation and over-estimation of equivalent annual zones based on Euclidean and Chord distance. * The majority of the variation is due to the absence of certain stations (see text).

4.2.9.2 Synopsis

The seasonal death foraminiferal variations modify the patterns of contemporary foraminiferal distribution across the intertidal zone. These variations are reflected in the altitudes of the three cluster zones. Consequently, a contemporary sample taken in one month can significantly under-estimate or over-estimate the altitudinal range of a zone. For example, a contemporary sample taken in one month can under-estimate the altitudinal range of Zone MEMF by as much as 0.46 m. Hence, the value of annual cluster zones as indicators of former sea levels can only be assessed following the consideration of seasonal errors which affect the calculation of their altitudes. Furthermore, comparisons between the two variants of cluster analysis show Euclidean zones to be less susceptible to seasonal variations than Chord zones. This is because the former detects clusters based upon frequencies of dominant taxa whereas the latter places more importance upon the minor taxa when classifying the data. The dominant taxa remain relatively stable during the year (Section 3.3.3), whereas, the species diversity indices show substantial fluctuations of minor taxa.

Seasonal foraminiferal variations have important implications for future contemporary sampling strategies. A contemporary assemblage sampled at any one occasion may or may not be in equilibrium with its environment or be typical of assemblages over a longer time period. Therefore, more frequent detailed observations must be used to assess the value of foraminifera as sea-level indicators.

4.2.10 Summary

The detailed investigation of Cowpen Marsh sought to elucidate the relationship between contemporary foraminiferal distributions and a series of environmental variables. The intention was to identify the patterns of contemporary foraminiferal distribution across the intertidal zone over an annual cycle so they can be related to fossil deposits. The following conclusions were reached:

- Statistical analyses indicate that the foraminiferal death distributions of the dominant taxa of Cowpen Marsh show strong relationships with altitude;
- The contemporary foraminiferal death assemblages of Cowpen Marsh are classified into Zones CIa, CIb and CII. Zone CIa is dominated by *J. macrescens* and *T. inflata*; Zone CIb is dominated by *M. fusca* and *J. macrescens*; and Zone CII is dominated by calcareous foraminiferal species, notably *H. germanica, E. williamsoni* and *Q.* spp;
- The seasonal death foraminiferal variations modify the patterns of contemporary foraminiferal distribution across the intertidal zone and, hence, the altitudes of the three cluster zones. Comparisons between Euclidean and Chord zones show the former to be less susceptible to seasonal variations.

This procedure of data analysis is now repeated for the data collected from Welwick, Thornham and Brancaster marshes with two amendments. First, the relationships between foraminifera and environmental variables are analysed using only altitude. This is because the scatter plot matrix of Cowpen Marsh shows strong relationships between altitude and LOI, grain size, pH, salinity and vegetation cover. Therefore, it is assumed that a similar relationship exists for the other field sites, and altitude is used as a surrogate for other variables. Second, multivariate analyses of the other field sites only involves cluster analysis of average annual assemblages based on Euclidean and Chord distance because annual constituents are more appropriate than monthly cluster constituents. The former are removed from seasonal variations and, therefore, can provide more accurate sea-level indicators. DCA is also omitted because it merely confirms the cluster analysis results.

The omitted analyses are referenced in an appendices 4 to 6.

4.3 Welwick Marsh

The contemporary analysis of Welwick Marsh follows the procedure set out in Section 4.2.

4.3.1 Environmental setting

The Humber estuary is located on the east coast of England (Figure 4.3.1) and is regarded as a type example of a macro-tidal estuary (Table 4.3.1). It is one of the largest estuaries in the UK with a maximum width of 14 km at the mouth and a tidal length of 120 km on the River Trent and 140 km on the River Ouse (Pethick, 1990). The area astride the Humber estuary is a low lying coastal plain drained by small rivers and artificial waterways. The only significant hills are the Lincolnshire Wolds which are typical chalk downlands. Most of the population of the area is concentrated in the Grimsby-Cleethorpes conurbation and in the suburbs of Hull. Commuter settlements extend eastwards from Hull and southwards from Cleethorpes. However, the greater part of the area is given over to arable farming, much of it in very large units, especially on the grade one soils of the reclaimed areas. Hydrocarbons are the basis of the largest industries: the refinery at Killingholme; petrochemicals at Salt End; and the pipeline terminal (from offshore production) at Easington. Although the coast attracts many tourists, much of the shoreline is undeveloped and long stretches of it are reserved for the Ministry of Defence's use and environmental conservation.

Lowest Astronomical Tide (LAT)	Mean Low Water Springs Tide (MLWST)	Mean Low Water Neaps Tide (MLWNT)	Mean Sea Level (MSL)	Mean High Water Neaps Tide (MHWNT)	Mean High Water Springs Tide (MHWST)	Highest Astronomical Tide (HAT)
-3.8 m OD	-3.0 m OD	-1.3 m OD	0.3 m OD	1.9 m OD	3.4 m OD	4.1 m OD

Table 4.3.1 Tide levels for Welwick Marsh (Source: Admiralty Tide Tables, 1997).

Welwick Marsh is a remnant of a once extensive area of marshes that occupied the north side of the Humber estuary between Sunk Island and Spurn Point. During the seventeenth and eighteenth centuries a combination of factors including embankment and reclamation of saltmarsh, drainage works and the growth of Spurn Head caused Sunk Island and the nearby Cherry Cobb Sands to grow rapidly in size (Sheppard, 1966). The embankment built in 1769-1770 led to increased silting (Figure 4.3.2) so that by the end of the eighteenth century Sunk

Island had become joined to the mainland (Dinnin, 1997). The Keyingham Drain act of 1802 resulted in the construction of a new outfall for the Keyingham Fleet which meant less scouring of the North Channel between Sunk Island and the mainland. Sediment deposition and subsequent land reclamation caused the channel to shrink to the extent that by 1850 Sunk Island was almost completely joined to southern Holderness. In 1897, the Winstead Drain outfall was altered, spelling the end of the Patrington Harbour and Sunk Island (Dinnin, 1997).

Welwick Marsh can be divided into middle and low marsh on the basis of the vascular flora (Figure 4.3.3). The middle marsh is dominated by *Elytrigia atherica*, *Spergularia* spp., *Atriplex portulacoides* and *Suaeda maritima* whereas the low marsh is dominated by *E. atherica*, *Inula crithmoides*, *Salicornia europaea* and *Spartina anglica.*

4.3.2 Geological history

The geology of the Humber estuary comprises predominantly Quaternary glacial and post-glacial deposits overlying Cretaceous chalk bedrock. The chalk forms a syncline beneath the Quaternary deposits, the axis of which dips gently from north-west to south-east (Ellis, 1997). No trace of the topmost Cretaceous bedrock is preserved in the area (Berridge and Pattison, 1994). The unconformity between the Cretaceous and the Quaternary materials indicates that deposits were not laid down during the intervening period probably because the Tertiary coast was situated some distance to the east of the present coastline and this period was, therefore, one of erosion rather than deposition (Catt, 1990).

The Quaternary deposits vary in thickness, reaching around 30 m in south-east Holderness, and comprise predominantly glacial till and glaciofluvial sand and gravel. Penny *et al.* (1969) have radiocarbon dated the deposits to *ca.* 18000 cal. yrs. BP. The Devensian glacial deposits have, until recently, been considered to comprise of two units: a lower Skipsea Till; and an upper Withernsea Till. The tills are suggested to originate from a two-tier ice sheet with the ice moving from two different directions (Madgett and Catt, 1978). Hence, they consist of different colours, grain sizes and chemical, mineralogical and petrographic properties (Madgett and Catt, 1978). A third till unit, Basement Till, has been re-assessed following amino acid dating of marine bivalves. This suggests that it is of Late Devensian (*ca.* 20000 cal. yrs. BP) rather than Wolstonian age (Eyles *et al.*, 1994).

In addition to the tills, sands and gravels were deposited by glacial meltwater flowing both beneath the ice and infront of it as it retreated in response to climatic warming towards the end of the Devensian. Melting of the ice resulted in an irregular relief developing at the till surface. Furthermore, drainage networks became established on the deglaciated surface with the main pathways running southwards and westwards to join the Rivers Humber and Hull, respectively.

Investigations of past sea-level changes in the Humber estuary and adjacent areas are based on lithostratigraphical and biostratigraphical analyses (Gaunt and Tooley, 1974; Tooley, 1978a; Shennan, 1983; Long *et al.*, in press). The predicted relative sea-level in the southern North Sea was between - 75 m and - 100 m OD at *ca.* 12000 cal. yrs. BP (Lambeck, 1995). It subsequently rose rapidly to between - 20 m and - 30 m OD at *ca.* 7000 cal. yrs. BP, after which it continued to rise more slowly to around OD (Lambeck, 1995). The Ouse and Trent incised deeply into sediments of the inner Humber between *ca.* 12000 cal. yrs. BP and *ca.* 7000 cal. yrs. BP which produced a channel whose base lies at - 20 m OD in the Vale of York (Gaunt, 1981), while at the outer estuary a deep channel was incised into glacial tills. In the Humber estuary sea level rose from - 9 m OD at *ca.* 7500 cal. yrs. BP to 0 m OD at *ca.* 4000 cal. yrs. BP (Long *et al.*, in press).

4.3.3 Materials and methods

Twenty stations were established at Welwick Marsh along a transect from middle marsh to mudflat. Samples were collected only four times during a twelve-month period (once in each season) because the study of monthly variations was investigated at Cowpen Marsh (Section 4.2.9). The material and methods follow the guidelines set out in Section 4.2.3.

4.3.3.1 Foraminifera analysis

Foraminiferal samples from stations 1 to 20 were analysed at three-monthly intervals during the twelve-month period. Preservation of foraminifera was variable and the number of tests counted varied from 32 to 3440 individuals/10 cm^3 sample.

4.3.3.2 Diatom analysis

Diatom samples from stations 1 to 20 were analysed once during the twelve-month period. Preservation of diatoms was variable but a minimum count of 200 diatom valves was possible for most samples.

4.3.3.3 Environmental variables

Four environmental variables were analysed from alternate sites on the transect from stations 1 to 20: altitude; pH; salinity; and substrate. To characterise foraminiferal substrate, grain size and LOI were measured. Vegetation cover was analysed from a 4 m^2 area around each station. Section 4.2.6 indicated that the environmental variables of Cowpen Marsh remain relatively stable during the twelve month study period, therefore the variables at Welwick Marsh were measured only once (in the summer season).

4.3.4 Foraminiferal assemblages

Thirty-one dead foraminiferal species have been identified from the twelve-month study of the intertidal zone of Welwick Marsh (Figure 4.3.4). The maximum number of species counted per sample is 17 and the mean sample foraminiferal concentration is 582 individuals/10 cm^3. The Shannon-Weaver (H(S)) or Fisher indices of diversity (α) show no relationship from middle marsh to mudflat (Figure 4.3.5).

The foraminiferal death assemblages are dominated by one agglutinated species (*Jadammina macrescens*) and two calcareous species (*Ammonia beccarii* var. *limnetes* and *Haynesina germanica*) (Figure 4.3.6). These species represent over 85 % of the death assemblage of Welwick Marsh.

J. macrescens dominates stations 1 to 3 with a maximum percentage of 77 % (station 1). The transition between the middle and low marsh (defined by vascular plant distributions) corresponds to a rapid decrease in abundance of this taxon. It is subsequently replaced by calcareous species such as *H. germanica*, *A. beccarii* var. *limnetes* and *Elphidium williamsoni.* The maximum abundance of *A. beccarii* var. *limnetes* (15 %) occurs within the low marsh zone (station 9). *H. germanica* dominates the mudflat zone (stations 16 to 20) with a maximum abundance of 90 % at station 17. The abundance of this taxon exceeds 83 % at each mudflat station.

4.3.5 Diatom assemblages

The study of Welwick Marsh has identified one hundred and twenty six diatom taxa (Figure 4.3.7). The dominant diatoms are polyhalobous, mesohalobous and oligohalobous taxa such as *Cocconeis scutellum*, *Paralia sulcata*, *Raphonesis minutissima*, *Nitzschia sigma*, *Navicula cari* var. *cincta* and *Navicula insociablis*. However, the diatom assemblages do not exhibit any ecological gradients based on salinity tolerance.

4.3.6 Environmental variables

Porewater salinity shows a steady state equilibrium across the intertidal zone (Figure 4.3.8). Minimum and maximum salinity occurs at stations 4 (3.0 ‰) and 16 (12.5 ‰), respectively.

The pH values show a general increase across the intertidal zone from 6.1 at station 1 to 7.3 at station 20. Conversely, grain size, LOI and vegetation cover show a general decrease across the intertidal zone from middle marsh to mudflat. The grain size distribution of Welwick Marsh is dominated by clay and silt size classes. The clay fraction decreases from a maximum of 39.5 % at station 1 to a minimum of 20.6 % at station 18.

LOI decreases from a maximum of 14.9 % at station 1 to a minimum of 10.6 % at station 20. The percentage vegetation cover shows a pronounced decrease within the low marsh from 100 % (station 5) to 5 % (station 16).

The scatter plot matrix (Figure 4.3.9) indicates that within the ranges observed there are strong relationships between altitude and LOI, grain size, pH and vegetation cover. Altitude versus LOI, clay fraction and vegetation cover show positive non-linear relationships and altitude versus pH show a negative non-linear relationship. The scatter graphs among the remaining environmental variables show no relationships.

4.3.7 Relationships between foraminifera and environmental variables

The annual average of the three most important dead foraminifera found on the intertidal zone of Welwick Marsh were related to altitude and salinity. The scatter plot matrix suggests variations of LOI, grain size, pH and vegetation cover are also related to altitude, and thus, altitude can be used as a surrogate of these variables. Therefore, the aim of this section is to determine if either altitude or salinity (within the ranges observed) appear to control foraminiferal distributions.

The omitted summaries of relationships between foraminifera and other environmental variables are referenced in Appendix 4, Section 4.1.

4.3.7.1 Foraminifera and altitude

The scatter plot of *J. macrescens* versus altitude (Figure 4.3.10a) shows a strong positive relationship indicating that the species dominates more elevated environments such as the middle marsh rather than low marsh and mudflat. The scatter plot of *H. germanica* shows a strong negative relationship suggesting dominance in low altitude environments with increased flooding frequency. The scatter plot for *A. beccarii* var. *limnetes* does not show a relationship with altitude.

4.3.7.2 Foraminifera and salinity

The scatter plot (Figure 4.3.10b) of *A. beccarii* var. *limnetes* shows a weak-bimodal relationship with salinity. *J. macrescens* and *H. germanica* show poor relationships with salinity.

4.3.7.3 Synopsis

J. macrescens and *H. germanica* show a strong relationship with altitude. Conversely, these taxa show weak relationships with salinity. The remaining variables (Appendix 4) further influence the distribution and abundance of the three species but these variables also change along the altitudinal gradient of the intertidal zone (Figure 4.3.9).

4.3.8 Multivariate analysis of contemporary foraminifera

The average annual foraminiferal assemblages of Welwick Marsh were investigated using cluster analysis. Two variants of cluster analysis were used: unweighted Euclidean distance; and unweighted Chord distance. The altitudes of each station within the cluster zones were used to determine the vertical zonation of Welwick Marsh. Only samples with counts greater than 40 individuals and species that reach 5 % of the total sum were included.

Cluster analysis of monthly assemblages based on unweighted Euclidean and Chord distance and DCA of monthly and annual assemblages are referenced in Appendix 4, Section 4.2.

4.3.8.1 Cluster analysis

The first variant of cluster analysis of annual assemblages (**unweighted Euclidean distance**) detects two cluster zones (Figure 4.3.11):

- Zone AEHG is dominated by calcareous species, notably *H. germanica* with low frequencies of *A. beccarii* var. *limnetes* and *E. williamsoni*. It is distinct from the other zone by having the highest percentages of *H. germanica* which exceed 42.9 % at all stations. The altitudes range from 3.37 m OD to 2.45 m OD (0.92 m) with a relatively small interquartile range of 0.31 m (2.95 m OD to 2.64 m OD) (Figure 4.3.12);
- Zone AEJM is dominated by the agglutinated species *J. macrescens*. The taxon's relative abundance exceeds 52 % at all stations. The altitude of the zone ranges from 3.54 m OD to 3.4 m OD (0.14 m) with an interquartile range of 0.07 m (3.51 m OD to 3.44 m OD).

The second variant of annual cluster analysis (**unweighted Chord distance**) similarly classifies the data into two zones (ACHG and ACJM). The sample and species composition of each zone are comparable with the equivalent clusters based on Euclidean distance (Figure 4.3.13). However, the altitudinal range of ACHG and ACJM are 0.42 m smaller and 0.31 m larger than AEHG and AEJM, respectively (Figure 4.3.14).

4.3.8.2 Synopsis

Annual cluster analyses based on unweighted Euclidean and Chord distance classify the contemporary foraminiferal death assemblages of Welwick Marsh into two zones. However, there are differences between the two variants. These are illustrated in the stacked bar comparisons (Figure 4.3.15). The general distribution of annual Euclidean and Chord zones across the intertidal zone are comparable: Euclidean and Chord Zones AEHG and ACHG dominate the seaward end; and AEJM and ACJM dominate the landward end of the transect. However, the exact distribution of the two variants differ. For example, the Euclidean Zone AEHG dominates stations 4 to 20 whereas the Chord Zone ACHG dominates stations 8 to 20. The differences are associated with transitional assemblages of *J. macrescens* and *H. germanica*. Subsequently, the exact sample and species composition and altitudinal range of the zonation of Welwick Marsh are derived from a combination of both variants of cluster analysis. Therefore, Zones WI and WII exhibit the maximum altitudinal ranges which cause an overlap of boundaries (Table 4.3.2). This classification is supported by monthly cluster analyses, and monthly and annual DCA (Appendix 4, Section 4.2).

Zone	Dominant species	Altitudinal Range (m OD)
WI	*Jadammina macrescens*	3.54 to 3.09
WII	*Haynesina germanica*	3.37 to 2.45

Table 4.3.2 Foraminiferal zones of Welwick Marsh derived from annual clusters based on unweighted Euclidean and Chord distance.

4.3.9 Summary

Analyses at Welwick Marsh followed the procedure set out in Section 4.2 to produce two conclusions:

- The foraminiferal distributions of the dominant taxa of Welwick Marsh show strong relationships with altitude.
- Multivariate analyses of Welwick Marsh classify the contemporary foraminiferal death assemblages into two zones: Zone WI is dominated by *J. macrescens*; and Zone WII is dominated by the calcareous foraminiferal species *H. germanica*. However, the altitudinal range of the zones differ between variants of cluster analyses causing an overlap of boundaries.

4.4 Thornham Marsh

The penultimate contemporary analysis follows the procedure set out in Section 4.2.

4.4.1 Environmental setting

Thornham Marsh and the final contemporary field site, Brancaster Marsh, lie on the North Norfolk coast (Figure 4.4.1). The coastline is composed of extensive intertidal sands and muds with more-or-less discrete saltmarsh units developed in the lee of complex recurved shingle barriers. Tidal range on this coast averages 6.5 m at springs and 3.1 m at neaps (Table 4.4.1). The HAT reaches approximately 4.0 m OD with some variability along the coast (a few decimetres) related to the period of the nodal tide (French *et al.*, 1995).

Lowest Astronomical Tide (LAT)	Mean Low Water Spring Tide (MLWST)	Mean Low Water Neap Tide (MLWNT)	Mean Sea Level (MSL)	Mean High Water Neap Tide (MHWNT)	Mean High Water Spring Tide (MHWST)	Highest Astronomical Tide (HAT)
-3.85 m OD	-3.15 m OD	-1.55 m OD	0.10 m OD	1.55 m OD	3.35 m OD	4.15 m OD

Table 4.4.1 Tide levels for Thornham Marsh (Source: Admiralty Tide Tables, 1997).

The apparent impact of human activity on the natural evolution of the North Norfolk coast has been minor, at least in comparison with estuarine marshes (e.g. Cowpen and Welwick marshes). From the time of the early Roman settlements (e.g. Branodunum; now Brancaster) trade flourished from numerous small harbours including those at Thornham, Brancaster, Burnham Overy and Wells. However, changing patterns of trade, together with the siltation that accompanied the growth of the saltmarshes, ultimately led to the decline of these harbours with only Wells now surviving (Allison, 1985).

Thornham Marsh is an extensive area of saltmarsh located on the North Norfolk coast to the west of Brancaster. The marsh is approximately 1 km in width and can be divided into high, middle and low marsh on the basis of the vascular flora (Figure 4.4.2). The high marsh is dominated by *Spergularia marina*, *Puccinellia maritima* and *Elytrigia atherica*. The number of species increases at the transition between high and middle marsh (3.16 m OD) with the latter dominated by *E. atherica*, *Atriplex portulacoides* and *Limonium vulgare*. The transition to the low marsh (2.56 m OD) is marked by a decrease in the number of species with only two remaining: *A. portulacoides*; and *Salicornia europaea*. The low marsh possesses a variable microtopography associated with ridge and runnel sand bars (Figure 4.4.1).

4.4.2 Geological history

The landforms of the North Norfolk coast are the result of Holocene sedimentation seaward of a pre-glacial coastline, the degraded form of which is visible along the landward margins of Thornham Marsh. Chalk cliffs occur at Hunstanton (mid-Cretaceous Carstone, Red Chalk and Lower Chalk) and at Weybourne (Upper Chalk) where they are mantled by Quaternary glacial deposits. Beneath the present intertidal zone, the chalk is overlain by Quaternary glacial till or fluvioglacial sands and sandy-gravels.

An outline chronology of past sea-level changes along the North Norfolk has been made by Funnell and Pearson (1989). They identify a number of distinctive sedimentary environments, the extent of which may be traced both spatially and temporally. The predicted relative sea-level in the southern North Sea was between - 75 m and - 100 m OD at *ca.* 12000 cal. yrs. BP (Lambeck, 1995). Subsequent sea-level rise apparently impeded coastal drainage and elevated groundwater levels. This led to the accumulation of freshwater peats along the present coastline overlying the pre-existing surface of glacial till or fluvioglacial sands and sandy-gravels. The freshwater peats were later progressively inundated and overlain by transgressive marine deposits. In numerous locations, a succession from intertidal muds through saltmarsh deposits is apparent with freshwater peats accumulating on top of the higher marsh deposits. At Titchwell, a pine woodland became established, dated to *ca.* 3500 cal. yrs. BP. This period of supra-tidal accumulation was relatively short-lived and was followed by intertidal sedimentation dated to *ca.* 2750 cal. yrs. BP which has continued to the present.

4.4.3 Materials and methods

Twenty-four stations were placed along a transect from high marsh to mudflat. Samples were collected at approximately three-monthly intervals, once in each season, for a twelve-month period. Materials and methods followed the guidelines set out in Section 4.2.3.

4.4.3.1 Foraminifera analysis

Foraminiferal samples from stations 1 to 24 were analysed at three-monthly intervals during the twelve-month period. Preservation of foraminifera was variable with the number of tests varying from 16 to 5936 individuals/10 cm^3 sample.

4.4.3.2 Diatom analysis

Diatom samples from stations 1 to 24 were analysed once during the twelve-month period. Preservation of diatoms was variable but a minimum count of 200 diatom valves was possible for most samples.

4.4.3.3 Environmental variables

Five environmental variables were analysed: altitude; pH; salinity; substrate; and vegetation cover. To characterise foraminiferal substrate, grain size and LOI were measured. Altitude, pH, salinity and substrate were measured from alternate sites on the transect from station 1 to 24 whereas vegetation cover was analysed from a 4 m^2 area around each station. All variables were measured only once during the twelve-month period (in the summer season).

4.4.4 Foraminiferal assemblages

The twelve-month study of the intertidal zone of Thornham Marsh has identified thirty-three dead foraminiferal species (Figure 4.4.3). The maximum number of species per sample is 23 and the mean sample foraminiferal abundance is 996 individuals/10 cm^3. The species diversity indices do not show a relationship along the transect from high marsh to mudflat (Figure 4.4.4).

The foraminiferal death assemblages are dominated by two agglutinated species, *Jadammina macrescens* and *Trochammina inflata*, and four calcareous species, *Ammonia beccarii* var. *limnetes*, *Elphidium williamsoni*, *Haynesina germanica* and *Quinqueloculina* spp. (Figure 4.4.5). *J. macrescens* and *T. inflata* show a bimodal distribution across the transect. They dominate the high and middle marsh (defined by vascular plant distributions) with a monospecific *J. macrescens* assemblage at the landward limit of the high marsh (station 1). The transition between the middle and low marsh corresponds to a decrease in the relative abundance of *J. macrescens* and *T. inflata* and an increase in calcareous species. However, the relative abundance of *J. macrescens* and *T. inflata* increases again between stations 13 and 15.

The relative abundance of *A. beccarii* var. *limnetes* increases along the transect from high marsh to mudflat: the maximum abundance (28 %) occurs at station 22. The relative abundance of *E. williamsoni*, *H. germanica* and *Q.* spp. increase from high to middle marsh. The maximum abundance of *Q.* spp. (34 %) occurs at the transition between the middle and low marsh (station 8) but declines thereafter. The stations from middle marsh to mudflat (stations 4 to 24) are dominated by calcareous species such as *A. beccarii* var. *batavus*, *E. excavatum*, *E. williamsoni* and *H. germanica*. The maximum abundances of both *E. williamsoni* and *H. germanica* occur within the low marsh at station 10 (22 % and 36 %, respectively).

4.4.5 Diatom assemblages

The study of Thornham Marsh has identified ninety-seven diatom taxa (Figure 4.4.6). All stations are rich in diatoms except for station 1 where diatom valves were absent.

The relative abundance of polyhalobous taxa show a general increase along the transect from high and middle marsh to mudflat. Conversely, the relative abundance of mesohalobous taxa remains relatively stable and oligohalobous taxa show a gradual decrease. The high and middle marsh stations are dominated by polyhalobians, mesohalobians and oligohalobians such as *Navicula ergadensis*, *Nitzschia bilobata*, *Nitzschia trybionella* and *Nitzschia fonticola*.

The dominant diatoms from low marsh stations are polyhalobians and mesohalobians such as *Paralia sulcata*, *Achnanthes delicatula* and *Navicula digito-radiata*. The maximum percentage of *Achnanthes delicatula* (41 %) and *Navicula digito-radiata* (48 %) occur at stations 13 and 17, respectively.

The dominant diatoms from mudflat stations are polyhalobous taxa such as *Cocconeis scutellum* and *Opephora pacifica* with some mesohalobous diatoms like *Achnanthes delicatula*.

4.4.6 Environmental variables

The porewater salinity of Thornham Marsh shows a general increase along the transect from a minimum of 6.9 ‰ at the landward limit of the high marsh (station 1) to a maximum of 25.8 ‰ within the mudflat (station 22) (Figure 4.4.7). However, this general trend is interrupted between stations 14 and 18 where salinity decreases to 9.2 ‰. Similarly, pH increases along the transect from 5.3 at station 1 to 7.0 at station 22 with a decrease in pH to 5.8 between stations 12 and 18.

The grain size distribution of most of the intertidal zone of Thornham Marsh is dominated by clay and silt size classes. The clay fraction decreases from high marsh to mudflat. The presence of a sand bar causes a rapid decrease in the clay fraction to 20.2 % (station 12).

LOI decreases from a maximum of 48.6 % at station 1 to a minimum of 1.1 % at station 24. The percentage vegetation cover shows a similar decline across the intertidal zone with a distinct threshold within the low marsh: vegetation cover decreases from 90 % (station 13) to 15 % (station 16).

The scatter plot matrix (Figure 4.4.8) indicates that within the ranges observed there are strong relationships between altitude and the other environmental variables. Altitude versus LOI, grain size and vegetation cover show strong positive non-linear relationships whereas altitude versus pH and salinity show the reverse. The scatter plots among the remaining environmental variables show poor relationships.

4.4.7 Relationships between foraminifera and environmental variables

The annual average of the six most important dead foraminifera found on the intertidal zone of Thornham Marsh were related to one variable: altitude. The scatter plot matrix shows that altitude can be used as a surrogate of all other variables. The aim is to determine if altitude (within the ranges observed) appears to control foraminiferal distributions.

The omitted summaries of relationships between foraminifera and other environmental variables are referenced in Appendix 5, Section 5.1.

4.4.7.1 Foraminifera and altitude

The scatter plot of *J. macrescens* versus altitude (Figure 4.4.9) shows a strong positive relationship indicating a dominance in more elevated environments such as the high and middle marsh rather than low marsh and mudflat environments. The scatter plot of *A. beccarii* var. *limnetes* shows a negative relationship. *T. inflata* and *Q.* spp. show weak unimodal relationships with altitude. *E. williamsoni* and *H. germanica* are not related to altitude.

4.4.7.2 Synopsis

The scatter plots of *J. macrescens*, *T. inflata*, *A. beccarii* var. *limnetes* and *Q.* spp. show strong non-linear relationships with altitude. Non-linear relationships are further observed among the six species and LOI, grain size, pH, salinity and vegetation cover (Appendix 5). These other variables influence the distribution and abundance of the species but the scatter plot matrix shows the variables to vary along the altitudinal gradient of the intertidal zone (Figure 4.4.8).

4.4.8 Multivariate analysis of contemporary foraminifera

The foraminiferal death assemblages (%) of Thornham Marsh were investigated using cluster analysis of average annual assemblages. Two variants of cluster analysis were used: unweighted Euclidean distance; and unweighted Chord distance. The altitudes of each station within the cluster zones have been used to determine the vertical zonation of Thornham Marsh. Only samples with counts greater than 40 individuals and species that reach 5 % of the total sum were included.

Cluster analysis of monthly assemblages based on unweighted Euclidean and Chord distance, and DCA of monthly and annual assemblages are referenced in Appendix 5, Section 5.2.

4.4.8.1 Cluster analysis

Cluster analysis of annual assemblages based on **unweighted Euclidean distance** detects two cluster zones (Figure 4.4.10):

- Zone AEJM is dominated by *J. macrescens* with lower frequencies of *T. inflata* and *Q.* spp. It differs from other zones by having the highest percentages of *J. macrescens* (exceeds 28 % total dead foraminifera in all samples). The altitudinal range is from 4.32 m OD to 2.35 m OD (1.97 m) (Figure 4.4.11). However, the upper quartile range is 1.27 m (4.32 m OD to 3.05 m OD). This extensive upper quartile is caused by the incorporation of samples at the landward limit of the high marsh that have a monospecific *J. macrescens* assemblage.
- Zone AEHG is dominated by calcareous species such as *A. beccarii* var. *batavus*, *A. beccarii* var. *limnetes*, *E. williamsoni* and *H. germanica*. The altitudes range from 2.64 m OD to 0.21 m OD (2.28 m) with a relatively large interquartile range of 1.39 m (2.28 m OD to 0.89 m OD).

Cluster analysis of annual assemblages based on **unweighted Chord distance** classifies the data into two zones ACJM and ACHG (Figure 4.4.12). The zones are comparable with the equivalent Euclidean zones in terms of sample and species composition and altitudinal range (Figure 4.4.13).

4.4.8.2 Synopsis

Cluster analyses (unweighted Euclidean and Chord distance) classify the annual contemporary foraminiferal death assemblages of Thornham Marsh into two zones: TI dominated by *J. macrescens* with lower frequencies of *T. inflata* and *Q.* spp.; and TII dominated by calcareous species such as *A. beccarii* var. *batavus*, *A. beccarii* var. *limnetes*, *E. williamsoni* and *H. germanica*. The stacked bar comparisons show an identical relationship between Euclidean and Chord zones (Figure 4.4.14). The bimodal distribution of both variants is related to the variable microtopography causing an overlap of altitudinal ranges.

The exact altitudinal range and species composition of each zone is based on either variant (Table 4.4.2). This classification is supported by monthly cluster analyses based on unweighted Euclidean and Chord distance (Appendix 5, Section 5.2). Furthermore, DCA of annual assemblages shows the zones to be mutually exclusive. Thus, the boundaries between the zones are statistically reliable.

Zone	Dominant species	Altitudinal Range (m OD)
TI	*Jadammina macrescens*	4.32 to 2.35
	Trochammina inflata	
	Quinqueloculina spp.	
TII	*Ammonia beccarii* var. *batavus*	2.64 to 0.21
	Ammonia beccarii var. *limnetes*	
	Elphidium williamsoni	
	Haynesina germanica	

Table 4.4.2 Foraminiferal zones of Thornham Marsh derived from annual clusters based on either unweighted Euclidean or Chord distance.

4.4.9 Summary

The analysis of Thornham Marsh produced the following conclusions:

- Foraminiferal death distributions of the dominant taxa of Thornham Marsh show equivocal non-linear relationships with altitude;
- Multivariate analyses of Thornham Marsh classify the contemporary foraminiferal death assemblages into two statistically reliable zones: Zone TI dominated by *J. macrescens* with low frequencies of *T. inflata* and *Q.* spp.; and Zone TII dominated by calcareous foraminiferal species. The zones show a bimodal distribution across the intertidal zone, causing an overlap of boundaries.

4.5. Brancaster Marsh

The final contemporary analysis follows the procedure set out in Section 4.2. This permits correlations between Brancaster Marsh and the other sites examined in this thesis.

4.5.1 Environmental setting

Brancaster Marsh is located on the North Norfolk coast (Section 4.4.1) with a macro-tidal range (Table 4.5.1). The marsh lies near Thornham on the lee of Scolt Head Island which is a natural dune-covered shingle barrier (Figure 4.5.1). Reclamation of extensive areas of saltmarsh, largely during the last 350 years has made use of the protection afforded by Scolt Head Island with earth banks constructed locally to complete the enclosures. For example, a seawall constructed in 1822 between Brancaster and Burnham Overy enclosed a large area of Brancaster Marsh. This is currently used for arable purposes, although it is one area that has been identified as a possible site for 'managed retreat' of the North Norfolk coast (Brown *et al.*, 1994).

Lowest Astronomical Tide (LAT)	Mean Low Water Spring Tides (MLWST)	Mean Low Water Neaps Tide (MLWNT)	Mean Sea Level (MSL)	Mean High Water Neap Tides (MHWNT)	Mean High Water Spring Tide (MHWST)	Highest Astronomical Tide (HAT)
-4.09 m OD	-3.39 m OD	-1.79 m OD	-0.14 m OD	1.31 m OD	3.11 m OD	3.91 m OD

Table 4.5.1 Tide levels for Brancaster Marsh (Source: Admiralty Tide Tables, 1997).

Brancaster Marsh can be divided into a middle and low marsh on the basis of the vascular flora (Figure 4.5.2). The middle marsh has the greatest number of floral species and is dominated by *Phragmites australis, Plantago maritima* and *Armeria maritima.* The number of species decreases at the transition between middle and low marsh (2.99 m OD) with the latter dominated by *Spartina* spp., *Artiplex portulacoides*, *Inula crithmoides* and *Salicornia europaea.* The middle and low marsh possess a variable microtopography formed by creeks, levees and pools.

4.5.2 Geological history

The geology of the North Norfolk coast is described in Section 4.4.2.

4.5.3 Materials and methods

Twenty-three stations were established along a transect from middle marsh to mudflat. Samples were collected at approximately three-monthly intervals (once in each season) for a twelve-month period. Materials and methods followed the guidelines set out in Section 4.2.3.

4.5.3.1 Foraminifera analysis

Foraminiferal samples from stations 1 to 23 were analysed at three-monthly intervals during the twelve-month period. Preservation of foraminifera was variable with the number of tests varying from 112 to 1800 individuals/10 cm^3 sample.

4.5.3.2 Diatom analysis

Diatom samples from stations 1 to 23 were analysed once during the twelve-month period. Preservation of diatoms was variable but a minimum count of 200 valves was possible for most samples.

4.5.3.3 Environmental variables

Five environmental variables were analysed (altitude; pH; salinity; substrate; and vegetation cover). Grain size and LOI were measured to characterise the foraminiferal substrate. Altitude, pH, salinity and substrate were measured from alternate sites on the transect from station 1 to 23 whereas vegetation cover was analysed from a 4 m^2 area around each station. All variables were measured only once during the twelve-month period (in the summer season).

4.5.4 Foraminiferal assemblages

Thirty-one dead foraminiferal species have been identified from the twelve-month study of the intertidal zone of Brancaster Marsh (Figure 4.5.3). The maximum number of species counted is 19 and the mean sample foraminiferal concentration is 709 individuals/10 cm^3. The Fisher index of diversity (Figure 4.5.4) shows a rapid increase in diversity from a minimum of 1.4 within the middle marsh (station 14) to a maximum of 4.0 within the mudflat (station 22). The Shannon-Weaver (H(S)) index shows no relationship.

The foraminiferal death assemblages are dominated by three agglutinated species, *Jadammina macrescens*, *Miliammina fusca* and *Trochammina inflata*, and three calcareous species, *Elphidium williamsoni*, *Haynesina germanica* and *Quinqueloculina* spp. (Figure 4.5.5). The agglutinated species dominate the middle marsh (defined by vascular plant distributions), representing over 70 % of the death assemblage for the majority of stations between 1 and 16. The exception (station 4) has a high relative abundance of *Q.* spp. This taxa shows a bimodal distribution along the transect. The second peak in abundance of *Q.* spp. occurs at the transition between middle and low marsh. Similarly, the abundance of *E. williamsoni* increases from 1 % at station 14 to a maximum of 16 % at station 16. The combination of *E. williamsoni* and *Q.* spp., plus the three agglutinated species induce an increase in mean foraminiferal concentration to a maximum of 1328 dead individuals/10 cm^3 at station 15. The abundances of the *J. macrescens* and *T. inflata* rapidly decrease at the transition between low marsh and mudflat. This corresponds to a decrease in mean foraminiferal concentration to 226 dead individuals/10 cm^3 at station 20. The agglutinated species are replaced by a more diverse calcareous assemblage, dominated by *H. germanica*. This species increases in relative abundance throughout the mudflat zone to a maximum of 73 % of total dead foraminifera at station 23.

4.5.5 Diatom assemblages

One hundred and ten diatom taxa have been identified from the study of Brancaster Marsh (Figure 4.5.6). Polyhalobous taxa show a gradual increase in abundance along the transect from middle marsh to mudflat. Conversely, mesohalobous and oligohalobous taxa show a gradual decrease. The middle marsh stations are dominated by mesohalobians and oligohalobians such as *Achnanthes delicatula*, *Navicula halophila*, *Nitzschia frustulum* and *Achnanthes minutissima* with some polyhalobous taxa.

The low marsh and mudflat stations are dominated by polyhalobous and mesohalobous taxa such as *Cocconeis scutellum*, *Nitzschia accuminata*, *Paralia sulcata* and *Nitzschia sigma*.

4.5.6 Environmental variables

Porewater salinity, pH and grain size vary little across the intertidal zone. Salinity increases from a minimum of 7.2 ‰ at the landward limit of the middle marsh (station 1) to a maximum of 13.8 ‰ at station 8 (Figure 4.5.7). Thereafter, salinity decreases to 7.1 ‰ at station 22. The minimum pH value (5.8) also occurs at station 1 with the maximum (7.0) occurring at station 20. The grain size distribution of Brancaster Marsh is dominated by clay and silt size classes. The minimum (14.6 %) and maximum (39.1 %) clay fractions occur at stations 6 and 16, respectively.

LOI and vegetation cover show a general decrease across the intertidal zone. LOI decreases from a maximum of 45.0 % at station 1 to a minimum of 11.9 % at station 23. The percentage vegetation cover shows a pronounced decrease between the low marsh and mudflat from 90 % (station 20) to 0 % (station 22).

The scatter plot matrix (Figure 4.5.8) among all environmental variables indicates that within the ranges observed there are strong correlations of altitude versus LOI, pH and vegetation cover. Altitude versus vegetation cover shows a strong positive linear relationship (r = 0.96) whereas altitude versus LOI and pH show strong positive and negative non-linear relationships, respectively. The scatter plots among the remaining environmental variables show weak relationships.

4.5.7 Relationships between foraminifera and environmental variables

The annual average of the six most important dead foraminifera found on the intertidal zone of Brancaster Marsh were related to altitude, grain size and salinity. The scatter plot matrix shows that altitude can be used as a surrogate of the remaining variables. The aim is to determine if any variable (within the ranges observed) appears to control foraminiferal distributions.

The omitted summaries of relationships between foraminifera and other environmental variables are referenced in Appendix 6.

4.5.7.1 Foraminifera and altitude

The scatter plot of *J. macrescens* versus altitude (Figure 4.5.9a) shows a strong positive non-linear relationship indicating that the taxon dominates more elevated environments such as the middle marsh. Conversely, *H. germanica* shows a strong negative non-linear relationship suggesting dominance in low altitude environments with increased flooding frequency such as the mudflat. The scatter plot for *T. inflata* shows a unimodal relationship with altitude. There are no relationships between *M. fusca*, *E. williamsoni* and *Q.* spp. and altitude.

4.5.7.2 Foraminifera and grain size

The grain size distribution of Brancaster Marsh is dominated by clay and silt size classes. The scatter plots of all foraminiferal species show weak relationships with clay fraction percentage (Figure 4.5.9b).

4.5.7.3 Foraminifera and salinity

The scatter plots of all foraminiferal species show weak relationships with salinity (Figure 4.5.9c).

4.5.7.4 Synopsis

The scatter plots of *J. macrescens*, *M. fusca*, *T. inflata* and *H. germanica* indicate a strong non-linear relationship with altitude. Conversely, weak relationships are observed against grain size and salinity. The remaining variables (Appendix 5, Section 5.1) also influence the distribution and abundance of the species, but the scatter plot matrix shows these variables to vary along the altitudinal gradient of the intertidal zone (Figure 4.5.8). However, there are significant sampling limitations. There are no samples between 2.3 m OD and 3.0 m OD and so conclusions from Brancaster Marsh should be interpreted with caution.

4.5.8 Multivariate analysis of contemporary foraminifera

Cluster analysis investigated the foraminiferal annual average death assemblages (%) of Brancaster Marsh. Two variants of cluster analysis were used: unweighted Euclidean distance; and unweighted Chord distance. The altitudes of each station within the cluster zones have been used to determine the vertical zonation of Brancaster Marsh. Only samples with counts greater than 40 individuals and species that reach 5 % of the total sum were included.

Cluster analysis of monthly assemblages based on unweighted Euclidean and Chord distance, and DCA of monthly and annual assemblages are referenced in Appendix 6.2.

4.5.8.1 Cluster analysis

Cluster analysis of annual assemblages based on **unweighted Euclidean distance** detects the following cluster zones (Figure 4.5.10):

- Zone AEAG is dominated by three agglutinated species, *J. macrescens*, *M. fusca* and *T. inflata*. These three species account for at least 50 % total dead foraminifera in all samples. The altitudinal range is from 3.27 m OD to 2.98 m OD (0.29 m) with an interquartile range of 0.12 m (3.22 m OD to 3.10 m OD) (Figure 4.5.11);
- Zone AEHG is dominated by calcareous species such as *H. germanica* with lower frequencies of *J. macrescens*, *E. magellanicum* and *E. williamsoni*. It differs from the other zones by having the highest percentages of *H. germanica* which exceed 45 % total dead foraminifera in all samples. The altitudes range from 2.48 m OD to 1.85 m OD (0.63 m) with an interquartile range of 0.46 m (2.35 m OD to 1.85 m OD). However, the lower quartile is found at 1.87 m OD. The low altitude of the median is caused by the inclusion of numerous samples at the seaward limit of the transect.

Cluster analysis of annual assemblages based on **unweighted Chord distance** detects cluster zones ACAG and ACHG (Figure 4.5.12). The sample and species composition and altitudinal range of the zones are comparable to the equivalent Euclidean zones (Figure 4.5.12, 4.5.13).

4.5.8.2 Synopsis

Cluster analyses of annual foraminiferal death assemblages of Brancaster Marsh based on Euclidean and Chord distance detect two zones (Table 4.5.2): BI is dominated by three agglutinated species, *J. macrescens*, *M. fusca* and *T. inflata*; and BII is dominated by calcareous species such as *H. germanica* with low frequencies of *J. macrescens*, *E. magellanicum* and *E. williamsoni*. The stacked bar comparisons show identical distributions across the intertidal zone for Euclidean and Chord zones (Figure 4.5.14). This classification is supported by monthly cluster analyses based on unweighted Euclidean and Chord distance (Appendix 6., Section 6.2). Furthermore, DCA of annual and monthly assemblages implies that the boundaries between the zones are reliable.

Zone	Dominant species	Altitudinal Range (m OD)
BI	*Jadammina macrescens*	3.27 to 2.98
	Miliammina fusca	
	Trochammina inflata	
BII	*Haynesina germanica*	2.48 to 1.85

Table 4.5.2 Foraminiferal zones of Brancaster Marsh derived from annual clusters based on either unweighted Euclidean or unweighted Chord distance.

4.5.9 Summary

Analyses of foraminifera and environmental variables of Brancaster Marsh produced two conclusions:

- Scatter plots indicate that the foraminiferal distributions of the dominant taxa of Brancaster Marsh are related to altitude;
- Multivariate analyses of Brancaster Marsh classify the contemporary foraminiferal death assemblages into two statistically reliable zones: Zone BI is dominated by *J. macrescens*, *M. fusca* and *T. inflata*; and Zone BII is dominated by calcareous foraminiferal species *H. germanica*.

4.6 Discussion

Thomas and Varekamp (1991) stressed that a prerequisite of employing foraminifera to determine former sea levels is that their contemporary distributions and controlling environmental variables are established. The scatter plots of the most important dead foraminifera from Cowpen, Welwick, Thornham and Brancaster marshes versus a series of environmental variables show comparable relationships between foraminifera and altitude. For example, *Jadammina macrescens* (the most important agglutinated species found on each contemporary site) at these sites show strong positive non-linear relationships with altitude indicating dominance in more elevated environments such as the high and middle marsh (Figure 4.6.1). Conversely, *Haynesina germanica* (the most important calcareous species found on each contemporary site) shows a strong negative relationship with altitude in 3 out of 4 sites (the exception is Thornham Marsh) suggesting dominance in low altitude environments such as the mudflat. The remaining environmental variables (LOI, grain size, pH, salinity and vegetation cover) further influence the distribution and abundance of species. However, scatter plot matrices of the environmental variables at each site show the majority of variables vary along the altitudinal gradient of the intertidal zone and, thus, are dependent upon the frequency of tidal flooding (Buzas, 1969a; Phelger, 1970). However, the variables that do appear to be independent of altitude show weak relationships with foraminiferal species. These results support previous research which concluded that the distribution of foraminifera in the intertidal zone is usually a direct function of altitude with the duration and frequency of intertidal exposure as the most important factors (Scott and Medioli, 1980a, 1986).

This conclusion contrasts with that of de Rijk (1995a, 1995b) and de Rijk and Troelstra (1997) who, using similar statistical techniques, concluded that foraminiferal distributions of the Great Marshes, Massachusetts did not correlate with altitude. The distributions on these marshes reflect variations in salinity and are the result not of tidal exposure, but of changes in the balance between seepage, precipitation and flooding. Cowpen and Welwick marshes are ideally suited for correlations between foraminiferal abundances and flooding frequency because they both slope gently towards the sea and lack an undulating topography formed by creeks, levees and pools (features common on many other mature saltmarshes). The Great Marshes, Massachusetts is relatively flat but possesses a more variable microtopography. Under these conditions de Rijk (1995a, 1995b) and de Rijk and Troelstra (1997) suggested that foraminiferal distributions are controlled by local spatial and temporal changes in a number of environmental variables (notably salinity) and not altitude. Nevertheless statistical analyses of Brancaster

Marsh, which possesses a variable microtopography, indicate that foraminiferal death distributions are related to altitude.

Since the aim of this thesis is to reconstruct relative sea-level, it is essential that the influence of altitude is resolved. A hypothesis that foraminiferal assemblages are related to altitude is tested in the next chapter using multivariate techniques (canonical and detrended correspondence analyses) that include all foraminiferal species, not just the dominant taxa.

The altitudes of each station from Cowpen, Welwick, Thornham and Brancaster marshes differ with respect to tidal range and, thus, are not comparable. To facilitate such comparison, the altitudes are expressed as a **standardised water level index** (SWLI):

$$x_{ab} = [((A_{ab} - MTL_b)/(MHWST_b - MTL_b)*100) + 100] \qquad (1)$$

where A_{ab} is the measured altitude (m OD) of station/tide level *a* at site *b*; MTL_b is the mean tide-level (m OD) at site *b*; $MHWST_b$ is the mean high water spring tide at site *b;* and x_{ab} is the SWLI of station/tide level *a* at site *b*. The addition of the constant (100) ensures that all reconstructed values within the training set are positive. For example, $x_{ab} = 200$ if the measured altitude of A_{ab} equals $MHWST_b$. Conversely, $x_{ab} = 100$ if the measured altitude of A_{ab} equals MTL_b. The constructions of SWLIs for stations and tide levels from the four sites are referenced in Appendix 7.

A comparison of constructed tidal levels using Equation One indicates that the procedure is reliable (Figure 4.6.2). The tide levels remain relatively stable with only LAT showing a significant divergence in the coefficient of variance (V_c = 0.07). The relationship between SWLI and flooding frequency is shown in Figure 4.6.3. Each contemporary site shows analogous linear relationships, with the Pearson's correlation coefficients (*r*) exceeding the critical value (0.492) at the 1 % significance level, indeed all exceed 0.94. Moreover, the scatter plots highlight the uneven sampling distributions of the intertidal zone, particularly for Welwick and Brancaster marshes where all stations have a SWLI between 171 and 205.

Alternative methods using HAT and LAT, and MHWST and MLWST have been investigated (Appendix 7., Section 7.2 and 7.3, respectively). However, MHWST and MTL were chosen as constants because they have the following advantages over the other tide levels:

- The majority (92 %) of the contemporary samples are found between MHWST and MTL;

- Constructions using the alternative methods show inferior tide level comparisons. The total coefficient of variance using HAT and LAT ($\Sigma V_c = 0.18$), and MHWST and MLWST ($\Sigma V_c = 0.18$) are larger than Equation One ($\Sigma V_c = 0.15$);
- The Admiralty Tide Tables (1997) state MHWST and MTL for Standard and Secondary Ports whereas HAT and LAT are only stated for Standard Ports. The values at Secondary Ports are extrapolated beyond the given differences for a tide that reaches the appropriate level at a Standard Port. Furthermore, MLWST is absent at many Secondary Ports because of lack of data;
- MHWST and MTL are the two most important reference water levels used in sea-level research. MHWST is an ecologically important reference level because many sea-level indicators are derived from certain saltmarsh plants that normally accumulate around or above MHWST level. Furthermore, the IGCP Projects 61 and 200 stated that for comparison it is necessary that the height of the samples or indicators all be expressed relative to MTL (Tooley, 1978a; Kidson and Heyworth, 1979; Kidson, 1986; Long, 1992; Shennan, 1992; Zong, 1992).

To briefly reiterate, Equation One is the most appropriate and reliable method of calculating SWLI and, therefore, permits comparisons among the contrasting intertidal zones to identify general and site-specific trends in foraminiferal assemblages.

The foraminiferal distributions of Cowpen, Welwick, Thornham and Brancaster marshes (determined by multivariate analysis) display vertical zonations (Scott and Medioli, 1978, 1986) with respect to SWLI, although, their zonation dimensions are shown to differ (Figure 4.6.4). The conclusions already drawn from each site are reiterated: two subzones of Zone I at Cowpen Marsh (CIa and CIb); overlapping zones at Welwick and Thornham marshes due to transitional assemblages and variable microtopography; and an absence of altitudinal values at Brancaster Marsh because of sampling limitations.

Faunal Zones I of Welwick, Thornham and Brancaster marshes (WI, TI and BI) occur between a SWLI of 230 and 169 and approximate to MHWST. The faunal zones consist of different percentages of three agglutinated species: *J. macrescens*; *Miliammina fusca*; and *Trochammina inflata*. Two subzones of Zone I (CIa and CIb) have been identified from Cowpen Marsh. The former subzone is comparable to Zones I of Welwick, Brancaster and Thornham marshes. The latter subzone is dominated by *J. macrescens* and *M. fusca* with low frequencies of calcareous species. Multivariate analyses did not identify any subzones of Zone I from the remaining marshes which illustrates the very localised nature of some distributions.

Zones II (CII, WII, TII and BII) occur between a SWLI of 200 and 71 and are characterised by a high diversity of foraminifera. They are dominated by calcareous species such as *H. germanica, Ammonia beccarii* var. *limnetes, Elphidium williamsoni* and *Quinqueloculina* spp.

The transition between Zones I and II occurs over a relatively narrow vertical SWLI range (196 to 171) because of the relatively stable SWLI range of Zone I and the upper boundary of Zone II (200 to 171). These zones may therefore be used to differentiate between saltmarsh and mudflat fossil deposits and have a potential application in reconstructing former sea levels (Chapter Five).

4.7 Chapter Summary

A detailed procedure was employed for data analysis and interpretation of the contemporary foraminiferal distributions of each intertidal zone. This method produced two conclusions that are incorporated in subsequent chapters.

(1) Foraminiferal death distributions of the dominant taxa of Cowpen, Welwick and Brancaster marshes show strong relationships with altitude. Other environmental variables (LOI, grain size, pH, salinity and vegetation cover) further influence the distribution and abundance of species, though the strong relationship of altitude versus the majority of other environmental variables implies that all environmental variables are heavily dependent on the frequency of tidal flooding. However, the evidence from Thornham Marsh is equivocal. A hypothesis that foraminiferal assemblages are related to altitude is tested in the next chapter using multivariate techniques (canonical and detrended correspondence analyses) that include all foraminiferal species.

(2) Multivariate techniques (Cluster analysis and DCA) use the relationships between contemporary foraminiferal death assemblages and altitude to determine a vertical zonation of the intertidal zones of Cowpen, Welwick, Brancaster and Thornham marshes. The contemporary foraminiferal death assemblages are classified into the following statistically reliable zones:

- Faunal Zone I of Welwick, Brancaster and Thornham marshes coincide with high and middle marsh floral zones and approximate to MHWST. The faunal zone consists of different percentages of three agglutinated species (*Jadammina macrescens*, *Miliammina fusca* and *Trochammina inflata*) and is characterised by high percentages of *J. macrescens*;
- Faunal Subzones CIa and CIb of Cowpen Marsh. The former subzone is comparable to Zones I of Welwick, Brancaster and Thornham marshes. The latter subzone coincides with the middle and low marsh floral zone and is dominated by *J. macrescens* and *M. fusca* with low frequencies of calcareous species. However, analyses at Welwick, Thornham and Brancaster marshes did not identify any subzones of Zone I. This shows the very localised nature of some distributions;
- Faunal Zone II of each contemporary site is characterised by a high diversity of foraminifera and coincides with the low marsh and mudflat floral zones. Zone II is dominated by calcareous species such as *Haynesina germanica, Ammonia beccarii* var. *limnetes, Elphidium williamsoni* and *Quinqueloculina* spp.

The foraminiferal distributions of each contemporary site display comparable vertical zonations with respect to SWLI. However, their dimensions and foraminiferal assemblages are shown to differ. This supports the inference that surface studies are an invaluable first step in assessing the value of foraminifera as palaeoenvironmental indicators (de Rijk and Troelstra, 1997). Furthermore, seasonal variations modify the patterns of contemporary foraminiferal distribution across the intertidal zone and, hence, the value of foraminiferal zones as indicators of former sea levels can only be assessed following the consideration of seasonal errors affecting the calculation of their altitudes.

This thesis will concentrate on the vertical zonation of foraminifera to reconstruct former sea-levels (Chapter 5). The diatom assemblages from the four contemporary field sites will be used in corroboration with foraminiferal data to confirm the meaning of a particular indicator. The diatom assemblages from Cowpen, Thornham and Brancaster marshes show an ecological gradient based on salinity tolerance. Polyhalobous and mesohalobous taxa show a gradual increase in abundance along the transects from high and middle marsh to mudflat. Conversely, oligohalobous taxa show a gradual decrease. The diatom assemblages of Welwick Marsh obscure any ecological gradients based on salinity tolerance.

Chapter 5: Quantitative water level reconstructions

5.1 Introduction

Many palaeoecological studies aim to reconstruct features of the past environment from fossil assemblages preserved in terrestrial, brackish or marine deposits. Although the fossil assemblages are quantitatively studied with individual diatom, foraminiferal and pollen counts, the environmental reconstructions may be qualitative and presented in terms such as 'dry', 'moist', 'wet', etc. Imbie and Kipp (1971) revolutionised Quaternary palaeoecology by presenting a procedure for quantitative reconstruction of past environmental variables from fossil assemblages involving transfer or calibration functions.

The primary objective of this chapter is to express the value of an environmental variable (e.g. standardised water level index) as a function of biological data (e.g. foraminiferal assemblages) or environmental proxy data (e.g. salinity, vegetation cover, etc.). This operation is termed the transfer function or biotic index (ter Braak, 1987a; Birks, 1995) and the construction thereof is described as calibration (ter Braak, 1987b; ter Braak and Prentice, 1988). The basic principle of quantitative environmental reconstruction is to reassemble one or more environmental variables (*Xo*) from fossil biological data (*Yo*) consisting of *m* species in *t* samples (Figure 5.1). To estimate values of *Xo* the contemporary response of the same *m* species to the environmental variable(s) of interest is modelled. This involves a contemporary 'training set' of *m* species at *n* sites (*Y*) studied as surface assemblages with an associated set of contemporary environmental variables (*X*) for the same *n* sites. The modern relationship between *Y* and *X* are modelled and the resulting function is then used as a transfer function to transform the fossil data (*Yo*) into quantitative estimates of the past environmental variable(s) *Xo* (Birks, 1995).

The previous chapter demonstrated the site-specific and seasonal nature of some foraminiferal distributions. This chapter aims to combine the foraminiferal and environmental data to create a training set containing a wide range of contemporary coastal environments to ensure that most fossil sites have a modern analogue. This will enable the production of techniques that are applicable on a regional scale and enable a range of indicative meanings from a variety of sedimentary environments to be reconstructed without the need of a local or seasonal surface study which is beyond the scope of this thesis, and indeed, most investigations of fossil sequences.

The aims and objectives of this chapter are as follows:

- Elucidate the relationship between the **combined** foraminiferal distributions from the four contemporary field sites and a series of environmental variables (standardised water level index, pH, salinity, substrate and vegetation cover);
- Determine whether the foraminiferal-environment response is linear-based or unimodal-based;
- Employ complementary quantitative reconstruction techniques that are appropriate for determining the indicative meaning of a range of Holocene index points.

5.2 Relationships between foraminifera and environmental variables

Statistical analyses indicate that the dominant dead foraminifera of Cowpen, Welwick and Brancaster marshes are related to altitude, though, the evidence from Thornham Marsh is equivocal (Chapter Four). However, this inference may be invalid for the combined foraminiferal assemblages from all four contemporary field sites including all foraminiferal species.

Canonical correspondence analysis (CCA) is employed to test the hypothesis that combined foraminiferal death assemblages are related to altitude. CCA is a relatively new multivariate technique which relates community composition to known variations in the environment (ter Braak, 1986, 1987a; ter Braak and Verdonschot, 1995). The technique is an extension of correspondence analysis (Chapter Four), an ordination technique which displays the main trends of variation of a multi-dimensional dataset in a reduced space of a few, linearly independent dimensions. Understanding of ordination axes are typically interpreted with help from external knowledge and/or data on environmental variables. This two step approach (ordination followed by environmental gradient identification) is termed 'indirect gradient analysis' by ter Braak (1986). In CCA, ordination axes are chosen in the light of known environmental variables by imposing the extra restriction that the axes be linear combinations of these variables. This technique is known as 'direct gradient analysis' (ter Braak, 1986) where community variations can be directly related to environmental variations.

5.2.1 Materials and methods

The relationship between annual foraminiferal death assemblages (%) and environmental variables from the four contemporary field sites was explored primarily by CCA with supporting evidence from DCA. CCA was used to extract environmental gradients from ecological datasets. The gradients were used as the basis for describing and illustrating the different habitat preferences of taxa via an ordination diagram.

The independence and relative strength of the major environmental gradients were estimated using a series of partial CCAs (Borcard *et al.*, 1992) to separate the total variation of foraminiferal data into components representing: first, the unique contributions of individual environmental variables; second, the contribution of covariance between variables; and third, the unexplained variance. When CCA and partial CCA are in use canonical eigenvalues are measures of the amount of variation accounted for by environmental variables. These measures were transformed into percentages of total variation of species data by dividing individual eigenvalues or sum of all canonical eigenvalues by the total inertia. The statistical significance of partial CCAs was determined using a Monte Carlo permutation test. The processes were based on computations made with the CANOCO program of ter Braak, release 3.12, 1991 (ter Braak, 1988, 1990).

The annual foraminiferal death assemblages from each marsh used an identical taxonomy (Appendix Two). Similarly, loss on ignition (LOI), clay fraction (*ca.* grain size), pH, salinity and vegetation cover from each marsh used the same constituents. Thus, both datasets from each marsh were combined. However, the altitudes of each station from Cowpen, Welwick, Thornham and Brancaster marshes differ with respect to tidal range and were, therefore, reconstructed as a **standardised water level index** (SWLI) using Equation One (Section 4.6). Only samples with counts greater than 40 individuals and species that reach 2 % of the total sum were included (following Fritz *et al.*, 1991). The percentage of species that were included was decreased compared to the previous multivariate investigations (Chapter Four: 5 %) to allow the inclusion of more minor taxa that may have a significant influence on the CCA analysis (Juggins, pers. comm., 1997).

5.2.2 Results

The CCA sample-environment and species-environment biplots are shown in Figure 5.2. CCA Axes One (eigenvalue = 0.56) and Two (eigenvalue = 0.23) explain 39.7 % of the total variance in the foraminiferal data (Table 5.1). The lengths of the environmental arrows approximate their relative importance in explaining the variance in the foraminiferal data and their orientation shows their approximate correlations to ordination axes and other environmental variables. Intra-set correlations of environmental variables with Axes One and Two show that vegetation cover, LOI, SWLI and pH are highly correlated with Axis One and that salinity and to some extent location are correlated with Axis 2 (Figure 5.2a). Axis One, therefore, reflects the major gradient from high marsh plotted on the right (dense vegetation cover, high LOI and SWLI and low pH) to tidal flat plotted on the left (barren vegetation, low LOI and SWLI and high pH). Axis Two reflects the salinity gradient and a general sequential order from Thornham (top), through Cowpen to Welwick and finally to Brancaster Marsh (bottom).

	Axis	1	2	3	4	Total inertia
CCA	Eigenvalues	0.56	0.23	0.07	0.05	2.00
	Species-environment correlations	0.93	0.83	0.74	0.66	
	Cumulative percentage variance:					
	-of species data	28.1	39.7	43.4	45.9	
	-of species environment relationship	57.0	80.5	87.9	92.9	
DCA	Eigenvalues	0.66	0.24	0.11	0.05	1.74

Table 5.1 Summary of CCA and DCA results from annual foraminiferal death assemblages of four contemporary field sites.

On the species-environment biplot the position of species projected perpendicularly onto environmental arrows approximate their weighted average optima along each environmental variable (Figure 5.2b). Therefore, species characteristic of a particular environment may be identified, for example *Jadammina macrescens*, *Miliammina fusca* and *Trochammina inflata* (high and middle marsh: dense vegetation cover; high LOI and SWLI; and low pH) and *Haynesina germanica* (tidal flat: barren vegetation; low LOI and SWLI; and high pH).

The first two DCA axes of the training set account for 38 % and 14 % of the total variance of species data (52 % in all). Thus, it is Axis One (eigenvalue = 0.66) that controls the ordination diagram (Figure 5.3). The ordination diagram shows each field site occupying similar ordination space. The exceptions are the calcareous samples from Thornham Marsh. Furthermore, the eigenvalues, species scores and samples configuration for DCA are similar to those for CCA. Thus, the gradients for SWLI, LOI, grain size, pH, salinity, vegetation cover and location account for a significant amount of composition in the foraminiferal data.

The six environmental variables account for 49.4 % of the explained variance in the foraminiferal data (Figure 5.4). Partial CCAs show that the total explained variance is composed of 18.5 % (salinity), 9.7 % (SWLI), 8.9 % (vegetation cover), 7.4 % (LOI), 6.0 % (pH) and 5.5 % (clay fraction). The associated Monte Carlo permutation tests (p = 0.01, 99 random permutations) indicate that all these variables are highly significant. Therefore, each of these gradients accounts for a significant proportion of the total variance in the foraminiferal data. However, 44.1 % of the total explained variance is accounted for by inter-correlations between environmental variables. This is to be expected because the previous chapter showed strong relationships of altitude (*ca.* SWLI) versus the other environmental variables (vegetation cover, LOI, pH and grain size). Thus the high inter-correlation probably decreases the explained variance of SWLI, vegetation cover, LOI, pH and grain size relative to salinity.

5.2.3 Synopsis

One striking fact raised by CCA is the large amount of unexplained variation: more than half the total variation of the species data remains unexplained. Whether this is due to some overlooked factor (e.g. air and/or ocean temperature) or to a large amount of stochastic variation remains unclear. Nevertheless, the explained percentage is considerably greater than those found in many other biological datasets with a large number of samples with many zero values (Dixit *et al.*, 1993; Gasse *et al.*, 1995). Furthermore, the Monte Carlo permutation tests suggest that the available environmental variables play a significant role. CCA supports the hypothesis that the combined foraminiferal death distributions of Cowpen, Welwick, Thornham and Brancaster marshes are related to SWLI. However, partial CCAs show that salinity, not SWLI, is the most important variable. This is expected because of the relatively high inter-correlation between SWLI and other variables. Thus, the SWLI gradient cannot be considered completely independent.

DCA shows each field site occupying a similar ordination space which suggests that most of the assemblages among sites are compatible.

5.3 Quantitative reconstruction from contemporary foraminiferal death assemblages

The objective of this section is to express the value of SWLI as a function of contemporary foraminiferal death assemblages. This will enable quantification of the precision and definition of the indicative meaning of a range of Holocene SLIs. To meet this objective, contemporary foraminiferal data collected by the ERC are combined with the training set of Cowpen, Welwick, Thornham and Brancaster marshes (Table 5.2). The locations of all contemporary field sites are shown in Figure 5.5. Further information regarding the additional sites is referenced in Appendix 8. To minimise the taxonomic, methodological and taphonomic differences, the modern training set is of consistent taxonomy and quality. However, the constituents of the foraminiferal data from Cowpen, Welwick, Thornham and Brancaster marshes are annual averages whereas the data from Nith estuary, Roudsea Marsh, Kentra Bay and Tramaig Bay are single measurements. This will introduce inherent 'noise' into the data set because foraminiferal assemblages are prone to seasonal variations (Section 4.2.9).

Site	Number of samples	Author
Cowpen Marsh	31	Mr B. P. Horton
Welwick Marsh	20	Mr B. P. Horton
Thornham Marsh	24	Mr B. P. Horton
Brancaster Marsh	23	Mr B. P. Horton
Nith estuary	15	Dr J. M. Lloyd
Roudsea Marsh	13	Dr J. M. Lloyd
Kentra Bay	6	Dr E. J. Twiddy
Tramaig Bay	3	Dr J. M. Lloyd

Table 5.2 Summary of contemporary foraminiferal training set.

Nevertheless, it is beneficial to combine datasets because it will increase the range of contemporary coastal environments. The training set consists of eight environments with differing physiographic conditions. They are found within estuaries, the shelter of spits, offshore bars or islands and protected bays, and developing on submerging, stable or emerging shorelines. Furthermore, they have different climates, water temperatures, organic-minerogenic ratios, sedimentation rates and tidal ranges.

Numerous methods have been developed to quantitatively reconstruct palaeoenvironmental variables. Some of these have a stronger ecological and/or statistical basis than others. Thus, some methods are more appropriate than others for quantifying the indicative meaning. The fundamental distinction between existing methods concerns the underlying taxon-environment response model (Birks, 1995). There are methods that assume a unimodal (Gaussian) model of species to their environment (Figure 5.6a). Alternatively, there are methods that assume a linear response model of species to their environment (Figure 5.6b).

5.3.1 Linear or unimodal foraminiferal-standardised water level index response models

The amount of biological compositional turnover along the environmental gradient of interest is used to decide whether linear-based or unimodal-based methods are appropriate (Birks, 1995). This was estimated using detrended canonical correspondence analysis (DCCA) with the environmental variable of interest (x) as the only environmental variable. DCCA with detrending by segments and non-linear rescaling provides an estimate (as the length of DCCA Axis One) of the gradient length in relation to x in standard deviation (SD) units (Birks, 1995; Korsman and Birks, 1995). If the gradient length is longer than 2 SD units several species will have their optima located within the gradient and unimodal-based methods of regression and calibration are appropriate (Birks, 1995). The length may vary for different environmental variables and the same biological data.

DCCA of the training set with SWLI as the only environmental variable has produced a gradient length of 2.74. This indicates a unimodal nature of the foraminiferal abundance data with respect to SWLI. Thus, unimodal-based methods of regression and calibration are used. Ter Braak and Prentice (1988) emphasised that, although ecological response curves are commonly thought to be more complex than is implied by the Gaussian-type unimodal models, they are a convenient and reliable approximation for the analysis of biological data that span gradients in excess of 2 SD. Two quantitative reconstruction techniques were chosen: weighted averaging (WA) regression and calibration; and modern analogue technique (MAT).

5.3.2 Weighted averaging regression and calibration

5.3.2.1 Materials and methods

WA is a unimodal-based method. It is based upon the theory that at a site with a particular environmental variable (x), species with their optima for x close to the site will tend to be the most abundant species present, if the species shows a unimodal relationship with x (ter Braak, 1987b; Birks *et al.*, 1990; Birks 1995). A simple, ecologically reasonable and intuitive estimate of a species optimum for x is the average of all x values for sites in which the species occurs, weighted by the species relative abundance. Therefore, the optimum is a weighted average, abundance weighted mean, or centroid of x (species absence carry zero weight). Similarly, the weighted or abundance weighted standard deviation of x is an estimate of the species tolerance or amplitude.

For a transfer function to be developed for SWLI, the variable should explain a significant part of the total variation of the foraminiferal data. Partial CCAs and associated Monte Carlo permutation tests indicated that statistically significant transfer functions can be developed for SWLI (Section 5.2). However, 44.1 % of the total explained variance of foraminiferal data is accounted for by inter-correlations between environmental variables and, therefore, the transfer function cannot be considered to be completely independent. For palaeoenvironmental reconstructions, it must be assumed that the joint distribution with SWLI in the training set is the same as in the fossil set (Le and Shackleton, 1994; Birks, 1995).

WA and tolerance-downweighting WA transfer functions for SWLI were developed using the program CALIBRATE of Juggins and ter Braak, release 0.70, 1997 (Juggins and ter Braak, 1992). The performance of transfer functions was assessed in terms of root-mean square of the error (RMSE) and squared correlation (r^2) of observed versus predicted values. RMSE and r^2 indicate the overall performance of the model where the former indicates prediction errors and the latter measures the strength of the relationship of observed versus predicted values. This allows comparisons among transfer functions (Gasse *et al.*, 1995).

The two parameters were calculated as both 'apparent' measures in which the whole training set was used to generate the transfer function and assess the predictive ability, and jack-knifed or 'leave-one-out' measures (ter Braak and Juggins, 1993). Jack-knifing is a simple cross-validation approach where the reconstruction procedure is applied n times using a training set of (n - 1). In each of the n predictions, one sample is omitted in turn and the transfer function based on the (n - 1) samples in the training set is applied to the omitted sample. This produces a predicted value and, by subtracting this from the observed value (x_i), generates a prediction error for the omitted sample (RMSEP$_{jack}$) (Birks, 1995). In addition r^2_{jack} can be calculated for each x_i when sample i is included in the test set but excluded from the training set. Jack-knifing measures are reliable indicators of the true predictive ability of the transfer functions as they are less-biased by sample re-substitution (Dixon, 1993).

RMSEP$_{jack}$ is an measure of the overall predictive abilities of the training set. It does not provide sample-specific errors for each fossil sample, as the observed x_i is not known for the fossil samples (Birks, 1995). Bootstrapping can be used to derive a standard error of prediction (SE$_{pred}$) (Birks *et al.*, 1990; Line *et al.*, 1994). This is interpreted, following Birks *et al.* (1990), as a sample-specific root mean squared error of prediction for individual fossil and modern samples. SE$_{pred}$ for an environmental variable in the past can vary from sample to sample depending upon the composition of the fossil assemblage and thus the presence or absence of taxa with a particularly strong signal for the environmental variable of interest (Birks, 1995). Bootstrapping for the estimation of sample specific errors has been implemented for WA regression and calibration (Birks *et al.*, 1990; Line *et al.*, 1994). SE$_{pred}$ was estimated using 1000 cycles with inverse and classical deshrinking regression. This computer intensive procedure used the program WACALIB, release 3.3 (Line *et al.*, 1994).

The large heterogeneous foraminiferal training set used will inevitably contain some samples that show a poor statistical relationship with SWLI. They have a poor fit because other environmental factors may become dominant in influencing the assemblage, or the composition of the assemblage may have been altered by differential preservation. Samples with a poor fit will have a high residual distance from the first ordination axis constrained by the SWLI. Such samples can decrease the predictive ability of the estimated transfer function coefficients (Martens and Naes, 1989). They should, therefore, be identified and removed from the training set (Gasse *et al.*, 1995; Jones and Juggins, 1995). The training set was screened after the initial transfer function for SWLI. Samples with an absolute residual (observed minus predicted) greater than the standard deviation of SWLI in the training set were deleted (Jones and Juggins, 1995).

5.3.2.2 Results

Data screening for SWLI has produced 34 samples with an absolute residual greater than the standard deviation of the environmental variable in the training set (SD for SWLI = 25.74). The majority of these samples are randomly distributed within each field site. However, all tidal flat samples of Kentra Bay are rejected. The intertidal zone of Kentra Bay is subject to acidic runoff from a raised bog. This enhances the dissolution of the calcareous foraminifera and causes abnormal assemblages with respect to SWLI.

WA transfer functions were developed using the remaining samples. To investigate the effect of deleting these samples on WA regression and calibration, WA coefficients derived from the original 135 sample foraminifera training set were plotted against those from the screened 101 sample set (Figure 5.7). Every foraminiferal species is close to the 1:1 line (r = 0.85). Thus, the removal of foraminiferal samples whose assemblages show a poor relationship with SWLI has not effected the estimates of species' coefficients.

The number of species and samples of the screened training set used in the transfer functions and their inverse-deshrinking and classical-deshrinking regression coefficients are shown in Table 5.3. In addition, summary statistics describing the predictive ability of the transfer functions are shown in Table 5.4.

Variable	Number of samples	Number of species	Method	Regression Inverse	coefficients	Classical	
				b0	b1	b0	b1
SWLI	101	36	WA	-117.01	1.63	96.24	0.48
			Tol - WA	-162.32	1.86	109.63	0.42

Table 5.3 Summary of statistics (after data screening) of the training set used to develop ordinary weighted averaging (WA) and tolerance-downweighted WA (Tol - WA) transfer functions for SWLI.

Method	Deshrinking	RMSE	r^2	$RMSEP_{jack}$	r^2_{jack}	SE_{pred}
WA	Inverse	10.52	0.79	11.58	0.74	11.72
Tol - WA	Inverse	10.70	0.78	13.12	0.67	13.31
WA	Classical	11.87	0.79	12.47	0.75	12.69
Tol - WA	Classical	12.12	0.78	14.25	0.67	14.47

Table 5.4 Statistics summarising the performance of ordinary weighted averaging (WA) and tolerance-downweighted WA (Tol - WA) transfer functions for SWLI.

Ordinary WA appears to perform marginally better than tolerance-downweighted WA when apparent and jack-knifed errors are considered: prediction errors (RMSE) are lower and squared correlations (r^2) are higher. Therefore, ordinary WA is the most appropriate method. Bootstrapped estimates of the RMSEP for ordinary and tolerance-downweighted WA are higher than the equivalent apparent errors, highlighting the importance of using a method of cross-validation to estimate the likely error when the transfer function is applied to unknown fossil samples (Gasse *et al.*, 1995).

The relationship between observed and foraminiferal-predicted SWLI shows the relative performance of the WA transfer functions for inverse (r^2_{jack} = 0.74) and classical (r^2_{jack} = 0.75) deshrinking regression (Figure 5.8). The former scatter graph has the greater accuracy in the mid-range of SWLI, while the latter has greater accuracy at high and low SWLIs. Both scatter graphs show a sigmoid shape due to the averaging effect of the method.

The coefficients of WA transfer functions have a direct ecological interpretation as species' optima and tolerance to SWLI (Jones and Juggins 1995). To reiterate, the optima and tolerance are the species' weighted average and standard deviation, respectively. For example, Figure 5.9 shows minor calcareous species that are commonly found in inner shelf environments (e.g. *Miliolinella subrotunda* and *Ammonia beccarii* var. *aberdoveyensis*) have the lowest SWLI optima. The optima of dominant calcareous species that are commonly found within the tidal flat and low marsh (e.g. *A. beccarii* var. *limnetes*, *E. williamsoni*, *H. germanica* and *Quinqueloculina* spp.) are higher with optimum occurrences between 157 and 185. The agglutinated species which dominate saltmarsh environments (e.g. *T. inflata*, *M. fusca* and *J. macrescens*) have the highest SWLIs with optima exceeding 189.

For each transfer function the number of occurrences of each taxon (N), its maximum relative abundance (Max) and Hill's N_2, the number of effective occurrences (Hill, 1973; ter Braak, 1990), are calculated (Table 5.5). The latter gives an indication of the number of samples contributing to the calculation of a WA species optima. For example, a species with 5 actual occurrences with values of 60 %, 1 %, 0.5 %, 0.2% and 0.1 % will have its WA optima effectively determined by the sample in which it occurs with 60 %. The N_2 for this species is thus close to 1 (Birks, 1995). Species' optima with a low number of occurrences or low N_2, should be interpreted with caution (Gasse *et al.*, 1995). Consequently, WA tolerances are corrected for bias by dividing the tolerances of the species by $(1 - 1/N_2)^{1/2}$ (Line *et al.*, 1994).

Species	Code	N	Max	N_2	Opt	Tol
Miliolinella subrotunda	MS	6	12.50	2.15	114.37	24.20
Ammonia beccarii var. *batavus*	AB	29	52.10	5.30	133.18	34.18
Planorbulina mediterranensis	PM	9	2.10	5.82	135.45	28.54
Ammonia beccarii var. *aberdoveyensis*	AA	11	2.10	6.91	137.00	29.64
Buliminella elegantissima	BE	9	3.05	4.66	150.80	22.52
Haynesina depressula	HD	2	3.05	1.14	150.93	39.96
Lagena sulcata	LS	8	2.25	4.70	151.54	13.42
Elphidium excavatum	EE	25	19.20	11.19	152.83	21.78
Elphidium incertum	EI	27	8.10	18.42	153.34	21.07
Cibicides lobatulus	CL	28	8.80	15.88	153.66	21.61
Ammonia beccarii var. tepida	AT	26	6.60	11.76	155.09	24.85
Fursenkoina fusiformis	FF	18	8.34	9.51	156.00	22.81
Ammonia beccarii var. *limnetes*	AL	56	27.90	24.41	157.78	27.76
Buccella frigida	BF	5	5.49	1.73	161.83	38.72
Glabratella milletti	GM	3	2.44	2.10	162.78	26.48
Elphidium earlandi	EA	43	8.28	22.62	163.10	21.20
Cassidulina obtusa	CO	6	2.00	4.23	165.17	8.18
Elphidium gerthi	EG	14	5.40	9.24	165.67	31.28
Haynesina germanica	HG	75	90.41	35.17	171.37	17.45
Rosalina williamsoni	RW	15	5.00	6.58	172.14	22.86
Globigerina quinqueloba	GQ	22	5.56	11.34	173.57	25.96
Elphidium magellanicum	Eg	37	14.29	17.10	173.73	23.37
Elphidium williamsoni	EW	70	23.53	36.95	174.04	20.87
Bulimina marginata	BM	6	2.04	2.61	174.13	34.27
Brizalina variabilis	BV	21	5.49	10.84	174.36	27.70
Cyclogyra involvens	CI	23	9.90	10.95	184.24	9.34
Quinqueloculina spp.	Qs	67	33.80	28.95	184.34	15.53
Brizalina inflata	BI	15	8.25	5.62	184.57	19.05
Trochammina ochracea	TO	10	7.14	4.29	185.55	14.38
Trochammina inflata	TI	69	47.88	37.25	189.98	9.15
Ammonia beccarii	Am	15	10.20	6.48	195.24	17.25
Miliammina fusca	MF	60	63.50	30.04	196.86	9.53
Jadammina macrescens	JM	94	100.00	63.34	198.58	15.44
Spirillina vivipara	SW	4	4.55	2.26	203.51	3.26
Haplophragmoides spp.	HH	39	24.32	13.70	205.03	12.11

Table 5.5 Summary statistics for SWLI of all species present in the training set. Species, Species code, number of occurrences (N), maximum relative abundance (Max), Hill's (1973) number of effective occurrences (N_2) and optima (Opt) and tolerances (Tol) are shown.

These optima can now be used to infer the SWLI from fossil foraminiferal assemblages using the calibration formula:

$$\text{initial } x_i = \sum_{k=1}^{m} y_{ik}\, u_k / \sum_{k=1}^{m} y_{ik} \qquad (2)$$

where y_{ik} is the abundance of taxon k in fossil sample i; u_k is the WA optimum for taxon k (k = 1,...m foraminiferal species); and initial x_i is the initial predicted value of SWLI for the fossil sample i.

In WA environmental reconstructions, averages are taken twice, once in WA regression and once in WA calibration. This results in shrinkage of the range of predicted values towards the mean of the environmental gradient. The correction of this simple linear 'deshrinking' can be achieved via inverse or classical regression (Birks *et al.*, 1990, ter Braak and Juggins, 1993). Inverse regression has the advantage of minimising RMSE in the training set (ter Braak and van Dam, 1989; Martens and Naes, 1989) but at the cost of introducing bias at the end points (ter Braak and Juggins, 1993; Gasse *et al.*, 1995). Classical regression deshrinks more than inverse regression (Martinelle, 1970) and it takes values further away from the mean of the training set (Birks, 1995). Therefore, the choice of inverse or classical deshrinking regression depends upon the part of the gradient of interest. Figure 5.10 shows the average inverse and classical residuals versus foraminiferal-predicted SWLI using classical deshrinking regression. The former regression method is preferable for predicted SWLIs between 140 and 210 whereas the latter is preferable outside this range (Table 5.6).

Predicted SWLI (classical)	Inverse residual	Classical residual
≤ 140	15.29 ± 6.86	7.24 ± 3.33
140 to 210	8.17 ± 5.91	10.09 ± 6.29
≥ 210	9.24 ± 6.86	6.51 ± 4.60

Table 5.6 Predicted SWLIs based on WA transfer functions using classical deshrinking regression and the associated inverse and classical residuals.

The regression coefficients shown in Table 5.3 should be used to deshrink the initial values to give final estimates of the foraminiferal-predicted SWLI using either inverse deshrinking:

$$\text{Final } x_i = (b_o + b_l)^* \text{initial } x_i \qquad (3)$$

or classical deshrinking:

$$\text{Final } x_i = (\text{initial } x_i - b_o)^* \; b_1 \quad (4)$$

where b_o is the intercept and b_1 is the slope of the linear regression.

5.3.2.3 Synopsis

WA regression and calibration shows strong and highly significant relationships between modern foraminiferal assemblages and SWLI. Transfer functions quantifying this relationship provide the means to reconstruct former sea levels from fossil foraminiferal assemblages. Bootstrapping provides a means of estimating sample-specific RMSEP for individual fossil samples.

5.3.3 Modern analogue technique

5.3.3.1 Materials and methods

The basic idea of a modern analogue technique (MAT) is to compare numerically, using an appropriate dissimilarity or similarity measure, the biological assemblage in a fossil sample with the biological assemblages in all available modern samples that have associated environmental data. Having found the modern sample(s) most similar to the fossil sample, the fossil environment for that sample is inferred to be the modern environmental variable(s) for analogous modern sample(s) (Birks, 1995). Analogue matching is an important means of evaluating the likely reliability of environmental reconstructions based on WA regression and calibration (Birks *et al.*, 1990).

Analogue matching is the 'least statistical' reconstruction procedure because it does not involve any underlying model of species-environment relationship (Guiot, 1990; Bartlein and Whitlock, 1993). To reconstruct SWLI, however, MAT clearly requires an extensive set of modern surface foraminiferal samples and associated SWLI data that cover the likely range of biotic assemblages and former sea-level conditions. These requirements can create serious limitations for MAT (Birks, 1995). A second problem is how to measure dissimilarity of fossil versus modern assemblages. However, the concept of dissimilarity between assemblages is complex because it must include the relative abundance of the species, the total taxonomic composition and the few dominant taxa (Birks, 1995). A third problem is how to assess whether the lowest dissimilarity found between a fossil and a modern sample represents a credible match and analogue. It should not automatically be assumed that modern and fossil assemblages with the lowest dissimilarity are necessarily good analogues (Huntley, 1990) simply because, in any comparison, some modern sample has to have the lowest dissimilarity measure. A common solution is to take the 5 %, 10 % or 20 % of the dissimilarities calculated between modern samples as an approximate threshold value to indicate a 'good analogue' (Anderson *et al.*, 1989; Birks *et al.*, 1990; Bartlein and Whitlock, 1993).

The analogue matching technique for reconstructing former sea levels was developed using the program MODERN ANALOGUE TECHNIQUE release 1.1 (Juggins, 1997). SWLI reconstruction was based on the weighted average of the 10 most similar modern samples with the weights being the inverse of the dissimilarity values. The modern samples that have the lowest dissimilarity (i.e. are most similar) will have the greatest weights in reconstruction (Bartlein and Whitlock, 1993). The dissimilarity coefficient used to identify the most similar modern samples was squared Chord distance (Prentice, 1980; Overpeck *et al.*, 1985; Birks *et al.*, 1990). This measure is implicit in DCA and CCA and, moreover, it maximises 'signal-to-noise' ratio when used with percentage data (Birks, 1995).

The predictive power of MAT was assessed by cross validation involving jack-knifing. The performance was assessed in terms of jack-knifed root-mean square of the error of prediction ($RMSEP_{jack}$) and squared correlation (r^2_{jack}) of observed versus predicted values. To be comparable with WA regression and calibration, MAT used the screened foraminiferal training set.

5.3.3.2 Results

Variable	Method	$RMSEP_{jack}$	r^2_{jack}	Percentile				
				$1^{st.}$	$2^{nd.}$	$5^{th.}$	$10^{th.}$	$20^{th.}$
SWLI	MAT	9.59	0.83	0.04	0.06	0.12	0.21	0.36

Table 5.7 Statistics summarising the performance and dissimilarity percentiles of MAT for SWLI.

The predictive ability and percentiles of MAT are shown in Table 5.7. $RMSEP_{jack}$ provides a reliable estimate of reconstruction errors for individual fossil samples. The relatively small $RMSEP_{jack}$ and large r^2_{jack} compared to WA transfer functions indicates a strong performance of the training set. The scatter plot of observed versus foraminiferal-predicted SWLI shows samples above a SWLI of 160 lying very close to the 1:1 line (Figure 5.11). However, samples below 160 show a poor performance.

Figure 5.12a shows that 98 out of 101 samples have a dissimilarity coefficient less than or equal to the $20^{th.}$ percentile. Furthermore, the mean absolute residual of SWLI (observed minus predicted) of samples above the $20^{th.}$ percentile is 583 % greater (Figure 5.12b). Therefore, it is concluded that the $20^{th.}$ percentile approximates a threshold value between 'good analogue' and 'no close analogue' (Table 5.8).

Analogue	Percentile range	Dissimilarity coefficient range
Good analogue	$\leq 20^{th.}$	≤ 0.36
No close analogue	$> 20^{th.}$	> 0.36

Table 5.8 Analogue indicator and percentile and dissimilarity coefficient range for MAT.

5.3.3.3 Synopsis

MAT has the advantage of being the 'least statistical' reconstruction procedure as it does not involve any underlying model of taxon-environment response. The main disadvantage is that MAT depends entirely upon the range and composition of the modern training set. The training set has an uneven sampling distribution with the majority of sites (85 %) found above a SWLI of 160. Consequently, the performance of MAT is unreliable below this SWLI. Nevertheless, MAT is an important means of evaluating the reliability of other quantitative reconstruction techniques (Birks *et al.*, 1990).

5.4 Discussion

Numerous methods are available for quantitative reconstruction but weighted averaging (WA) regression and calibration and modern analogue techniques (MAT) were chosen. Cluster analysis and DCA, although extensively used in Chapter Four, did not fulfil the main objective of this thesis which is the quantification of the precision and definition of the indicative meaning of a range of SLIs. The results and discussion of cluster analysis and DCA are referenced in Appendix 8.

WA regression and calibration and MAT have different underlying theories and rationale. WA regression and calibration is a unimodal-based method that assumes a unimodal response of foraminiferal species to their environment whereas MAT does not have an underlying taxon-environment response model. Both methods produced strong regional reconstructions for SWLI from the foraminiferal training set. Statistical measures, apparent and jack-knifed, indicate that the WA transfer functions are statistically reliable. SE_{pred} provides an accurate estimate of reconstruction errors for individual fossil samples (Gasse *et al.*, 1995). Classical and inverse deshrinking regression produced results with greater accuracy at extreme and mid-SWLI values, respectively (Figure 5.13a, 5.13b). Nevertheless, both regressions show significant residuals, particularly at high and low SWLIs.

Figures 5.14a to 5.14d show the predictive performance of WA transfer functions for selected sites of Cowpen, Welwick, Thornham and Brancaster marshes (certain sites are excluded due to the lack of sufficient foraminiferal data, low counts, sample screening, etc.). The vast majority of observed altitudes lie within the foraminiferal-predicted altitudinal range, though, 9 of the 79 selected sites are anomalous. The anomalous sites are clustered within the upper and lower ends of the transect which concurs with the conclusions of the previous figure (Figure 5.13) regarding the magnitude of residuals for observed versus foraminiferal-predicted SWLIs.

The predictive performance of MAT indicates reliable and informative reconstructions for samples whose SWLI exceeds 160 (Figure 5.13c). This relationship is supported by evidence from the reconstructions of site altitudes of Cowpen, Welwick, Thornham and Brancaster marshes (Figure 5.15a to 5.15d). For example, sites from the seaward end of the Cowpen and Thornham marshes show large residuals between the observed and foraminiferal-predicted altitudes. Furthermore, the reconstructions are relatively poor compared to the WA transfer functions: 14 observed altitudes lie outside the predicted altitudinal range compared to 9 for WA. Birks (1995) suggested that MAT reconstructions often show greater variations than reconstructions based on other, more statistically based techniques because MAT depends entirely on the range and composition of the training set.

In conclusion, it is beneficial to reconstruct SWLI using each procedure and develop a 'consensus reconstruction' (Birks, 1995):

- Ordinary WA regression and calibration produces precise reconstruction of fossil samples. WA bootstrapped calculations of the squared error of prediction (SE_{pred}) estimate the indicative range of individual reconstructed values. Reconstructions are corrected for shrinkage by either classical or inverse linear regression. Classical regression is used if the predicted SWLIs using classical deshrinking regression are ≤ 140 or ≥ 210. Conversely, inverse regression is used if the predicted SWLIs using classical deshrinking regression are between 140 and 210;

- MAT evaluates the likely reliability of SWLI reconstructions based on WA regression and calibration (Table 5.8). A 'good analogue' exists for fossil samples with dissimilarity coefficients less than or equal to 0.36. Thus, the indicative meaning is assumed to be reliable. In contrast, 'no close analogue' exists for fossil samples with dissimilarity coefficients greater than 0.36 and, thus, the indicative meaning should be ignored.

The reconstruction procedures do have disadvantages. First, there is an uneven spatial sampling regime with respect to SWLI. The majority of sites (85 %) are found above a SWLI of 160. Second, the training set consists of eight environments with differing physiographic conditions. The foraminiferal and environmental data are based on annual (Cowpen, Welwick, Thornham and Brancaster) and single (Nith, Roudsea, Kentra and Tramaig) measurements. Therefore, the effect of increasing the diversity of coastal environments acts to reduce the predictive ability by introducing unmodelled or 'nuisance' variables into both methods. Third, in both methods the foraminiferal data are calibrated to one environmental variable (SWLI). This may unrealistically force the influence of all environmental factors onto a single parameter and give misleading results (Le, 1992; Huntley, 1993). Fourth, weighted averaging causes a reduction of extreme values. These four factors are responsible for the majority of variations between observed and predicted SWLIs.

5.5 Summary

(1) CCA and DCA using the training set of combined foraminiferal death distributions from Cowpen, Welwick, Thornham and Brancaster marshes show a strong and highly statistically significant relationship with SWLI. However, partial CCAs show that salinity, not SWLI, is the most important variable. This is expected because of the relatively high inter-correlation between SWLI and other variables. Thus, the SWLI gradient cannot be considered completely independent. Furthermore, there is a large amount of unexplained variation due to either overlooked factors or stochastic variation.

(2) The training set was enlarged with data collected by the ERC to cover a greater geographical area and biotic and environmental gradients. For reconstruction purposes, it was essential to determine whether linear or unimodal statistical methods are suitable for the training set in relation to SWLI (Birks, 1995). DCCA of the expanded training set with SWLI as the only environmental variable produces a gradient length longer than 2 SD units. This implies that unimodal-based methods of regression and calibration are appropriate, convenient and reliable (ter Braak and Prentice, 1988; Birks, 1995).

(3) Two techniques are chosen for quantitative palaeoenvironmental reconstruction from the contemporary foraminiferal training set. The following techniques are applicable on a regional scale, deeming unnecessary a local or seasonal surface study:

- WA regression and calibration shows strong and highly significant relationships between modern foraminiferal assemblages and SWLI;
- MAT provides reliable reconstructions for samples whose SWLI is above 160. Significantly, MAT provides a means of evaluating the reliability of other quantitative reconstruction techniques.

Chapter 6: Holocene sea-level index points from the margin of the western North Sea

6.1 Introduction

One of the main aims of the LOIS project, of which this thesis is a part, is to develop and validate models of some of the major characteristics of the Holocene evolution of the western North Sea. Much of the data for palaeoenvironmental reconstruction existed before the project began. However, the sea-level index point (SLI) database is very clustered spatially and temporally, and dominated in numerical terms by data from the Fenland. The limitations of such a dataset were discussed by Flemming (1982) and Shennan (1989) and even though the present dataset is much larger, 1574 compared to 974 (Shennan, 1989), some of the limits on statistical reliability remain.

With the objectives of LOIS in mind, primary data (SLIs) have been collected from chosen locations along the margin of the western North Sea, within the RACS area, and from specific time periods during the Holocene. These data will be used to calibrate the crustal deformation models. Additional new data collected through other projects within LOEPS will validate Lambeck's Earth rheology model (1993a, 1993b) though some may be used in the initial calibration phase.

This chapter presents results of lithostratigraphical and biostratigraphical analyses from twelve fossil field sites along with the available results of radiocarbon (^{14}C) dating. The indicative meanings of SLIs are calculated using two methods: first, the methodology developed during the IGCP Projects 61 and 200; and second, the quantitative reconstruction techniques developed in Chapter Five. The objectives of this chapter are as follows:

- Systematic study of the fossil sites using lithostratigraphical and biological techniques;
- Determine the geographical location, altitude (that can be related to former sea level), age and indicative meaning of fossil samples to produce new SLIs;
- Repeat the procedure for index points collected by the ERC and other LOIS partners if statistical measures indicate that the new SLIs of this thesis are reliable.

6.2 Materials

Site	Core	Site selection	Sampling strategy	Lith.	Diatom	Foraminifera	Pollen
Warkworth	WA953	ERC	Horton	Horton	Horton	Horton	ERC
Teesside	T2	BGS	LOIS	LOIS	Horton	Horton	ERC
Dunswell	HMB2	BGS	ERC	LOIS	ERC	Horton	ERC
Marshchapel	LM2	BGS	ERC	LOIS	ERC	Horton	ERC
Theddlethorpe	LM5a	BGS	Horton/ERC	LOIS	ERC	Horton	ERC
	LM5b	BGS	Horton/ERC	LOIS	ERC	Horton	ERC
Wrangle Bank	F4	BGS	ERC	LOIS	ERC	Horton	ERC
Clenchwarton	F13	BGS	ERC	LOIS	ERC	Horton	ERC
South Lynn	F15a	BGS	ERC	LOIS	-	Horton	ERC
	F15b	BGS	ERC	LOIS	-	Horton	ERC
Spalding	F19	ERC	ERC	LOIS	-	Horton	ERC
Brancater	NNC29	BGS	LOIS	LOIS	Horton	Horton/LOIS	ERC
Thornham	NNC35	BGS	LOIS	LOIS	Horton	Horton/LOIS	ERC
Salthouse	NNC40	BGS	LOIS	LOIS	ERC	Horton/LOIS	ERC

Table 6.1 The structure of data collection and relevant authors used in the production of new SLIs for this thesis. Lith. = lithostratigraphical analysis. Author abbreviations are BGS = British Geological Survey; ERC = Environmental Research Centre; and LOIS = Land and Ocean Interaction Study partners.

The RACS area consists of a variety of sedimentary environments both onshore and offshore which record the evolution of the coast in detail. Areas preserving such information range widely in size from a small embayment (less than 1 km ^{2}) to an open coast such as the Fenland (approximately 4000 km ^{2}). A consistent methodology must be used if evidence from such diverse spatial scales and environments is to be correlated successfully and local and regional factors separated. Only then can the status of various causal factors be established (Shennan, 1989).

The majority of the sampling strategy and lithostratigraphical and biostratigraphical (diatom and pollen) results used to produce new SLIs for this thesis are provided by ERC and other LOIS partners. The structure of this data collection and the relevant authors are shown in Table 6.1. All field sites were chosen after an examination of the borehole logs (produced by ERC or LOIS) with the objective of identifying sites that exhibit a range of environments comparable to the contemporary field sites of this thesis. The data were subsequently classified into six geographical locations, covering the entire range of the RACS area (Berwick upon Tweed to

North Norfolk): Northumberland; Teesside; Humber estuary; Lincolnshire Marshes; Fenland; and North Norfolk (Figure 6.1).

6.3 Methods

6.3.1 Sampling strategy

The majority of samples for lithostratigraphical and biostratigraphical analyses were collected by BGS as part of the LOIS central coring programme. In addition, samples were collected independently by ERC for the specific scientific objectives of LOIS Special Topic Project Numbers 316 "Modelling the Holocene depositional regimes in the western North Sea at 1000 year time intervals", 313 "Differential crustal movements within the RACS study site" and 348 "Holocene evolution of the Humber estuary". A 50 mm diameter piston corer was used to retrieve samples for laboratory and radiocarbon analyses. All cores were instrumentally levelled to OD and their grid references estimated to the nearest 10 m.

In the laboratory, centimetre slices of sediment were cut from the core at specific sampling intervals for biostratigraphical (diatom, foraminifera and pollen) and/or radiocarbon analyses.

6.3.2 Lithostratigraphy

The lithostratigraphy of all samples collected by the ERC was recorded using the Troels-Smith (1955) scheme of stratigraphic notation (Appendix One). This descriptive scheme allows direct comparisons with data obtained by other researchers in the UK and abroad (Tooley, 1978a). For each stratigraphic unit identified the following results were recorded:

- Upper and lower depths below ground surface;
- Composition of unit;
- Degree of humification of organic horizons;
- Physical properties of the unit;
- A short description.

However, the stratigraphical notation of the LOIS central coring programme did not use the Troels-Smith (1955) scheme. Instead, a short written description of the nature of the layer seen in the core was provided. This includes the depths, components and degree of humification (if applicable).

6.3.2 Biostratigraphy

The indicative meanings of new SLIs were estimated using primarily foraminiferal microfossils. In the absence of suitable foraminiferal data, diatom and pollen analyses were used to quantify the indicative meaning of an index point. Pollen analysis was further used as a relative dating technique.

6.3.2.1 Diatom analysis

See Section 4.2.3.2.

6.3.2.2 Foraminiferal analysis

See Section 4.2.3.1.

6.3.2.3 Pollen analysis

Samples for pollen analysis (1 cm^3) were collected and prepared using the standard procedures of Moore and Webb (1978) (Appendix One). Pollen identification and taxonomic nomenclature were made with reference to Clapham *et al.* (1962), Faegri and Iversen (1964) and Moore *et al.* (1991). There are various methods of calculating the pollen sum depending on the type of material analysed and the aims of the study (Moore and Webb, 1978). The exclusion of aquatic pollen and ferns from the pollen sum is common practice because the former are produced in a different environment to terrestrial pollen and the latter are formed in a different manner to pollen grains. Within the context of this study pollen frequencies were expressed as a percentage of total land pollen less aquatic pollen and spores.

6.3.3 Indicative meaning

The concept of the indicative meaning has been discussed in Chapters Two and Five. It suffices here to reiterate that the indicative meaning of a dated sample is the relationship between the environment in which it accumulated and a reference tide level. The indicative meanings of each index point were estimated by Methods I and/or II (outlined below). To allow comparisons it was necessary that the altitude of the dated samples be expressed as MTL relative to OD:

$$x_i = \quad ALT_i + ID_i - MO_i - RWL_i \qquad (5)$$

where x_i is the MTL of sample i expressed relative to OD; ALT_i is the altitude (m OD) of sample i; ID_i is the indicative difference (m) of sample i; MO_i is the difference between MTL and OD for sample i; and RWL_i is the reference water level (m OD) of sample i.

6.3.3.1 Method I

This methodology for estimating the indicative meaning of dated samples was developed during the IGCP Projects 61 and 200 (Preuss, 1979; van de Plassche, 1982, 1986; Shennan, 1982; Tooley, 1982a; Shennan *et al.*, 1983). Shennan (1982) compiled numerous results (Godwin, 1940; Kidson and Heyworth, 1979; van de Plassche, 1979; Tooley, 1979) to make estimates of the indicative meanings of commonly dated materials (Table 6.2). A basis peat is a basal peat formed as the result of rising relative sea-level (Shennan, 1986).

Dated Material	Indicative Range	Reference Water Level
Phragmites or monocot peat:		
- directly above saltmarsh deposit;	± 20 cm	[(MHWST + HAT)/2]-20 cm
- directly below saltmarsh deposit;	± 20 cm	MHWST-20 cm
- directly above fen wood deposit;	± 20 cm	MHWST-10 cm
- directly below fen wood deposit;	± 20 cm	[(MHWST + HAT)/2]-10 cm
- directly above and below saltmarsh deposit;	± 40 cm	MHWST
- middle of layer.	± 70 cm	infer from stratigraphy
Fen wood peat:		
- directly above *Phragmites* or saltmarsh deposit;	± 20 cm	(MHWST + HAT)/2
- directly below *Phragmites* or saltmarsh deposit.	± 20 cm	MHWST
Basis peat:		
- directly below *Phragmites* or saltmarsh deposit;	± 20 cm	MHWST
- directly below Fen wood deposit.	± 80 cm	MTL to MHWST

Table 6.2 Indicative range and reference water level for commonly dated materials (Source: Shennan, 1982). The indicative range (given as a maximum) is the most probable vertical range in which the sample occurs. The reference water level is given as a

mathematical expression of tidal parameters ± an indicative difference. This is the distance from the mid-point of the indicative range to the reference water level.

These indicative meanings were developed from the theory that in intercalated coastal sequences, deposits that were found vertically adjacent without a hiatus must have formed in environments that existed side by side in space. Therefore, the transition from a saltmarsh to a freshwater community has an indicative range equal to the range of the transition from one community to the other, not that of the individual community. For example, Preuss (1979) stated the indicative range of *Phragmites* to be 0.70 m whereas Shennan (1982) argued that the range of a *Phragmites* peat directly above or below a clastic saltmarsh deposit is 0.20 m.

6.3.3.1 Method II

The indicative meaning of dated samples was derived from a training or calibration dataset of contemporary foraminiferal death assemblages and associated environmental measurements collected as part of this thesis. The methodology is discussed in detail in Chapter Five. To briefly reiterate:

- WA was used to produce precise reconstructions of a **standardised water level index** (SWLI) together with a sample-specific error of prediction for individual fossil samples (bootstrapped SE_{pred}). The choice of deshrinking method depends on the part of the gradient of interest. A classical deshrinking regression was used if the predicted SWLIs are ≤ 140 or ≥ 210. A inverse regression is used if the predicted SWLIs are between 140 and 210;
- MAT evaluated the likely reliability of SWLI reconstructions based on WA regression and calibration. The dissimilarity coefficient of the reconstructed fossil samples indicated whether the modern training set possessed a 'good analogue' or 'no close analogue'. The indicative meaning was assumed to be reliable if a 'good analogue' was indicated. Conversely, the indicative meaning was ignored if a 'no close analogue' was indicated.

Only samples with counts greater than 40 individuals and species that reach 2 % of the total sum were included in the reconstruction of SWLI for each SLI (following Fritz *et al.*, 1991; Gehrels, 1994a).

6.3.4 Radiocarbon dating

Thirty-five samples were collected for ^{14}C dating from LOIS and ERC cores. Samples were selected following the completion of all lithostratigraphical and biostratigraphical analyses which ensured that the indicative meaning (using Method I) of each sample was estimated. The outer layer of the sample was removed to avoid the possibility of contamination as a result of smearing during sampling. Organic material visible to the naked eye was picked with tweezers for AMS dating.

The dating strategy was based upon ^{14}C dates of transgressive and regressive contacts with a known altitudinal relationship to sea-level. In addition, the AMS dating technique presented a unique opportunity for dating calcareous benthic assemblages (foraminifera, molluscs, ostracods, etc.) in clastic deposits with known indicative meanings (using Method II). Although only a limited number of sample were selected, the preliminary results were used to assess whether it was a viable alternative to 'peat dates'. However, to compare the calcareous marine ^{14}C ages with the continental chronologies from 'peat dates', all ^{14}C dates obtained on foraminifera were corrected for the 'marine reservoir age effect'. It was assumed that the 400 yr. reservoir effect (R) estimated by Bard *et al.* (1990) for North Sea water was applicable to the RACS area. This value was applied to all calcareous AMS dates with the simplifying assumption of a deviation $\Delta R = 0$ (Heier-Nielsen *et al.*, 1995; Kristensen, *et al.*, 1995; Jiang *et al.*, 1997).

Previous research has illustrated numerous anomalies regarding AMS dates from calcareous foraminifera. These include age inversions, high top core ages and deviating ^{14}C ages for sample pairs of different planktic foraminiferal species (Heier-Nielsen, 1995; Bard *et al.,* 1990). Heier-Nielsen (pers. comm., 1996) stated that wherever possible AMS dates of calcareous foraminifera should be cross referenced. It was proposed, therefore, to calibrate each foraminiferal date with suitable material (e.g. bivalves), to distinguish between possible causes of observed age anomalies (e.g. carbonate dissolution or reworking).

Calcareous material was extracted from the sediment samples following the procedures described by Feyling-Hanssen *et al.* (1971), Meldgaard and Knudsen (1979) and Heier-Nielsen (1995) (Appendix One). Samples of mixed calcareous assemblages ideally contain a representative fraction of all species present in the sample and in all sizes. However, in practice the larger specimens will inevitably be over-represented in the picked sample when compared to the original because larger foraminifera contain proportionally larger amounts of carbonate and the time required for picking a sample can be reduced considerably by picking larger specimens. As size is generally related to species this tendency must be considered when interpreting dating results on mixed foraminiferal assemblages (Heier-Nielsen, 1995). Moreover, even if smaller specimens are represented in the correct proportions in the dated sample, they still contribute very little to the total carbonate available for dating. Therefore, the age of a sample of mixed benthic foraminifera does not necessarily reflect the average age of the faunal composition as derived from statistical species distribution. Hence, it was preferable to date where possible, monospecific calcareous benthic foraminiferal assemblages.

Thirty-five radiocarbon samples were accepted by Natural Environmental Research Council (NERC) Scientific Services, though, the majority of dates had not been returned by the time of writing this thesis.

6.3.5 Consideration of errors

It was important to assess the magnitude of errors produced during the estimation of altitude and age of the SLIs (Section 2.7). Potentially serious altitudinal errors occur in the use of the piston corer which are related to compaction during sampling and extrusion. Estimations of compaction of samples were based upon the ratio between known depth sampled and extruded sample length (Appendix One). The total altitudinal error of a SLI was calculated using the following formula:

$$x_i = \sqrt{(a^2 + b^2 + c^2 + d^2 + e^2)} \qquad (6)$$

where x_i is the altitudinal error (m) of SLI i; a is the levelling error of SLI i; b is the sample thickness of SLI i; c is tide level error of SLI i; d is the altitudinal difference between two tide stations of SLI i (only determined if the tide levels are calculated as a combination of two tide stations); and e is the indicative range of SLI i. Problems of palaeotidal changes (Section 2.7.3) were not assessed due to the lack of suitable data.

The ^{14}C dates were converted into calendar years with the program CALIB 3.0 (Stuiver and Reimer, 1993) using the bidecadal dataset. The ages were calculated using the intercept method (A) and an error multiplier of 1. They were reported as calendar years before present (1950 AD) with an age range which contains 95.4 % of the area under the probability distribution curve ($\pm 2\sigma$).

6.4 Results

Thirty-three reliable new SLIs are produced from twelve fossil sites within the RACS area using results collected by ERC and other LOIS partners (Figure 6.1). The lithostratigraphy and foraminiferal (if necessary diatom and/or pollen) data from each site are described, together with estimates of their indicative meaning (using Methods I and/or II). Further information regarding the indicative meanings are referenced in Table 6.9.

6.4.1 Northumberland

6.4.1.1 Warkworth WA953

In 1992 only fourteen validated SLIs were available from Northumberland (Shennan, 1992). However, borehole surveys by the ERC (unpublished) show that this database can be extended back to at least 8000 cal. yrs. BP and for the more recent periods a more spatially comprehensive database is possible.

Warkworth is a principal field site of LOIS Special Topic Project Number 313 'Differential crustal movements within the RACS study site'. Lambeck (1993a, 1993b) indicated that the sediments are potentially very sensitive indicators for testing the mantle viscosity parameters. The field site is immediately downstream of Warkworth where the River Coquet emerges from an incised meander into a small lowland, in the lee of an area of drift-covered bedrock and coastal dunes (Figure 6.2). Plater and Shennan (1992) analysed a series of over 30 boreholes from Warkworth which describe Holocene sediments overlying Devensian deposits. The sedimentary sequence was divided into a seaward minerogenic facies consisting predominantly of sand with silt and gravel, and a landward sequence of peat beds intercalated with clay-silt (Plater and Shennan, 1992).

A series of borings were taken in the vicinity of Maudlin Farm by ERC. Subsequent stratigraphic analysis indicated which area would provide new SLIs. Piston core WA953 was extruded for lithostratigraphical and biostratigraphical analyses (Grid reference: NV 2519 0516).

1. Lithostratigraphy

A diamicton consisting of a stiff pink clay occurs at the base of the core (Figure 6.3). Directly overlying the diamicton is a sand-clay with organic patches. This unit grades into an amorphous peat at a depth of 539 cm which is subsequently overlain by a clay-peat at a depth of 532 cm. Overlying this unit is a blue-grey clay-silt with dispersed organic remains of *Phragmites*.

2. Biostratigraphy

The core has been sampled for foraminifera and diatom analyses but no diatom valves are present. Foraminiferal tests are also absent from the diamicton at the base of the core. The top of the overlying sand-clay is dominated by *Jadammina macrescens* with low frequencies of *Miliammina fusca*, *Haynesina germanica* and *Ammonia beccarii* var. *limnetes* (Figure 6.3). This unit is replaced by the peat which is further dominated by *J. macrescens*. These assemblages are indicative of higher-high saltmarsh environments. Above the peat unit, in the clay-peat, the percentage of *J. macrescens* falls as the abundance of *M. fusca* and numerous calcareous species increases. The abundance of calcareous foraminifera continues to increase within the clay-silt and is dominated by *Haynesina* and *Elphidium* species, indicative of estuarine or tidal flat environments. Therefore, the transgressive contact between the peat and the overlying clay-silt is characterised by a change in depositional environment from saltmarsh to estuary or tidal flat.

3. Indicative meaning

- **Method I**

Two samples are selected from Core WA953 for ^{14}C dating to produce new SLIs. The first is the regressive contact of the sand-clay and overlying peat (539 cm) and the second is at the transgressive contact between the clay-peat and clay-silt (526 cm). Lithostratigraphical and biostratigraphical evidence indicate samples 539 cm and 526 cm are *Phragmites* or monocot peats directly above and below clastic saltmarsh deposits, respectively (Table 6.9). The estimated indicative meaning of sample 539 cm is 2.55 ± 0.20 m OD whereas sample 526 cm is 2.25 ± 0.20 m OD.

- **Method II**

SWLIs are reconstructed using WA transfer functions. The maximum SWLI occurs within the peat (2.72 ± 0.27 m OD; 539 cm to 534 cm) above MHWST (2.45 m OD). It subsequently declines within the clay-peat and clay-silt to reach a minimum of 1.44 ± 0.27 m OD (512 cm).

The summary statistics of the two SLIs are shown in Table 6.9. Reconstructions of the lower (539 cm) and upper (526 cm) contacts are based upon classical and inverse deshrinking regression, respectively. The former sample requires greater accuracy at high SWLIs whereas the latter requires greater accuracy at mid-SWLIs. MAT indicates that a 'good analogue' exists for both SLIs which suggests the indicative meanings are reliable. The SWLIs are subsequently back-transformed relative to OD and indicative range is expressed in metres.

6.4.1.2 Summary

Site	Core/Sample (cm)	^{14}C Age (BP ± 1σ)	Calibrated age (cal. yrs. BP)	ALT (m OD)	M	RWL (m OD)	RSL (m OD)
Warkworth	WA953/526	Not	available	-2.54	I	2.25 ± 0.20	-4.51 ± 0.21
	WA953/539	Not	available	-2.67	I	2.55 ± 0.20	-5.04 ± 0.21
	WA953/526	Not	available	-2.54	II	2.28 ± 0.26	-4.54± 0.27
	WA953/539	Not	available	-2.67	II	2.72 ± 0.27	-5.11 ± 0.28

Table 6.3 Radiocarbon dates and SLIs from Warkworth. The calibrated ages shown are the age ranges which contain 95.4 % of the area under the probability curve. ALT = altitude (m OD) of top of dated sample. M = Method of calculating indicative meaning. RWL = present altitude of reference water level and indicative range. RSL = relative sea level (m OD) with error estimates for reference water level and measurement of altitude.

SLIs' WA953/526 and WA953/539 are produced from Warkworth (Table 6.3). The former SLI is the transgressive contact of an intercalated peat with a clay-silt which is shown by foraminifera to be estuarine or tidal flat in origin. The latter SLI is from the base of a peat resting on sand-clay. Foraminifera show that peat inception took place under saltmarsh conditions. The indicative meanings of these SLIs are calculated using both methods. The reference water levels of Method I are 3 cm to 17 cm lower than Method II. Furthermore, the indicative range of Method I is 6 cm to 7 cm smaller.

6.4.2 Teesside

6.4.2.1 Teesside industrial estate T2

Core T2 was sampled as part of the LOIS central coring programme to provide new SLIs for the Tees estuary. Previous SLIs from Hartlepool Bay, north of the mouth of the Tees and within the Tees have been described by Tooley (1978a) and Shennan (1992). Unpublished stratigraphic work carried out by ERC from within the Tees estuary and at Hartlepool Bay show that additional high quality SLIs can be obtained for most of the period 3000 to 9000 cal. yrs. BP and probably all of the Holocene. The field site lies on the north side of the Tees estuary within Portrack Marsh at the intersection of the A178 Road and the old River Tees (Grid reference: NZ

4675 1871) (Figure 6.4). Tooley (unpublished) suggested the site had the potential to investigate the palaeodevelopment of the old River Tees.

1. Lithostratigraphy

An olive grey medium sand with occasional clay and silt-clay partings is found at the base of Core T2. This is overlain by a black amorphous peat at 1378 cm with a gradational contact. Similarly, the upper contact of the peat (1365 cm) and the overlying olive grey silt-clay is gradational.

2. Biostratigraphy

The foraminiferal sample below the regressive contact (within the medium sand) is dominated by the agglutinated species *J. macrescens* and the calcareous species *H. germanica* (Figure 6.5). The sample above the contact, within the peat, is barren of foraminifera. A monospecific *J. macrescens* assemblage is observed within the peat below the transgressive contact and is indicative of a higher-high saltmarsh environment. The relative abundance of *J. macrescens* subsequently decreases in the overlying silt-clay, to be replaced by numerous calcareous species (e.g. *H. germanica*). Therefore, the transgressive contact between the peat and the overlying silt-clay is characterised by a change in depositional environment from saltmarsh to estuarine or tidal flat.

Diatom analysis is employed in the absence of suitable foraminiferal data from 1378 cm, to quantify the indicative meaning of the index point. The diatom assemblage of sample 1378 cm is dominated by the polyhalobous taxa *Paralia sulcata* with some mesohalobians (e.g. *Achnanthes delicatula*) which is indicative of a saltmarsh environment.

3. Indicative meaning

- **Method I**

The regressive (1378 cm) and transgressive (1365 cm) contacts of T2 are used to produce new SLIs (Table 6.9). Lithostratigraphical and biostratigraphical data indicate sample 1378 cm is a *Phragmites* or monocot peat directly above a clastic saltmarsh deposit and sample 1365 cm is a *Phragmites* or monocot peat directly below a clastic saltmarsh deposit. Their indicative meaning are 2.86 ± 0.20 m OD and 2.55 ± 0.20 m OD, respectively.

- **Method II**

SWLIs are reconstructed using WA transfer functions where sufficient foraminifera are identified. The SWLI for the transgressive contact of the peat (3.04 ± 0.29 m OD; 1365 cm) occurs above MHWST (2.75 m OD) and coincides with the monospecific *J. macrescens* assemblage. The remaining two samples have lower reconstructed values in association with the numerous calcareous species. MAT indicates that there is a 'good analogue' for the indicative meaning of the reconstructed transgressive contact (Table 6.9).

6.4.2.2 Summary

The data indicate an intercalated saltmarsh peat underlain and overlain by clastic sediments which are shown by foraminifera to be of estuarine or tidal flat origin. The regressive (T2/1378) and transgressive (T2/1365) contacts of the peat are used to produce new SLIs (Table 6.4). However, foraminiferal tests are absent in the former contact, therefore, Method I is used exclusively to reconstruct the indicative meaning. Comparisons of the methods for the latter contact show the reference water level and indicative range of Method I are 0.49 m lower and 0.09 m smaller than Method II, respectively.

Site	Core/Sample (cm)	Age (BP ± 1σ)	Calibrated age (cal. yrs. BP)	ALT (m OD)	M	RWL (m OD)	RSL (m OD)
Teesside	T2/1365	Not	available	-6.99	I	2.55 ± 0.20	-9.14 ± 0.21
	T2/1378	Not	available	-7.12	I	2.86 ± 0.20	-9.56 ± 0.21
	T2/1365	Not	available	-6.99	II	3.04 ± 0.29	-9.63 ± 0.30

Table 6.4 Radiocarbon dates and SLIs from Teesside. The calibrated ages shown are the age ranges which contain 95.4 % of the area under the probability curve. ALT = altitude (m OD) of top of dated sample. M = Method of calculating indicative meaning. RWL = present altitude of reference water level and indicative range. RSL = relative sea level (m OD) with error estimates for reference water level and measurement of altitude.

6.4.3 Humber estuary

6.4.3.1 Dunswell HMB2

The database for the Humber estuary is poor. Existing data are reported by Gaunt and Tooley (1974), Tooley (1978a), Shennan (1983) and Long *et al.* (in press). However, very little is known about the Holocene evolution of one of Britain's most important estuaries. Dunswell HMB2 was sampled by LOIS central coring programme to provide data for LOIS Special Topic Project number 348. The project aims are to reconstruct changes in the form and function of the Humber estuary in response to sea-level change, variations in climate and changes in its extensive catchment. Dunswell lies on the north side of the Humber estuary within a low lying coastal plain drained by the River Hull (Grid reference: TA 0746 3503) (Figure 6.6). The site is being used to investigate the evolution of the Hull valley (Metcalfe, unpublished).

1. Lithostratigraphy

The base of the core consists of a diamicton of light grey silty fine grained sand. This unit is replaced by a brownish black peat with silt (394 cm). Overlying the peat is a brownish grey silt regularly laminated with fine grained sand (384 cm). The lower and upper contacts of the peat are gradational.

2. Biostratigraphy

Foraminiferal tests are absent from the diamicton and the base of the peat. However, agglutinated species (e.g. *J. macrescens* and *M. fusca*) dominate the remaining peat samples (Figure 6.7). These data indicate a transition from freshwater to saltmarsh peat. The overlying silt with sand laminations is dominated by numerous calcareous species (e.g. *H. germanica* and *A. beccarii* var. *limnetes*).The transgressive contact between the peat and the overlying silt is characterised by a change in depositional environment from saltmarsh to estuarine or tidal flat.

3. Indicative meaning

- **Method I**

One SLI is produced from the upper contact of the peat (384 cm). Lithostratigraphical and biostratigraphical data indicate sample 384 cm is a *Phragmites* or monocot peat directly below a clastic saltmarsh deposit. The estimated indicative meaning is 3.40 ± 0.20 m OD (Table 6.9).

- **Method II**

Reconstructed SWLIs of peat samples are above MHWST (3.4 m OD). The maximum altitude (3.77 ± 0.40 m OD) occurs at 390 cm. The SWLI from the overlying silt (1.41 ± 0.41 m OD) is below MHWST. The indicative meaning of sample 384 cm (3.52 ± 0.37 m OD) is reconstructed using inverse deshrinking regression because greater accuracy is required at mid-SWLIs. Furthermore, MAT indicates that a 'good analogue' exists.

6.4.3.2 Summary

One SLI is produced from Core HMB2: the transgressive contact of the peat and the overlying silt with sand laminations (384 cm). Biostratigraphical data indicate a change in deposition across the contact from saltmarsh to estuarine or tidal flat. Estimates of the indicative meaning show the reference water level of Method I occurs at a lower altitude and has a smaller range than Method II (Table 6.5).

Site	Core/Sample (cm)	Age (BP ± 1σ)	Calibrated age (cal. yrs. BP)	ALT (m OD)	M	RWL (m OD)	RSL (m OD)
Dunswell	HMB2/384	Not	available	-0.55	I	3.40 ± 0.20	-3.75 ± 0.21
	HMB2/384	Not	available	-0.55	II	3.52 ± 0.37	-3.87 ± 0.38

Table 6.5 Radiocarbon dates and SLIs from the Humber estuary. The calibrated ages shown are the age ranges which contain 95.4 % of the area under the probability curve. ALT = altitude (m OD) of top of dated sample. M = Method of calculating indicative meaning. RWL = present altitude of reference water level and indicative range. RSL = relative sea level (m OD) with error estimates for reference water level and measurement of altitude.

6.4.4 Lincolnshire Marshes

The coast between the Humber estuary and Chapel Point has not been systematically studied and no SLIs have yet been dated. However, suitable sediments are known to exist (Gaunt and Tooley, 1974; Shennan, 1980). The area is important to link the relative sea-level histories, differential crustal movements and coastal evolution of the Humber and Wash. Subsequently, Marshchapel Core LM2, Theddlethorpe LM5a and Theddlethorpe LM5b were sampled as part of the LOIS central coring programme. The field site of LM2 is approximately 5 km inland from the Lincolnshire coast (Grid reference: TF 3597 9873) (Figure 6.8). It is immediately south of Marshchapel and is an important site to complete the transect with Horseshoe point (Brew, unpublished a). LM5 is situated 2 km south-east of Theddlethorpe and approximately 350 m west of the Gas Terminal on the Lincolnshire Coast (Grid reference: TF 4823 8716). The core was allocated a top priority by BGS because of the potential to record both an intermediate and basal peat (Brew, unpublished b).

Theddlethorpe LM5 was re-sampled as part of this thesis with the objective of providing material for AMS dating of calcareous foraminifera. The core was selected because of the high abundance of calcareous foraminifera.

6.4.4.1 Marshchapel LM2

1. Lithostratigraphy

A diamicton of yellowish brown silt-clay is found at the base of the core. It is overlain by a thin peat at 996 cm which is replaced at 993 cm by a light olive grey silt-clay. Furthermore, stratigraphical descriptions by LOIS indicate the upper and lower contacts of the peat are gradational.

2. Biostratigraphy

Foraminiferal tests are absent from the diamicton. However, the peat is dominated by *J. macrescens* (a monospecific assemblage occurs at 996 cm) with low frequencies of *Haplophragmoides* spp. and *M. fusca* (Figure 6.9). The abundance of *J. macrescens* decreases within the overlying clay and is replaced by *Trochammina inflata*. Every foraminiferal assemblage of Core LM2 is indicative of a saltmarsh environment, though the data show a transition up-core from higher-high marsh (monospecific *J. macrescens* assemblage) to middle marsh (mixed agglutinated assemblage) environments.

3. Indicative meaning

- **Method I**

The lower (996 cm) and upper (993 cm) contacts of the basal peat provide new SLIs from Core LM2 (Table 6.9). Biostratigraphical data indicate the peat to be saltmarsh in origin. Sample 996 cm is a basis peat directly below a *Phragmites* or clastic saltmarsh deposit and sample 993 cm is a *Phragmites* or monocot peat directly below a clastic saltmarsh deposit. The estimated indicative meaning of samples 996 cm and 993 cm are 3.00 m ± 0.20 m OD and 2.80 m ± 0.20 m OD, respectively.

- **Method II**

WA reconstructions of SWLI show a gradual decrease from the uppermost sample in the peat to the overlying silt-clay. However, the SWLIs of samples from the silt-clay are exceptionally high: indeed sample 991 cm (3.05 m ± 0.34 m OD) is above MHWST (3. 0 m OD). This is caused by the absence of calcareous foraminifera within the clastic unit. Therefore, the assemblage is dominated by agglutinated foraminifera (e.g. *J. macrescens* and *T. inflata*) with optima high in the tidal range. As a result, the change in SWLI across the transgressive contact is relatively small with respect to tidal range compared to similar sequences from other fossil cores. For example, the change in SWLI across this transgressive contact is approximately 6 (212.59 to 206.56) compared to approximately 29 for Core WA953 (194.14 to 165.39).

Notwithstanding, MAT indicates that a 'good analogue' exists for upper and lower contacts of the peat. The reconstructed indicative meanings of two SLIs are shown in Table 6.9.

6.4.4.2 Theddlethorpe LM5a

1. Lithostratigraphy

An olive grey silt-clay is found at the base of Core LM5a. There is a transition at 632 cm from the silt-clay to a peat with silt-clay. The peat is 31 cm thick and is overlain by a green-grey clay with a gradational contact.

2. Biostratigraphy

Foraminiferal tests occur in all samples except 622 cm and 626 cm from the peat (Figure 6.10). The foraminifera in the middle of the peat suggest a move towards fresher conditions before increased marine influence returns. The remaining samples in the peat and clastic units are dominated by agglutinated species (e.g. *J. macrescens*, *M. fusca* and *T. inflata*) which suggest a saltmarsh environment.

3. Indicative meaning

- **Method I**

The regressive (632 cm) and transgressive (601 cm) contacts of Core LM5a are used to produce two SLIs (Table 6.9). Lithostratigraphical and biostratigraphical data indicate sample 632 cm is a *Phragmites* or monocot peat directly above a clastic saltmarsh deposit and sample 601 cm is a *Phragmites* or monocot peat directly below a clastic saltmarsh deposit. Their estimated indicative meanings are 3.32 ± 0.20 m OD and 3.05 ± 0.20 m OD, respectively.

- **Method II**

Contrary to lithostratigraphical evidence, the WA reconstructed SWLIs remain relatively stable throughout the core. The SWLIs of the underlying and overlying silt-clay units are exceptionally high (numerous samples are above MHWST) because of the absence or low abundance of calcareous species. Nevertheless, the indicative meanings are constructed for the regressive (632 cm) and transgressive (601 cm) contacts (Table 6.9). MAT indicates these results are reliable.

6.4.4.3 Theddlethorpe LM5b

1. Lithostratigraphy

A diamicton consisting of stiff clay is found at the base of the core. Directly overlying the diamicton is a thin, well-humified peat. The peat is found at a depth of 1295 cm to 1287 cm.

The peat is overlain by an olive-grey silt-clay with dispersed organic remains and numerous bi-valve fragments. The upper and lower contacts of the peat are gradational.

2. Biostratigraphy

The foraminiferal data indicate a transition within the peat from freshwater to saltmarsh with an assemblage dominated by two agglutinated species (*J. macrescens* and *T. inflata*). Both these species are indicative of a saltmarsh environment (Figure 6.11). The saltmarsh peat is overlain by a silt-clay dominated by a calcareous foraminiferal assemblage, indicative of an estuarine or tidal flat environment.

3. Indicative meaning

- **Method I**

The lithostratigraphical and biostratigraphical data suggest the upper (1287 cm) contact of the peat is a *Phragmites* or monocot peat directly below a clastic saltmarsh deposit (3.05 ± 0.20 m OD) (Table 6.9).

- **Method II**

WA reconstructions of SWLI show a metastable equilibrium up-core. The maximum and minimum values occur within the basal peat (3.18 ± 0.35 m OD; 1291 cm) and overlying silt-clay (0.68 ± 0.46 m OD; 1205 cm), respectively. The threshold occurs at the transgressive contact (1287 cm) between these two units (reference water level decreases by 2.5 m in 0.86 m) which concurs with the lithostratigraphical evidence.

The indicative meanings of the SLIs are shown in Table 6.9. Samples from within the peat (1287 cm) and the overlying slit-clay (1281 cm, 1265 cm and 1215 cm) are based upon inverse and classical deshrinking regression, respectively. MAT indicates that a 'good analogue' exists for all samples.

6.4.4.4 Summary

Three cores (LM2, LM5a and LM5b) have been systematically studied using lithostratigraphical and biostratigraphical techniques. SLIs are produced from the upper (993 cm) and lower (996 cm) contacts of the thin basal peat of LM2. Foraminiferal assemblages of the contacts are indicative of a saltmarsh environment. Methods I and II estimate the indicative meanings of both the lower and upper contacts of the peat (Table 6.6). Radiocarbon results have been returned for these SLIs. The results are stratigraphically consistent indicating that they are reliable index points.

Two cores have been analysed from Theddlethorpe (LM5). An intercalated peat underlain and overlain by clastic units was recovered in Core LM5a. Foraminiferal data suggest a move within the peat from saltmarsh towards fresher conditions before increased marine influence returns. The indicative meanings of the transgressive (LM5a/601) and regressive (LM5a/632) contacts of the peat and clastic units are estimated using Methods I and II. The subsequent radiocarbon results are stratigraphically consistent.

Site	Core/Sample (cm)	Age (BP ± 1σ)	Calibrated age (cal. yrs. BP)	Alt (m OD)	M	RWL (m OD)	RSL (m OD)
Marshchapel	LM2/993	6485±55	7437-7232	-7.46	I	2.80±0.20	-10.11±0.21
	LM2/996	6495±55	7440-7239	-7.49	I	3.00±0.20	-10.34±0.21
	LM2/993	6485±55	7437-7232	-7.46	II	3.36±0.36	-10.67±0.37
	LM2/996	6495±55	7440-7239	-7.49	II	3.35±0.36	-10.69±0.37
Theddlethorpe	LM5a/601	4485±45	5294-4979	-4.01	I	3.05±0.20	-6.91±.21
	LM5a/632	5375±50	6286-6162	-4.32	I	3.32±0.20	-7.49±0.21
	LM5a/601	4485±45	5294-4979	-4.01	II	3.28±0.35	-7.14±0.36
	LM5a/632	5375±50	6286-6162	-4.32	II	3.09±0.35	-7.26±0.36
Theddlethorpe	LM5b/1287	7360±55	8205-7977	-10.87	I	3.05±0.20	-13.95±0.21
	LM5b/1215a*	6650±110	7648-7322	-10.15	II	0.68±0.46	-10.68±0.47
	LM5b/1215b*	6860±70	7793-7539	-10.15	II	0.68±0.46	-10.68±0.47
	LM5b/1265a*	7170±95	8128-7753	-10.65	II	0.64±0.49	-11.14±0.50
	LM5b/1265b*	7410±65	8329-8066	-10.15	II	0.64±0.49	-11.14±0.50
	LM5b/1281a*	7155±55	8013-7875	-10.81	II	0.88±0.43	-11.54±0.44
	LM5b/1281b*	7060±65	7945-7694	-10.81	II	0.88±0.43	-11.54±0.44
	LM5b/1287b*	7360±55	8205-7977	-10.87	II	3.10±0.35	-13.82±0.36

Table 6.6 Radiocarbon dates and SLIs from Lincolnshire Marshes (* the dates are corrected for the marine reservoir effect). The calibrated ages shown are the age ranges which contain 95.4 % of the area under the probability curve. ALT = altitude (m OD) of top of dated sample. M = Method of calculating indicative meaning. RWL = present altitude of reference water level and indicative range. RSL = relative sea level (m OD) with error estimates for reference water level and measurement of altitude.

A diamicton is found at the base of Core LM5b. Directly overlying the diamicton is a thin, well-humified basal peat. SLI LM5b/1287 is derived from the upper contact. The indicative meaning of the upper contact is estimated using Methods I and II. A further six SLIs are produced from the clastic silt-clay unit of LM5b. The indicative meaning of each SLI is estimated using Method II exclusively (Method I is invalid). Each foraminiferal assemblage date (LM5b/1215a, LM5b/1265a and LM5b/1281a) is paired with *Hydrobia ulvae* shells (LM5b/1215b, LM5b/1265b and LM5b/1281b) to distinguish between possible causes of observed age anomalies. Field observations during this thesis show the assemblages and shells to co-exist in tidal flat environments. The mean foraminiferal dates of depths 1215 cm and 1265 cm plot younger than the equivalent *Hydrobia ulvae* dates (181 cal. yrs. BP and 257 cal. yrs. BP, respectively) whereas the mean foraminiferal date of 1281 cm plots 124 cal. yrs. BP older than the equivalent *Hydrobia ulvae* date. There is an age inversion of the *Hydrobia ulvae* dates between 1265 cm and 1281 cm and, thus, they should be treated with caution. However, the age ranges of the foraminiferal dates are nearly identical, indicating that these index points are reliable.

The altitudinal and calibrated data from SLIs of the Lincolnshire Marshes are summarised in Figure 6.22a. All index points show a general trend of rising sea-level (approximately 8m in 3500 years). These include calcareous dates which suggest that they are reliable index points. Investigations of the indicative meanings show the indicative range of Method I to be smaller than Method II.

6.4.5 Fenland

An apparently comprehensive database exists for this area. However on closer inspection, the coastal zone is poorly sampled with respect to early Holocene SLIs. Thus, Wrangle Bank F4, Clenchwarton F13, South Lynn F15a and F15b, and Spalding F19 were sampled as part of the LOIS coring project to provide new SLIs for the 5000 to 7000 cal. yrs. BP period, for which only 12 reliable SLIs exist (Shennan, 1992). Wrangle Bank F4 lies within the West Fens, approximately 4 km west of the coast (Grid reference: TF 4392 5382) (Figure 6.12). The core forms part of the north-west to south-east transect across the western Wash margin.

The Clenchwarton F13 field site is situated west of Kings Lynn, near the main A17 road, approximately 1.5 km north of Tilney All Saints (Grid reference: TF 5713 1916). South Lynn F15 lies in close proximity to Clenchwarton, south-west of Kings Lynn, adjacent to the south-east side of the River Ouse (Grid reference: TF 6119 1836). The field site of Spalding F19 is on the eastern bank of the Welland deviation (Grid reference: TF 2595 2208). The three sites were selected to obtain information regarding the Holocene succession at the edge of the Wash-Fen Basin.

6.4.5.1 Wrangle Bank F4

1. Lithostratigraphy

A diamicton of brown and light grey mottled silt-clay is found at the base of Core F4. This is replaced by a sand-silt at a depth of 365 cm. The sand-silt is overlain by a firm peat-clay which grades into a dark brown peat at 348 cm. Overlying the peat at 344 cm is an organic silt-clay which is replaced at 330 cm by blue clay. The lower and upper contacts of the peat are gradational.

2. Biostratigraphy

Foraminiferal tests are either absent or limited in number within the diamicton and overlying sandy silt (Figure 6.13). *J. macrescens* dominates the foraminiferal assemblages of the firm peat-clay and suggests a higher-high saltmarsh environment. The abundance decreases in higher samples from the overlying peat and clastic units. These samples are dominated by a combination of *J. macrescens* and *T. inflata* which suggests a high to low saltmarsh environment.

3. Indicative meaning

- **Method I**

Method I estimates the indicative meanings from the regressive (352 cm) and transgressive (344 cm) contacts of the intercalated peat (3.87 ± 0.20 m OD and 3.28 ± 0.20 m OD, respectively). Samples 352 cm and 344 cm are classified as *Phragmites* or monocot peats directly above and below a clastic saltmarsh deposits, respectively (Table 6.9).

- **Method II**

The lower and upper contacts of the peat have the highest (3.91 ± 0.41 m OD) and lowest (3.33 ± 0.38 m OD) values, respectively. Furthermore, MAT shows these sample have a 'good analogue' (Table 6.9). Similar to Cores LM2 and LM5a, the absence of calcareous foraminifera within the clastic units causes exceptionally high reconstructed SWLIs.

6.4.5.2 Clenchwarton F13

1. Lithostratigraphy

A diamicton consisting of silt-clay is found at the base of the core. This is overlain by a thin peat between 1508 and 1494 cm which grades into a shelly-clay.

2. Biostratigraphy

The transgressive contact between the peat and the overlying clay is characterised by a change from an agglutinated monospecific *J. macrescens* assemblage to a calcareous foraminiferal assemblage dominated by *A. beccarii* (Figure 6.14). This is indicative of a rapid switch in depositional environment from higher-high saltmarsh to estuarine or tidal flat.

3. Indicative meaning

- **Method I**

Method I can only estimate the indicative meaning for the transgressive contact (1494 cm) of the peat (3.57 ± 0.20 m OD). Analyses indicate the sample is a *Phragmites* or monocot peat directly below a clastic saltmarsh deposit (Table 6.9).

- **Method II**

The WA transfer function shows SWLI to rapidly decrease from the peat (4.16 ± 0.38 m OD; 1494 cm) to the overlying clastic unit (3.65 ± 0.42 m OD; 1486 cm). However, the indicative meaning is only estimated for the clastic sample (1486 cm). The transgressive contact is omitted due to an insufficient number of foraminiferal tests (only samples with counts greater than 40 individuals are included). Furthermore, MAT indicates that sample 1486 cm possesses 'no close analogue' and, subsequently, the indicative meaning should be ignored (Table 6.9).

6.4.5.3 South Lynn F15a

1. Lithostratigraphy

A blue clay is found at the base of Core F15a which is subsequently replaced by an organic clay at 537 cm. This unit is overlain by a humified peat. The peat is found at a depth of 528 cm to 496 cm. Overlying the peat are a grey silt-clay (496 cm to 486 cm) and a brown silt-clay (486 cm to 480 cm). The contacts of the peat and the underlying and overlying clastic sediments are gradational.

2. Biostratigraphy

The foraminiferal data show a transition from a mixed agglutinated and calcareous assemblage dominated by *J. macrescens*, *T. inflata*, *Elphidium williamsoni* and *H. germanica* to a monospecific *J. macrescens* assemblage across the regressive contact (Figure 6.15). This indicates a rapid change in depositional environment from estuarine or tidal flat to higher-high saltmarsh. Conversely, the transgressive contact of the peat and overlying silt-clay shows a transition from a predominately agglutinated (abundance of *J. macrescens* is greater than 70 %)

to a high diversity, calcareous assemblage and, therefore, a change from saltmarsh to estuarine or tidal flat environment.

3. Indicative meaning

- **Method I**

Indicative meanings are estimated for both the regressive (528 cm) and transgressive (496 cm) contacts of the intercalated peat (3.95 ± 0.20 m OD and 3.57 ± 0.20 m OD, respectively) (Table 6.9). Lithostratigraphical and biostratigraphical data indicate that samples 528 cm and 496 cm are *Phragmites* or monocot peats directly above and below clastic saltmarsh deposits, respectively.

- **Method II**

WA reconstructions of SWLI show a metastable equilibrium up-core. SWLI thresholds are crossed at the regressive and transgressive contacts which supports the lithostratigraphical evidence. The indicative meaning of the former contact (4.16 ± 0.40 m OD) is based on classical deshrinking regression whereas the latter (3.51 ± 0.37 m OD) is based on inverse deshrinking regression.

6.4.5.4 South Lynn F15b

1. Lithostratigraphy

A sand unit, overlain by a thin clay peat (1081 cm to 1080 cm) is found at the base of the core. The peat is subsequently replaced by an organic clay which grades into a clay at 1069 cm.

2. Biostratigraphy

The foraminiferal assemblages of the sand and overlying peat are limited in number and are dominated by *J. macrescens* which suggests a higher-high saltmarsh environment (Figure 6.16). The remaining samples are dominated by a combination of five agglutinated species which collectively indicate a saltmarsh environment.

3. Indicative meaning

- **Method I**

Lithostratigraphical and biostratigraphical evidence indicates the lower (1081 cm) and upper (1069 cm) contacts of the intercalated peat are *Phragmites* or monocot peats directly above and below clastic saltmarsh deposits, respectively (Table 6.9). The estimated indicative meaning of sample 1081 cm is 4.15 ± 0.20 m OD and sample 1069 cm is 3.57 ± 0.20 m OD.

- **Method II**

The reconstructed SWLIs show a gradual decrease up-core. The maximum SWLI occurs at the regressive contact of the intercalated peat (4.21 ± 0.40 m OD). However, in the absence of calcareous foraminifera, the upper and lower clastic units have abnormally high SWLIs. Nevertheless, MAT indicates that the indicative meanings of the regressive and transgressive contacts of the peat are reliable. They are reconstructed using classical and inverse deshrinking regression, respectively (Table 6.9).

6.4.5.5 Spalding F19

1. Lithostratigraphy

In Core F19 a thin peat (1078 cm to 1058 cm) overlies a dark grey silt-clay diamicton. The peat is gradually overlain by soft clay with scattered shell fragments and silt lenses.

2. Biostratigraphy

Foraminifera are absent from the diamicton and the lower section of the peat (Figure 6.17). However, assemblages dominated by relatively low numbers of *J. macrescens* are found at the top of the peat. The overlying clay is dominated by calcareous taxa including *A. beccarii*. Therefore, the foraminiferal data imply a rapid change in environment from higher-high saltmarsh to estuarine or tidal flat.

3. Indicative meaning

- **Method I**

The indicative meaning is estimated for the upper contact (1058 cm) of the peat (3.60 ± 0.20 m OD). Foraminiferal data indicate it to be a *Phragmites* or monocot peat directly below a clastic saltmarsh deposit (Table 6.9).

- **Method II**

Reconstruction by WA transfer functions shows values to rapidly decrease up-core from a maximum (4.03 ± 0.43 m OD) within the peat (1060 cm) to a minimum (3.53 ± 0.47 m OD) in the overlying clay (1050 cm). The indicative meanings of the peat (1058 cm) and clastic (1054 cm) samples are based on classical and inverse deshrinking regression, respectively. MAT indicates that the former sample possesses a 'good analogue' and, therefore, the indicative meaning is reliable (Table 6.9). However, the latter has 'no close analogue' and subsequently, the indicative meaning must be ignored.

6.4.5.5 Summary

Five cores (F4, F13, F15a, F15b and F19) have been selected for lithostratigraphical and biostratigraphical analyses. The transgressive (344 cm) and regressive (352 cm) contacts of the intercalated peat of Core F4 are chosen as SLIs (Table 6.7). Foraminiferal data indicate the peat is of saltmarsh origin. Estimates of the indicative meaning of both SLIs are made with Methods I and II.

Core F13 shows a basal peat from which two samples are selected as SLIs: the transgressive contact of the peat within estuarine or tidal flat shelly-clay (F13/1494); and a sample from the shelly-clay itself (F13/1486). The indicative meaning of the former sample is estimated using Method I whereas the latter sample uses Method II. However, MAT indicates that F13/1486 has 'no close analogues' and, thus the indicative meaning is ignored.

Two cores have been analysed from South Lynn (F15a and F15b). Foraminiferal data of Core F15a show an intercalated saltmarsh peat within estuarine or tidal flat clastic units. The upper and lower contacts are selected as SLIs and their indicative meanings are estimated using Methods I and II.

The lower core (F15b) has two organic units. Foraminiferal data indicate the whole organic sequence to be saltmarsh in origin. The lower (F15b/1069) and upper (F15b/1081) contacts of the organic sequence are selected for SLIs and their indicative meanings are estimated using both methods.

Data from Core F19 reveal a thin basal peat (1078 cm to 1058 cm) which overlies a diamicton. Two SLIs are selected from the core. The first index point (F19/1058) is the transgressive contact of the peat and the overlying clastic unit. Foraminiferal assemblages imply a change from saltmarsh to estuarine or tidal flat environments across the contact. The second index point (F19/1054) is a sample from the upper clastic unit. Foraminiferal assemblages of this unit are dominated by estuarine or tidal flat species. The indicative meaning of the transgressive contact is estimated using both methods. However, the clastic sample is estimated using just Method II and, furthermore, MAT suggests the indicative meaning is invalid.

The indicative ranges of Method I are consistently smaller than Method II and the reference water levels are generally lower (the exception is the transgressive contact of F15a/496). However, the difference between reference water levels for transgressive and basis dates is greater than for regressive dates. The complete SLIs (i.e. those with radiocarbon dates) are summarised on an age-altitude graph (Figure 6.22b)

Site	Core/Sample (cm)	Age (BP ± 1σ)	Calibrated age (cal. yrs. BP)	ALT (m OD)	M	RWL (m OD)	RSL (m OD)
Wrangle Bank	F4/344	Not	available	-2.50	I	3.28±0.20	-5.53±0.29
	F4/352	Not	available	-2.58	I	3.87±0.20	-6.20±0.29
	F4/344	Not	available	-2.50	II	3.33±0.38	-5.58±0.44
	F4/352	Not	available	-2.58	II	3.91±0.41	-6.24±0.46
Clenchwarton	F13/1494	7035±65	7927-7681	-12.41	I	3.57±0.20	-15.36±0.21
	F13/1486	Not	available	-12.33	II	3.65±0.42	-15.36±0.43
South Lynn	F15a/496	Not	available	-0.25	I	3.57±0.20	-3.20±0.21
	F15a/528	Not	available	-0.57	I	3.95±0.20	-3.90±0.21
	F15a/496	Not	available	-0.25	II	3.51±0.37	-3.14±0.38
	F15a/528	Not	available	-0.57	II	4.16±0.40	-4.11±0.41
	F15b/1069	Not	available	-5.98	I	3.57±0.20	-8.93±0.21
	F15b/1081	Not	available	-6.10	I	4.15±0.20	-9.63±0.21
	F15b/1069	Not	available	-5.98	II	3.82±0.37	-9.18±0.38
	F15b/1081	Not	available	-6.10	II	4.21±0.40	-9.69±0.41
Spalding	F19/1058	6230±80	7249-6899	-8.20	I	3.60±0.20	-11.45±0.21
	F19/1054	Not	available	-8.16	II	3.61±0.48	-11.42±0.49
	F19/1058	6230±70	7249-6899	-8.20	II	3.99±0.43	-11.84±0.44

Table 6.7 Radiocarbon dates and SLIs from Fenland. The calibrated ages shown are the age ranges which contain 95.4 % of the area under the probability curve. ALT = altitude (m OD) of top of dated sample. M = Method of calculating indicative meaning. RWL = present altitude of reference water level and indicative range. RSL = relative sea level (m OD) with error estimates for reference water level and measurement of altitude.

6.4.6 North Norfolk

The general stratigraphy of the North Norfolk coast is described by Funnell and Pearson (1989). One of the LOIS objectives is to understand the sedimentary evolution of the North Norfolk barrier island coastline in the context of Holocene sea-level change. Consequently, Brancaster NNC29, Thornham NNC35 and Salthouse NNC40 were sampled by the LOIS central coring programme to provide SLIs. NNC29 is located between Brancaster and Burnham Overy in the lee of Scolt Head Island which is a natural dune-covered shingle barrier (Grid reference: TF 7829 4540) (Figure 6.18). NNC35 is situated on Thornham Marsh (Grid reference: TF 7350

4464). Thornham Marsh is an extensive marsh located on the North Norfolk coast (Section 4.4). NNC40 is located east of Brancaster, near Cley-next-the-Sea (Grid reference: TG 0709 4400).

Foraminiferal data from the clastic units of NNC29, NNC35 and NNC40 were supplied by Dr I. Boomer (LOIS).

6.4.6.1 Brancaster NNC29

1. Lithostratigraphy

A blue grey clay is found at the base of Core NNC29. It is overlain by a dark chestnut brown intercalated peat. The peat is found at the depths of 901 cm to 875 cm. It is abruptly overlain by a fine to medium yellow brown sand with broken shell fragments.

2. Biostratigraphy

The foraminiferal assemblage from the lower clastic unit is dominated by *T. inflata* which indicates a saltmarsh environment (Figure 6.19). However, foraminifera tests are absent from the regressive contact of the intercalated peat. Foraminiferal data from the transgressive contact of the peat is dominated by agglutinated foraminifera (*J. macrescens* and *T. inflata*) whereas the assemblage from the overlying sand shows an increase in abundance of calcareous foraminifera (*A. beccarii*, *H. depressula* and *H. germanica*).

The diatom assemblage of the lower contact (901 cm) of the intercalated peat is dominated by mesohalobous taxa (e.g. *Caloneis westii*) suggesting a saltmarsh origin of the intercalated peat.

3. Indicative meaning

- **Method I**

Estimates of the indicative meanings of the regressive (901 cm) and transgressive (875 cm) contacts are made from lithostratigraphical and biostratigraphical data (3.20 ± 0.20 m OD and 2.85 ± 0.20 m OD, respectively). Sample 901 cm is a *Phragmites* or monocot peat directly above a clastic saltmarsh deposit and sample 875 cm is a *Phragmites* or monocot peat directly below a clastic saltmarsh deposit (Table 6.9). However, the evidence for the latter contact is ambiguous because of the erosional nature of the contact.

- **Method II**

The lower and upper clastic units show relatively low reconstructed SWLIs compared to the peat. However, the altitudes are relatively high with respect to tidal range because of the absence or low abundance of calcareous foraminifera. The maximum SWLI occurs at the top of intercalated peat (3.12 ± 0.32 m OD; 875 cm). This sample is selected as an index point and MAT indicates that the indicative meaning is reliable (Table 6.9).

6.4.6.2 Thornham Marsh NNC35

1. Lithostratigraphy

Two peat layers are found in Core NNC35: a lower peat resting on sandy gravel; and an upper peat within a long silt-clay sequence. The lower and upper peats are found at depths of 673 cm to 592 cm and 472 cm to 386 cm, respectively. Stratigraphical descriptions indicate the upper and lower peat contacts are gradational.

2. Biostratigraphy

Foraminiferal tests are absent at the lower contacts of both peats (Figure 6.20). However, samples from the top of the peats are dominated by *J. macrescens* suggesting a higher-high saltmarsh environment. The clastic samples are dominated by *T. inflata* which suggests a saltmarsh environment.

The diatom assemblages of the lower peat contacts (673 and 472 cm) are dominated by polyhalobous (e.g. *Opephora pacifica* and *P. sulcata*) and mesohalobous taxa (e.g. *Achnanthes delicatula* and *Navicula peregrina*), respectively, which indicates that the peat must have been deposited under saltmarsh conditions.

3. Indicative meaning

- **Method I**

The indicative meanings of the regressive and transgressive contacts of both peats are estimated from the lithostratigraphical and biostratigraphical data. The regressive contacts (673 cm and 472 cm) are assumed to be *Phragmites* or monocot peats directly above clastic saltmarsh deposits whereas the transgressive contacts (592 cm and 386 cm) are *Phragmites* or monocot peats directly below clastic saltmarsh deposits. (Table 6.9).

- **Method II**

Reconstructed SWLIs of the peat unit (where possible) are marginally higher than the underlying or overlying clastic units, though, the lithostratigraphy suggest the difference between units should be greater. The altitudes of the clastic units are exceptionally high with respect to tidal range because of the absence of calcareous foraminifera. The estimated indicative meanings of the transgressive contacts 592 cm and 386 cm are 3.14 ± 0.32 m OD and 3.39 ± 0.35 m OD, respectively (Table 6.9).

6.4.6.3 Salthouse NNC40

1. **Lithostratigraphy**

A dark brown, decomposed intercalated peat with some wood fragments is found between a depth of 575 cm and 554 cm. Underlying and overlying the peat with gradational contacts are grey silt-clays with organic fragments.

2. **Biostratigraphy**

The foraminiferal assemblage of the lower clastic unit and the intercalated peat are dominated by agglutinated foraminifera which are indicative of a saltmarsh environment (Figure 6.21). The calcareous species *H. germanica* occurs in the assemblage of the upper clastic unit and indicates an increase in marine influence but still a saltmarsh environment.

3. **Indicative meaning**

- **Method I**

Lithostratigraphical and biostratigraphical data indicate that the regressive (575 cm) and transgressive (554 cm) contacts are *Phragmites* or monocot peats directly above and below clastic saltmarsh deposits, respectively (Table 6.9). The indicative meaning of sample 575 cm is estimated as 2.66 ± 0.20 m OD and sample as 554 cm as 2.35 ± 0.20 m OD.

- **Method II**

The reconstructed SWLIs of the upper and lower contacts of the peat are higher than the underlying and overlying clastic sediments. The estimated indicative meanings of the transgressive and regressive contacts are 2.59 ± 0.34 m OD and 2.52 ± 0.29 m OD, respectively (Table 6.9). All samples are dominated by agglutinated foraminifera and their altitudes are, therefore, consistently above MHWST (2.55 m OD).

6.4.6.4 Summary

Three cores have been examined from the North Norfolk Coast (NNC29, NNC35, NNC40). The lithostratigraphical and biostratigraphical analyses are used to generate several new SLIs (Table 6.8). Two SLIs are derived from the transgressive (NNC29/875) and regressive contacts (NNC29/901) of intercalated peat of Core NNC29. However, the former index point should be treated with caution because of the erosional nature of the contact. Nevertheless, foraminiferal and diatom assemblages of the peat suggest deposition in a saltmarsh environment. The indicative meanings of the transgressive contact is estimated using Methods I and II. However, only Method I is used for the regressive contact because of the absence of foraminiferal tests.

Site	Core	Age (BP ± 1σ)	Calibrated age (cal. yrs. BP)	ALT (m OD)	M	RWL (m OD)	RSL (m OD)
Brancaster	NNC29/875	2700 ± 40	2857-2751	-1.68	I	2.85 ± 0.20	-4.23 ± 0.23
	NNC29/901	3260 ± 45	3579-3370	-1.95	I	3.20 ± 0.20	-4.85 ± 0.23
	NNC29/875	2700 ± 45	2857-2751	-1.68	II	3.12 ± 0.32	-4.50 ± 0.34
Thornham	NNC35/386	2640 ± 55	2863-2709	-1.11	I	2.85 ± 0.20	-3.66 ± 0.23
	NNC35/472	3785 ± 50	4300-3984	-1.97	I	3.20 ± 0.20	-4.87 ± 0.23
	NNC35/592	4380 ± 80	5094-4829	-3.17	I	2.85 ± 0.20	-5.72 ± 0.23
	NNC35/673	8750 ± 75	9902-9528	-3.98	I	3.20 ± 0.20	-6.88 ± 0.23
	NNC35/386	2640 ± 55	2863-2709	-1.11	II	3.39 ± 0.35	-4.20 ± 0.37
	NNC35/592	4380 ± 80	5094-4829	-3.97	II	3.14 ± 0.32	-6.01 ± 0.34
Salthouse	NNC40/554	3940 ± 50	4457-4231	-2.14	I	2.35 ± 0.20	-4.24 ± 0.21
	NNC40/575	4495 ± 50	5302-4980	-3.64	I	2.66 ± 0.20	-6.05 ± 0.21
	NNC40/554	3940 ± 50	4457-4231	-2.14	II	2.59 ± 0.34	-4.48 ± 0.35
	NNC40/575	4495 ± 50	5302-4980	-3.64	II	2.52 ± 0.29	-5.92 ± 0.30

Table 6.8 Radiocarbon dates and SLIs from North Norfolk. The calibrated ages shown are the age ranges which contain 95.4 % of the area under the probability curve. ALT = altitude (m OD) of top of dated sample. M = Method of calculating indicative meaning. RWL = present altitude of reference water level and indicative range. RSL = relative sea level (m OD) with error estimates for reference water level and measurement of altitude.

A lower peat resting on sandy gravel and an upper peat within a long silt-clay sequence are found in Core NNC35. The regressive (NNC35/673 and NNC35/472) and transgressive (NNC35/592 and NNC35/386) contacts of both peats are used to produce new SLIs. Biostratigraphical analyses indicate both peats to be of saltmarsh origin. The indicative meanings of transgressive index points are estimated using Methods I and II whereas only Method I is used for regressive index points.

SLIs' NNC40/554 and NNC40/575 are produced from the intercalated peat of Core NNC40. The former index point is the transgressive contact of the peat within silt-clay. Foraminifera show the overlying clay and upper part of the peat to be saltmarsh. The latter index point is the regressive contact of the peat within silt-clay. Foraminifera show the peat and underlying silt-clay to be saltmarsh. The indicative meanings of both SLIs are estimated using Methods I and II.

The SLIs of North Norfolk are plotted on the age-altitude graph (Figure 6.22c). The graph shows index point NNC35/673 as an outlier. Pollen evidence suggests the radiocarbon date is erroneous (Innes pers. comm., 1997). Furthermore, examination of their indicative meanings endorses the inferences of the Lincolnshire Marshes and Fenland. In other words, the indicative ranges of Method I are consistently smaller than Method II and the differences between reference water levels are dependent on the type of dated material.

No.	Site	Core	Sample (cm)	Description	Method I RWL (m OD)	IR (m)	Method II Deshrinking type	SWLI	SE_{pred}	DC	Method II RWL (m OD)	IR (m)
1	Warkworth	WA953	526	Transgressive contact	2.25	0.20	Inverse	192.29	11.83	0.25	2.28	0.26
2		WA953	539	Regressive contact	2.55	0.20	Classical	212.45	12.64	0.00	2.72	0.27
3	Teesside industrial	T2	1365	Transgressive contact	2.55	0.20	Classical	212.45	12.64	0.00	3.04	0.29
	estate	T2	1378	Regressive contact	2.86	0.20						
4	Dunswell	HMB2	384	Transgressive contact	3.40	0.20	Inverse	204.05	11.81	0.08	3.52	0.37
5	Marshchapel	LM2	993	Transgressive contact	2.80	0.20	Classical	212.59	12.56	0.00	3.36	0.36
6		LM2	996	Basis peat	3.00	0.20	Classical	212.45	12.64	0.00	3.35	0.36
7	Theddlethorpe	LM5a	601	Transgressive contact	3.05	0.20	Inverse	204.50	11.83	0.05	3.28	0.35
8		LM5a	632	Regressive contact	3.32	0.20	Inverse	198.04	11.74	0.07	3.09	0.35
		LM5b	1215a	Clastic			Classical	117.70	15.19	0.34	0.68	0.46
		LM5b	1215b	Clastic			Classical	117.70	15.19	0.32	0.68	0.46
		LM5b	1265a	Clastic			Classical	109.89	16.44	0.34	0.64	0.49
		LM5b	1265b	Clastic			Classical	109.89	16.44	0.34	0.64	0.49
		LM5b	1281a	Clastic			Classical	124.41	14.22	0.28	0.88	0.43
		LM5b	1281b	Clastic			Classical	124.41	14.22	0.28	0.88	0.43
9	Theddlethorpe	LM5b	1287	Transgressive contact	3.05	0.20	Inverse	202.02	11.74	0.02	3.10	0.35
10	Wrangle Bank	F4	344	Transgressive contact	3.28	0.20	Inverse	197.98	11.75	0.21	3.33	0.38
11		F4	352	Regressive contact	3.87	0.20	Classical	213.34	12.63	0.00	3.91	0.40

Table 6.9 ***The indicative meaning of SLIs from the RACS area*** **based on Methods I and II (* implies that the indicative meanings should be ignored). No. = number of SLI used in Figures 6.23, 6.24 and 6.25. RWL = present altitude of reference water level (m OD). IR = indicative range (m). SWLI = standardised water level index. SE_{pred} = estimated standard error of prediction . DC = dissimilarity coefficient.**

No.	Site	Core	Sample (cm)	Description	Method I RWL (m OD)	IR (m)	Method II Deshrinking type	SWLI	SE_{pred}	DC	Method II RWL (m OD)	IR (m)
	Clenchwarton	F13	1486	Clastic			Inverse	199.21	13.35	1.16	3.65*	0.42*
		F13	1494	Transgressive contact	3.57	0.20						
12	South Lynn	F15a	496	Transgressive contact	3.57	0.20	Inverse	191.88	11.81	0.16	3.51	0.37
13		F15a	528	Regressive contact	3.95	0.20	Classical	212.45	12.64	0.00	4.16	0.40
14		F15b	1069	Transgressive contact	3.57	0.20	Inverse	201.48	11.78	0.02	3.82	0.37
15		F15b	1081	Regressive contact	4.15	0.20	Classical	213.93	12.63	0.00	4.21	0.40
	Spalding	F19	1054	Clastic			Inverse	197.13	13.33	1.12	3.61*	0.48*
16		F19	1058	Transgressive contact	3.60	0.20	Classical	210.82	11.87	0.02	3.99	0.43
17	Brancaster	NNC29	875	Transgressive contact	2.85	0.20	Inverse	202.60	11.78	0.08	3.12	0.32
		NNC29	901	Regressive contact	3.20	0.20						
18	Thornham	NNC35	386	Transgressive contact	2.85	0.20	Classical	212.45	12.64	0.00	3.39	0.35
		NNC35	472	Regressive contact	3.20	0.20						
19		NNC35	592	Transgressive contact	2.85	0.20	Inverse	203.19	11.77	0.05	3.14	0.32
		NNC35	673	Regressive contact	3.20	0.20						
20	Salthouse	NNC40	554	Transgressive contact	2.35	0.20	Inverse	201.83	12.52	0.10	2.59	0.34
21		NNC40	575	Regressive contact	2.66	0.20	Inverse	198.97	12.17	0.10	2.52	0.29

Table 6.9 (continued) The indicative meaning of SLIs from the RACS area based on Methods I and II (* implies that the indicative meanings should be ignored). No. = number of SLI used in Figures 6.23, 6.24 and 6.25. RWL = present altitude of reference water level (m OD). IR = indicative range (m). SWLI = standardised water level index. SE_{pred} = estimated standard error of prediction. DC = dissimilarity coefficient.

6.5 Discussion

Numerous authors (Godwin, 1940; Shennan, 1986; Tooley, 1986; Zong, 1992) have speculated on the relationship of peat to its contemporary water level: a relationship referred to as the indicative meaning. Godwin (1940) concluded that freshwater peat did not form below MSL and that at the seaward end of a tidal river, freshwater peat cannot form below MHWST. Furthermore, a high saltmarsh peat of *Phragmites* or *Juncus maritimus* was indicative of a high water mark. Van de Plassche (1986) argued that ideally the indicative meaning should be based on long-term and widespread measurements which account for temporal variability of the reference water level and height variability of the indicator as a function of environmental and other factors. In previous research this ideal has not been feasible. Therefore, the majority of sea-level studies have used the indicative meanings (**Method I**) compiled by Shennan (1982, 1986), taking into account references and observational databases when determining or evaluating fossil sea-level indicators (van de Plassche, 1986).

The indicative meaning is expressed in terms of an indicative range and a reference water level. Shennan (1982, 1986) expressed the reference water level as a mathematical function of tidal parameters (e.g. the mid-point between MHWST and HAT), rather than a single tide level ± a large constant factor because the constant factor will indicate quite different tidal inundation characteristics for areas of different tidal range. This implies application of water levels to other areas. However, Method I was originally compiled from numerous sources with the objective of reconstructing Holocene sea-level changes in the Fenland. Therefore, the ranges of these levels may be site-specific and transformation using a simple mathematical function may cause inherent variations among sites (Shennan, 1986; Horton, in press). Similarly, the indicative range is constant, irrespective of tidal range. However, it is probable that the range will vary between areas of different tidal ranges and become larger as tidal range increases. For example, Zong (1992) estimated indicative meanings for dated samples from Morecambe Bay using Gray and Scott's (1987) study of vascular plants. Zong (1992) calculated the indicative range of a *Phragmites* or monocot peat directly below a clastic saltmarsh deposit to be 60 cm (40 cm larger than Method I). The difference is the result of the relatively large tidal amplitude in Morecambe Bay compared to the Fenland.

This thesis provides an independent database of foraminiferal assemblages and SWLIs to determine indicative meanings using contemporary distributions of one microfossil group (**Method II**). However, this method is not without its disadvantages.

Limitations regarding the training set and the quantitative techniques were discussed in Chapter Five. There are further problems regarding the fossil data. First, the majority of SLIs collected by the ERC and other LOIS partners are not based on foraminifera. Either they have been sampled for other biostratigraphical techniques (e.g. diatoms), or if they have been sampled, the foraminiferal tests are in low number or absent. Method II is only applicable to samples counts greater than 40 individuals. It should also be noted that the sampling strategy adopted by ERC and other LOIS partners was limited by time constraints. The objective focused upon the production of SLIs with minimum biostratigraphical analysis. Hence, many indicative meanings were based on one sample either side of the transgressive or regressive contact. Consequently, any erroneous reconstructed SWLIs cannot easily be identified and trends are difficult to establish.

Second, there are species that occur in a fossil sample but not in the training set, notably *Balticammina pseudomacrescens* and *Tiphotrocha comprimata*. This is despite the screening of fossil foraminiferal species (only species that reach 2 % of the total sum are included). *B. pseudomacrescens* and *T. comprimata* are found in assemblages dominated by agglutinated foraminifera (e.g. *J. macrescens*) which are indicative of saltmarsh environments. These interpretations correspond with the contemporary analyses of Gehrels (1994a, 1994b) and Gehrels and van de Plassche (in press). They found peak abundances of *B. pseudomacrescens* and *T. comprimata* within the high marsh of saltmarshes of the coast of Maine, USA. Thus, their absence in the training set is not detrimental to reconstructed indicative meanings.

Third, some foraminiferal-predicted changes in SWLI between peat and clastic units are surprisingly low, contradicting the other lithostratigraphical and biostratigraphical evidence (e.g. LM2: Figure 6.9). Such uniformity of SWLIs occurs where there is an absence or low abundance of calcareous foraminifera within clastic units. This is probably the result of poor preservation of the calcareous tests within saltmarsh deposits (Scott and Medioli, 1980a; Scott and Leckie, 1990; Jennings and Nelson, 1992). Calcareous tests can be rapidly destroyed after death through dissolution (Green *et al.*, 1993). These clastic samples violate one of the basic assumptions of quantitative palaeoenvironmental reconstructions (Imbie and Kipp, 1971; Birks *et al.*, 1990): the taxa in the training or calibration set and their ecological responses to the environmental variable(s) of interest have not changed significantly over the time span represented by the fossil assemblage (Birks, 1995). The implications for Method II are discussed in the following chapter.

It is assumed that the influence of dissolution is minor for peat and clastic samples selected as SLIs. First, Method I indicates the reference water levels for peat dates are in high saltmarsh environments. Field observations during this thesis show the abundance of calcareous foraminifera in these environments is low. Second, the calcareous dates are from carbonate-rich clastic deposits and the foraminiferal tests show no evidence of dissolution (etching). Subsequently, these units are considered to be dissolution-free depositional environments. Thus, the contemporary patterns of taxon abundance in relation to SWLI can be used to reconstruct changes in SWLI through time (Birks, 1995).

6.5.1 The indicative meanings of Methods I and II

The indicative meanings of SLIs are calculated (where possible) using Methods I and II. The results differ with respect to the reference water level and indicative range. The indicative ranges of Method I are consistently smaller than Method II and the differences between reference water levels are dependent on the type of datable material.

Data were made available by the ERC and other LOIS partner to test these inferences. The indicative meanings were calculated using Methods I and II, following the procedures set out in Section 6.3.3 (Table 6.10). These results were combined with the indicative meanings of this thesis and divided into 4 classifications: transgressive; regressive; basis; and interval (samples that come from the whole of a stratigraphic unit) dates. These classifications are summarised in Figures 6.23, 6.24 and 6.25, respectively.

The summary statistics of both methods using the combined dataset are shown in Table 6.11. The most striking features of the comparisons between methods are the differences in the indicative range. The indicative range of Method II is 0.14 ± 0.09 m larger than Method I. This trend applies to all classifications except interval dates where the opposite is found (i.e. Method I greater than II). However, only one sample is observed and thus the evidence is equivocal. Furthermore, the difference between methods is more pronounced in macro-tidal areas (e.g. Wrangle Bank F4/344) because the indicative range of Method I is constant regardless of tidal range. It is to be expected that the indicative ranges of Method II are larger because they are estimated from a database consisting of 8 sites and 101 samples from profoundly different physiographic conditions.

No.	Site	Core	Sample (cm)	Description	Method I RWL (m OD)	IR (m)	Method II RWL (m OD)	IR (m)
	Northumberland							
22	Warkworth	WA942	78	Transgressive contact	2.25	0.20	2.74	0.27
23	Alnmouth	AL951	180	Transgressive contact	2.15	0.20	2.60	0.25
24		AL951	244	Basis peat	2.35	0.20	2.60	0.25
25	Bridge Mill	BM957	132	Transgressive contact	2.20	0.20	2.63	0.27
26	Cresswell Pond	CP958	43	Basis peat	2.45	0.20	2.72	0.27
27	Broomhouse Farm	BR968	72	Regressive contact	2.49	0.20	2.66	0.27
28		BR968	86	Transgressive contact	2.20	0.20	2.65	0.27
	Teesside							
29	Holme Fleet	HMBB5	527.5	Regressive contact	2.86	0.20	3.04	0.30
30	Portrack Marsh	PMC5	454	Regressive contact	2.86	0.20	3.07	0.30
	Humber							
31	Dirtness Levels	DL961	332	Transgressive contact	4.00	0.20	4.63	0.40
32	South Marsh	HMB5	864	Transgressive contact	3.20	0.20	3.78	0.40
33	Immingham	HMB10	974	Transgressive contact	3.20	0.20	3.79	0.40
	Lincolnshire Marshes							
34	Sand-le-mere	SM954	250	Transgressive contact	2.65	0.20	3.29	0.36
35		SM954	268	Transgressive contact	2.65	0.20	3.34	0.36
36		SM955	17	Regressive contact	3.16	0.20	3.12	0.33

Table 6.10 The indicative meaning of SLIs collected by ERC and other LOIS partners based on Methods I and II. No. = number of SLI used in Figures 6.23, 6.24 and 6.25. RWL = present altitude of reference water level (m OD). IR = indicative range (m).

No.	Site	Core	Sample (cm)	Description	Method I RWL (m OD)	Method I IR (m)	Method II RWL (m OD)	Method II IR (m)
	Fenland							
37	Wrangle Lowgate	F5	1350	Interval (whole of layer)	3.15	0.40	3.51	0.38
38		F5	1385	Transgressive contact	2.95	0.20	3.48	0.38
39	Gedney Fen	F8	297	Transgressive contact	3.60	0.20	4.18	0.43
40	Cowbit	F16	738	Transgressive contact	3.60	0.20	4.17	0.43
41	Gosberton	F17	565	Transgressive contact	3.60	0.20	4.08	0.43
42		F17	571	Regressive contact	4.01	0.20	3.97	0.43
43	Adventurers' Land	F21	446	Transgressive contact	3.57	0.20	4.15	0.40
44		F21	477	Regressive contact	3.95	0.20	4.16	0.40
	North Norfolk							
45	Blakeney	NNC2	815	Transgressive contact	2.35	0.20	2.63	0.27
46		NNC2	823	Regressive contact	2.66	0.20	2.63	0.27
47	Scolt Head	NNC28	1103	Transgressive contact	3.25	0.20	3.60	0.38
	Offshore							
48	Dogger Bank	55/+02/213VE	406	Transgressive contact	2.20	0.20	2.51	0.27

Table 6.10 (continued) The indicative meaning of SLIs collected by ERC and other LOIS partners based on Methods I and II. No. = number of SLI used in Figures 6.23, 6.24 and 6.25. RWL = present altitude of reference water level (m OD). IR = indicative range (m).

Classification	RWL (m)	IR (m)		
	D (II - I)	Method I	Method II	D (II - I)
Total	0.29 ± 0.22	0.20	0.35 ± 0.08	0.14 ± 0.09
Transgressive	0.39 ± 0.20	0.20	0.35 ± 0.10	0.16 ± 0.10
Regressive	0.06 ± 0.14	0.20	0.34 ± 0.06	0.14 ± 0.06
Basis	0.29 ± 0.04	0.20	0.30 ± 0.04	0.10 ± 0.04
Interval	0.37	0.40	0.38	-0.02

Table 6.11 Summary statistics for Method I and II of calculating the indicative meaning for the total combined dataset and transgressive, regressive, basis and interval subsets. The mean and standard deviation are shown. D = difference between methods.

A second important feature regards the altitude of the reference water levels. Shennan (1986) stressed that the calculation of the indicative meaning is dependent on the type of stratigraphic contact under consideration.

The altitudes of transgressive (Figure 6.23) and basis dates (Figure 6.25) for Method II are higher than Method I. Method I estimates the tide level for transgressive dates as MHWST minus 20 cm (Section 6.3). This tide level approximates the *in situ* drowning of a saltmarsh or freshwater peat and the formation of a tidal flat. Similar tide levels are calculated using numerical modelling of marsh submergence (French *et al.*, 1995). French *et al.* (1995) calculated the height difference between marsh elevation and the HAT using the intrinsic relationship between germination and zonation of marsh halophytes and tidal inundation frequency (Wiehe, 1935; Chapman, 1960). These simulations show that as the rate of sea-level rise increases, the equilibrium elevation of the marsh relative to the highest tide decreases. French *et al.* (1995) concluded that if the differential elevation exceeds more than approximately 1.5 to 2.0 m (tidal range approximately 8 m) then the marsh will presumably revert to unvegetated tidal flat. Similarly, Method I estimates the tide level for basis dates in a tidally influenced area as *in situ* telmatic basal peat growth (i.e. the peat surface remaining subaerial). The estimation of the reference water level for Method I (MHWST) corresponds to the work concerning the relationships between basal peat formation and water or tide levels (Jelgersma, 1961; Roeleveld, 1974; Tooley, 1978a; Behre and Streif, 1980; van de Plassche, 1982; van de Plassche and Roep, 1989; Denys and Baeteman, 1995).

The tide levels for transgressive and basis dates using Method II occur at higher altitudes because of properties of the fossil data and problems associated with the training data. First, Method II estimates the tide level for a foraminiferal assemblage at one point in time and space. It does not estimate the tide level for a change in assemblage from one environment to another.

Furthermore, the response time of microfossil systems is quicker than lithological systems (Long, 1992; Allen, 1995; Reed, 1995). Second, and more importantly, the training set does not possess any sites with a modern analogue of a retreating marsh (i.e. from a transgressive coastline). The most probable sites are those from the North Norfolk coast (regional subsidence of between 1 and 1.5 mm/yr.; Shennan, 1989), though French (1989, 1991, 1993) has shown that the marshes exist roughly in equilibrium with present-day changes in relative sea level because of high sedimentation rates. Thus, indicative meanings calculated by Method II do not differentiate between transgressive, basis and regressive dates.

The reference water levels using both methods for regressive dates are comparable (Figure 6.24). The maximum difference between any two samples is 0.11 m. Method I estimates the tide level of regressive contacts to be the mid-point between MHWST and HAT minus 20 cm. This corresponds to numerical models of marsh growth (Allen 1990a, 1990b, 1995; French, 1993; Reed, 1995). Allen (1990a, 1990b; 1995) presented the results of a comprehensive series of numerical modelling which were designed to investigate the controls on Holocene marsh growth within the Severn estuary, UK. He identified several possible scenarios with reference water levels between MHWST and HAT. Similarly, French (1993), using a one-dimensional model, stated that a reference water level approximately 0.6 to 0.8 m below HAT is required to simulate marsh growth with a vertical range of marsh growth of approximately 0.5 m. The altitudes of Method II are comparable to Method I because the majority of marshes within the training dataset are from regressive shorelines (e.g. Nith estuary and Kentra Bay).

To summarise, the results of both methods are comparable. The differences of tide levels between the two methods are generally incorporated within the indicative range of Method II. Thus, the independent dataset of Method II confirms the indicative meanings of Method I.

6.5.2 AMS dating of calcareous foraminifera

It was previously stated that a major disadvantage of Method II is that it is applicable to a limited number of data points from organic deposits. Conversely, the indicative meanings of clastic samples can only be estimated using Method II. Shennan (1982, 1986) did not estimate the indicative meaning for clastic samples because a suitable dating technique was yet to be developed. Nevertheless, Godwin (1993) constructed a sea-level curve from tidal flat deposits for Maltby Marsh, UK, over the last 7500 ^{14}C years. He used a bizonal scheme based upon two foraminiferal species (*A. beccarii* and *Elphidium excavatum*). However, this technique was only semi-quantitative. It was based on a small, site-specific, contemporary foraminiferal dataset compiled by Coles (1977) and Coles and Funnell (1981) which was corroborated by lithostratigraphical data (Brew 1990; Brew *et al.*, 1992). The chronology was also ambiguous: it was provided by peat dates from other cores with similar altitudes.

The development of the AMS technique for radiocarbon dating in the 1980's greatly increased the range of possible datable sedimentary deposits (Hajdas *et al.*, 1995; Jiang *et al.*, 1997). The AMS technique reliably differentiates between different biological species or between different chemical fractions using only 1 mg of carbon. It is possible, therefore, to extend the range SLIs used in sea-level analysis away from changes in lithology between terrestrial and marine deposits. One such use of the AMS technique within LOIS projects is the dating of calcareous foraminifera within clastic units.

Previous studies have employed molluscs and foraminifera for AMS dates of inner-shelf, outer-shelf and deep sea sediments (Austin *et al.*, 1995; Heier-Nielsen *et al.*, 1995; Kristensen, *et al.*, 1995). This thesis presents for the first time dated calcareous materials from intertidal environments. Several samples were selected for dating: three samples were selected from LM5b and paired with a *Hydrobia ulvae* (to distinguish between possible causes of observed age anomalies); and one sample was taken from each of Cores F13 and F19.

The age differences of the paired foraminiferal and *Hydrobia ulvae* dates of Core LM5b (Figure 6.11) are shown on an age-altitude graph (Figure 6.26). The mean foraminiferal dates of depths -10.68 m OD and -11.14 m OD plot younger than the equivalent *Hydrobia ulvae* dates (181 cal. yrs. BP and 257 cal. yrs. BP) whereas the mean foraminiferal date of -11.54 m OD plots 124 cal. yrs. BP older. However, the age ranges overlap at ± 2 standard deviations (a figure used in interpretation of SLIs, e.g. Shennan *et al.*, 1996a). Faunal composition (preferential reworking or bioturbation) has often been cited as the cause of age anomalies (Bard *et al.*, 1990). Reworking is used in the sense of lateral transport and redeposition whereas bioturbation would be vertical movement within the sediment column. Ideally, bioturbation does not alter the ^{14}C age, unless it is coupled with abundance change (e.g. due to change in sedimentation rate) or dissolution effects. Reworking influences the foraminiferal assemblages by introducing additional species and specimens. For example, Knudsen *et al.* (1996) attributed observed age anomalies of *ca.* 5000 cal. yrs. in the Skagen core, Skagerrak-Kattegat basin, North Sea to older *Miliolid* spp. Therefore, by dating single species, it enables the detection of ***in situ*** species as well as species that have been reworked. The results from LM5b do not show any differences between mixed and monospecific assemblages which suggests the age anomalies are due to bioturbation rather than reworking (Heier-Nielsen, pers. comm., 1997). Notwithstanding this, the age anomalies from LM5b are less than many previous studies (Heier-Nielsen *et al.*, 1995;

Kristensen, *et al.*, 1995) which suggests that the AMS dating of calcareous foraminiferal assemblages from intertidal sediment is a viable addition to the traditional use of transgressive and regressive contacts in sea-level chronologies.

The indicative meanings of each sample are estimated using Method II. However, a further limitation of AMS dating of calcareous foraminifera is the poor calibration data. The uneven spatial sampling regime of the intertidal investigations with respect to SWLI means that the training set has only 15 % of samples below a SWLI of 160. MAT indicates that the samples from LM5b possess 'good analogues' whereas F13 (Figure 6.14) and F19 (Figure 6.17) possess 'no close analogue'. Subsequently, the indicative meanings of F13 and F19 are ignored.

6.6. Summary

(1) Thirty-three reliable SLIs are collected from the margin of the western North Sea, within the RACS area, to fulfil the objective of providing a comprehensive database to validate the final runs of the LOIS crustal model before inputting to the tidal model.

(2) The indicative meanings of each index point are estimated by Methods I and/or II. The results are compared and the conclusions substantiated with evidence collected by ERC and other LOIS partners. The indicative range of Method II is greater than Method I and the altitudes of transgressive, basis and interval dates for Method II are higher than Method I. Nevertheless, the disparity between the two methods is incorporated within the indicative range of Method II. In contrast, the reference water levels of Methods I and II for regressive index points are comparable.

(3) This thesis also produces SLIs from clastic sediments. For the first time, calcareous material from intertidal environments are dated and the indicative meanings accurately estimated.

Chapter Seven: Foraminiferal assemblages as indicators of sea-level change

7.1 Introduction

This chapter summarises the contemporary analyses of foraminiferal assemblages of Cowpen, Welwick, Thornham and Brancaster marshes, the development of quantitative techniques to reconstruct former sea levels and the application of these techniques to produce new sea-level index points (SLIs).

The aims and objectives of this chapter are as follows:

- To summarise the distribution of foraminifera and the controlling environmental variable(s) from the margin of the western North Sea and compare this with published data from other marshes in the UK and abroad;
- To evaluate the use of foraminifera as a tool for quantifying the indicative meaning of a range of Holocene SLIs.

7.2 Contemporary investigations

Foraminiferal assemblage studies (Scott and Medioli, 1978) have proved invaluable in many palaeoenvironmental reconstructions. The well-defined foraminiferal zones that subdivide a saltmarsh increase the accuracy to which fossil marsh deposits can be related to sea level (Horton, in press). However, before employing foraminifera to determine former sea levels their contemporary distributions and controlling environmental variables must be established. Consequently, the objectives of the contemporary study were to elucidate the relationship between foraminiferal distributions and a series of environmental variables (altitude, pH, salinity, substrate and vegetation cover) and to identify the patterns of contemporary foraminiferal distribution across the intertidal zone.

Following a series of pilot studies, a foraminiferal sampling design was developed to meet these objectives (Chapter 3). Foraminiferal death assemblages proved to be the most reliable dataset for studying patterns of foraminiferal distribution. This contrasts with previous work which suggested that either total (Scott and Medioli, 1980b) or life (Murray, 1991) assemblages should be used. Furthermore, Murray (1991) suggested that the composition of the death assemblage may differ from the life assemblage from which it is derived through life processes (e.g. production) and post-mortem changes. Thus, he concluded that some death assemblages may not be in equilibrium with the depositional environment in which they are found. However, statistical analyses indicate that sub-surface assemblages (from a depth of 7 cm), the foci of palaeoenvironmental studies, accurately represent death surface assemblages.

7.2.1 Foraminifera and environmental variables

There are differing opinions regarding the influence of altitude on foraminiferal distributions. The work of Scott and Medioli (1980a, 1986) and others (Scott and Leckie, 1990) suggest a strong vertical zonation of foraminiferal species. This concept (Scott and Medioli, 1980a, 1986) implies that all environmental variables that determine foraminiferal distribution are related to tidal submergence which, in turn, are correlated with altitude of the marsh surface. Accordingly, sedentary organisms of the saltmarsh are distributed in clearly identifiable vertical zones. In contrast, de Rijk (1995a, 1995b) and de Rijk and Troelstra (1997) found that the salinity of the porewater mainly governs foraminiferal distribution in the Great Marshes, Massachusetts. No vertical zonation is found there because the salinity gradient is not controlled by marsh elevation. Through careful mapping of the marsh surface, de Rijk (1995a, 1995b) and de Rijk and Troelstra (1997) have argued that, in comparison with the saltmarshes mentioned above, the topography of the Great Marshes does not slope progressively seawards but displays an irregular surface which complicates the simple vertical zonation model.

Using similar techniques to de Rijk (1995a, 1995b) and de Rijk and Troelstra (1997), the scatter plots of the most important dead foraminifera from Cowpen, Welwick and Brancaster marshes versus a series of environmental variables show similar strong, non-linear relationships between foraminifera and altitude, though the evidence from Thornham Marsh is equivocal (Chapter 4). For example, the most abundant agglutinated (*Jadammina macrescens*) and calcareous species (*Haynesina germanica*) show positive and negative relationships with altitude, respectively. Thomas and Varekamp (1991) also claimed that *J. macrescens* is inversely related to flooding frequency in the marshes of Clinton, Connecticut. Furthermore, the transect of Brancaster marsh, studied as part of this thesis, possesses a variable microtopography but statistical analyses indicate that foraminiferal distributions are related to altitude.

Chapter 5 discusses the CCA and partial CCAs of the combined foraminiferal and environmental data in testing a hypothesis that foraminiferal death assemblages are related to altitude and hence tidal submergence. The foraminifera and majority of environmental variables from each marsh use identical constituents and can, therefore, be combined. However, the altitudes of each marsh differ with respect to tidal range. This problem is overcome by converting the altitudes to a **standard water level index** (SWLI); where SWLIs are a function of MHWST and MTL (Section 4.6). The statistical results suggest that the combined foraminiferal death distributions of Cowpen, Welwick, Thornham and Brancaster marshes are related to SWLI (*ca.* altitudes). However, partial CCAs show that salinity, not SWLI, is the most important variable. This is expected because of the relatively high inter-correlation between SWLI and other variables.

The high inter-correlation between variables reiterates the conclusions drawn from the site-specific scatter plot matrices among environmental variables. Consequently, the SWLI gradient cannot be considered completely independent. In reality, the structure of foraminiferal assemblages is more likely to be jointly affected by many linear or non-linear related factors (Be, 1977). Similar inter-correlations among variables have been observed by Gasse *et al.* (1995) and Jones and Juggins (1995) during the production of diatom-based transfer functions. Therefore, for palaeoenvironmental reconstructions, it must be assumed that the joint distribution with SWLI in the training set is the same as in the fossil set (Birks, 1995). Le and Shackleton (1994) assessed this assumption using simulated biological species data. Their simulations show that transfer functions do have potential pitfalls regarding their sensitivity to joint distributions. However, they concluded that if used with caution, they are reliable working methods when applied within the calibration range.

7.2.2 The vertical zonation of foraminifera from the margin of the western North Sea and comparisons with assemblages of other temperate intertidal zones

The relationships between contemporary foraminiferal death assemblages and SWLI are used to determine a vertical zonation within the intertidal zones of Cowpen, Welwick, Thornham and Brancaster marshes, although their zonation dimensions differ (Figure 7.1). This figure summarises the conclusions from the multivariate analyses of foraminiferal assemblages from each site (Chapter 4): Zone I of Cowpen Marsh is subdivided into two subzones (CIa and CIb); the vertical zonation of Zones I and II of Welwick and Thornham marshes overlap because of transitional foraminiferal assemblages and variable microtopographies; and there is an absence of SWLI values at Brancaster Marsh because of sampling limitations.

The vertical zonation of foraminiferal assemblages also broadly reflects major marsh zones as indicated by the distribution of vascular plants. Faunal Zones I of Welwick, Thornham and Brancaster marshes (WI, TI and BI) occur between a SWLI of 230 and 169 which coincides with high, middle and low marsh floral zones and approximates to MHWST. The faunal zones are characterised by high percentages of *J. macrescens* and in most areas *Miliammina fusca* and *Trochammina inflata*. Similar faunal zonations have been well-documented from the Atlantic (Scott and Medioli, 1978, 1980a; Smith *et al.*, 1984; Gehrels, 1994a, 1994b) and the Pacific Coasts of North America (Williams, 1989; Patterson, 1990; Jennings and Nelson, 1992; Guilbault *et al.*, 1995, 1996; Jennings *et al.*, 1995; Scott *et al.*, 1996), and Europe (Coles, 1977; Coles and Funnell, 1981; Petrucci *et al.*, 1983). Williams (1989) identified *T. inflata* as the major species of the high and middle marsh of the Fraser River delta in British Columbia. A more detailed study of the same area by Patterson (1990) revealed *J. macrescens* to be the principal species in the high marsh. However, *T. inflata* co-dominates with *J. macrescens* in samples from sites with decreased input from the Fraser River. Jennings and Nelson (1992) and Jennings *et al.* (1995) identified *M. fusca* and low percentages of *Haplophragmoides* as the other main components in the Oregon tidal marshes.

Coles (1977) and Coles and Funnell (1981) studied the central Broadlands, UK. They identified a high saltmarsh zone dominated by *J. macrescens* and *T. inflata* with minor influences from *Haplophragmoides* spp.

Assemblages near the landward boundary of Cowpen and Thornham marshes differ from assemblages in the rest of the high marsh samples. The highest high marsh assemblages have rapid decreases in foraminiferal concentrations and in percentages of *M. fusca* and *T. inflata*, and increases in the percentage of *J. macrescens*. In Oregon, higher-high marsh samples have increases in the percentages of *H.* spp. and or *T. inflata* (Jennings and Nelson, 1992; Jennings *et al.*, 1995). Similarly, Smith *et al.* (1984), Coles (1977) and Coles and Funnell (1981) defined a high-high marsh subzone on the basis of high percentages of *T. inflata*. Conversely, Scott and Medioli (1978, 1980a) and Gehrels (1994a, 1994b) observed low abundance, monospecific assemblages of *J. macrescens* at the upper boundary of the high marshes of Chezzetcook Marsh, Nova Scotia and the Maine Coast, respectively. Scott and Leckie (1990) did not identify this boundary within the Great Sippewissett Saltmarsh, Massachusetts, arguing that the zone was restricted by the altitudinal range of assemblage zones and the sampling regime undertaken. Williams (1989) and Patterson (1990) concluded that the number of samples and the accuracy of sample elevation are not adequate to decipher whether faunas at the upper edge of the high marsh differ from lower faunas. In like manner, DCA and cluster analysis did not identify the samples from the upper edge of the high marsh of Cowpen and Thornham marshes as a separate zone; it was incorporated within Zone I (CIa and TI). Thus, it can only be suggested that a more detailed sampling regime might lead to the identification of a higher-high marsh subzone.

Zone I of Cowpen Marsh can be divided into subzones, CIa and CIb. The former subzone is comparable to Zones I of Welwick, Brancaster and Thornham marshes. The latter subzone is dominated by *J. macrescens* and *M. fusca*. Many researchers have observed two subzones of middle and low marsh foraminiferal assemblages (Coles, 1977; Scott and Medioli, 1978, 1980a; Coles and Funnell, 1981; Williams, 1989; Patterson, 1990; Scott and Leckie, 1990; Jennings and Nelson, 1992; Gehrels, 1994a, 1994b). On the western Atlantic seaboard, Scott and Medioli (1980a), Smith *et al.* (1984) and Scott *et al.* (1991) based an upper subzone on equal numbers of *T. inflata* and *M. fusca* and a lower subzone on increased abundances of *M. fusca* and species characteristic of tidal flat environments. On the Pacific coast, Patterson (1990) divided the low marsh faunal zone into higher and lower subzones on the basis of significant numbers of *Cribroelphidium gunteri.*

Welwick, Brancaster and Thornham marshes do not display any subzones within Zone I which illustrates the very localised nature of some distributions. Similarly, Jennings and Nelson (1992) and Jennings *et al.* (1995) had too few samples to determine whether any subzones can be identified in the Oregon tidal marshes.

Zone II (CII, WII, TII and BII) occurs between a SWLI of 200 and 71. The zone is characterised by a high diversity of foraminifera and coincides with the low marsh and tidal flat floral zone. It is dominated by calcareous species such as *H. germanica, Ammonia beccarii* var. *limnetes, Elphidium williamsoni* and *Quinqueloculina* spp. Most previous studies of cool temperate intertidal environments have not identified low marsh and mudflat faunal zones because most taxa found in the middle and lower marshes extend into the tidal flat area (Scott and Medioli, 1980a; Williams, 1989; Patterson, 1990; Scott and Leckie, 1990). For example, Patterson (1990) identified a *M. fusca* biofacies which ranged from the lower part of the lower marsh (0 to 40 cm above MSL) through much of the elevational range of the tidal flat (0 to 80 cm below MSL). In contrast to most previous studies, faunal Zone II is distinguished because agglutinated species are restricted to the marsh zone. Similarly, Coles (1977) and Coles and Funnell (1981) identified a tidal flat faunal zone dominated by calcareous species such as *A. beccarii* var. *limnetes, E. excavatum* and *H. germanica*. Conversely, Jennings and Nelson (1992) identified a mudflat faunal zone along the central Oregon coast because the agglutinated species *Reophax nana* was restricted to this environment.

7.2.3 Seasonal variations of foraminiferal assemblages and standard water level indices

The vertical zonations of Cowpen, Welwick, Thornham and Brancaster marshes are based on annual averages of foraminiferal death assemblages. However, seasonal investigations of Cowpen Marsh show that these vertical zonations fluctuate through time. Therefore, a contemporary sample taken in one month can significantly under-estimate or over-estimate the SWLI (*ca.* altitude) range of a zone. There are also short-term periodic rises and falls of the oceanic and coastal waters due to systematic variations in the relative position of the earth, moon and sun. Known tidal periodicities vary from semi-diurnal, through diurnal, fortnightly, monthly, seasonal, annual and even longer (Carter, 1988; Woodworth *et al.*, 1991; Richards *et al.*, 1993).

Therefore, based upon the strong relationship between annual foraminiferal death assemblages and SWLI, it is hypothesised that the monthly variations in foraminiferal assemblages are correlated with monthly variations in SWLI. Figure 7.2 shows the monthly variations in the altitude of high water spring tide (HWST) during the study period (May 1995 to May 1996). However, the scatter graphs for the six most abundant species of Cowpen Marsh show no relationship between the altitudes of species optima (weighted average) and the altitudes of HWST at the time of sampling (Figure 7.3). The altitudes of optima for *J. macrescens*, *M. fusca*, *T. inflata*, *E. williamsoni* and *H. germanica* remain relatively constant irrespective of changes in the HWST altitude. The analysis rejects the hypothesis that seasonal variations in the altitude of HWST are reflected in seasonal variations in foraminiferal assemblages. The foraminiferal variations are probably due to other factors such as air or ocean temperature (Murray, 1968; Dublin-Green, 1992), or stochastic variations. Furthermore, spatial differences in local tide levels may explain some of the variations (van der Molen, 1997). Redfield (1972), de Rijk and Troelstra (1997) and van der Molen (1997) have shown that HWST is not uniform across the intertidal zone. Nevertheless, these investigations support the assumption that the Admiralty Tide Tables (annual average tide levels) used in this thesis provide appropriate and reliable levels with which to develop quantitative reconstruction techniques.

Seasonal foraminiferal variations have important implications for future contemporary sampling strategies. A contemporary assemblage sampled at any one occasion may or may not be in equilibrium with the environment or be typical of assemblages over a longer time period. Therefore, such sampling is comparable to observing "a single frame of a motion picture" (Buzas, 1968, p.11). Figure 7.4 shows the relationship between altitudinal errors for the Cowpen Marsh transect (observed versus foraminiferal-predicted) and the number of measurements per year (see following section for the methodology to predict the transect altitudes). The magnitude of the errors are relatively high especially if measurements are taken only once or twice per year (Coles, 1977; Coles and Funnell, 1981; Scott and Leckie, 1990; Jennings and Nelson, 1992; Gehrels, 1994a, 1994b). However, there is a noticeable reduction in the standard deviation for four measurements per year. Further measurements are time consuming and do not appreciably decrease the error.

7.3 Foraminiferal-based transfer functions for reconstructing former sea levels

The foraminiferal zonation of the margin of the western North Sea provides a tool for interpreting former sea levels from fossil environments. However, the large vertical ranges of Zones I and II limit the precision with which indicative meanings can be estimated. Furthermore, with only two zones being classified the indicative meaning can only be reconstructed for a limited range of index points. The very localised nature of some distributions implies that they are not regionally applicable.

As a result, the second stage of this thesis utilised the relationship between the contemporary foraminiferal assemblages and SWLIs to calibrate a transfer function or biotic index. Thus, a range of indicative meanings from a variety of sedimentary environments can be reconstructed without the need of a local or seasonal surface study.

7.3.1 Materials and methods

The dataset of average annual foraminiferal death assemblages and SWLIs from Cowpen, Welwick, Thornham and Brancaster marshes were enlarged to include data collected by other members of the ERC. This expanded the scope of contemporary analogues in the training set.

The weighted averaging (WA) regression and calibration and modern analogue technique (MAT) were chosen as appropriate, convenient and reliable methods for quantitative reconstruction. WA regression and calibration is a unimodal-based method that assumes a unimodal response of foraminiferal species to their environment. MAT compares numerically, using a dissimilarity measure, the foraminiferal assemblage in a fossil sample with the foraminiferal assemblages in the training dataset that have associated SWLI data.

The root mean squared error (RMSE) and squared correlation (r^2) for WA and MAT were calculated to assess the performance of the contemporary training set. RMSE assesses the prediction error whereas r^2 is a measure of the strength of the relationship between observed and foraminiferal-predicted SWLIs (Gasse *et al.*, 1995).

7.3.2 Results

WA and MAT were used in combination to develop a 'consensus reconstruction' (Birks, 1995) known as **Method II**: WA is used to produce precise reconstructions of SWLI together with an error range (bootstrapped SE_{pred}); and MAT evaluates the reliability of the reconstructions.

Apparent and jack-knifed (cross-validation approach) statistical measures imply that WA and MAT provide reliable reconstructions of the intertidal zone. However, scatter graphs of observed versus foraminiferal predicted SWLIs show significant residuals at the landward and seaward limits (Figures 5.8, 5.11 and 5.13). These systematic differences in the predictions are substantiated by reconstructions of the transects of Cowpen, Welwick, Thornham and Brancaster marshes (Figures 5.14a, 5.14b, 5.14c and 5.14d). The large residuals are clustered within the upper and lower ends of the transect. The vast majority of observed altitudes lie within the foraminiferal-predicted altitudinal range and only 9 and 14 of the 79 selected sites were anomalous (WA and MAT, respectively).

Moreover, the precision of the altitudinal reconstructions (Table 7.1) compares favourably with previous research. In Nova Scotia, Scott and Medioli (1980a) and Gehrels (1994a, 1994b) suggested that the former position of HAT can potentially be estimated to a precision of 20 cm by identifying the upper boundary of foraminiferal Zone IA (monospecific assemblages of *J. macrescens*). Scott and Leckie (1990) identified high marsh zone ranges of 10 to 22 cm and transitional high marsh zone ranges of 26 to 36 cm from two transects in Massachusetts. The vertical ranges of high marsh floral and faunal zones on the Pacific coast of North America are larger than the equivalent marsh zones on the Atlantic Coast. For example, Jennings and Nelson (1992) measured high marsh zone ranges of 60 to 85 cm from Oregon Marshes. Furthermore, Williams (1989) and Patterson (1990) indicated a precision of 80 to 90 cm for their high marsh faunal zones. However, their evidence is somewhat ambiguous as the altitudes were estimated from a topographic map.

The foraminiferal assemblage zones from both the west and east coasts of North America are important tools in reconstructing the history of relative sea-level change because they provide a means of recognising narrow zones with a defined altitudinal relation to sea level. However, the precision of reconstructions is site and assemblage specific. This supports the inference of de Rijk and Troelstra (1997) that surface studies are an invaluable first step in assessing the value of foraminifera as palaeoenvironmental indicators.

Site	Altitudinal range (cm)	
	Classical regression	Inverse regression
Cowpen Marsh	29	27
Welwick Marsh	39	36
Thornham Marsh	41	38
Brancaster Marsh	41	38

Table 7.1 The precision of reconstructions for Cowpen, Welwick, Thornham and Brancaster Marsh using weighted average transfer functions.

A vital advantage of the quantitative reconstruction techniques developed in this thesis (Method II) is that they are developed from numerous measurements and environments, each with differing physiographic conditions. Thus, Method II has a variety of modern analogues which are applicable on a regional scale without the need for local or seasonal surface studies.

7.4 Fossil investigations

The final stage of this thesis was to apply Method II to Holocene deposits from the margin of the western North Sea, to determine the indicative meaning and thus produce new SLIs. These indicative meanings were compared with those compiled by Shennan (1982, 1986) which are used in the majority of sea-level studies (**Method I**). Method I was developed during the IGCP Projects 61 and 200 (Preuss, 1979; van de Plassche, 1982, 1986; Shennan, 1982; Tooley, 1982a; Shennan *et al.*, 1983) and is based upon lithostratigraphical and biostratigraphical evidence.

7.4.1 Quantification of the indicative meaning

The indicative meanings of thirty-five SLIs were calculated using Methods I and/or II (Chapter 6). Method I was used for all organic dates, typically transgressive and regressive contacts but also basis and interval dates. However, Method II was only applicable to organic sequences with sufficient foraminifera. Conversely, the indicative meanings of clastic dates were exclusively calculated by Method II. Comparisons of index points where both methods were used, reveal the indicative range of Method I to be smaller than Method II. Furthermore, the reference water levels differ depending on the type of datable material. The reference water levels of Method I for transgressive, basis and interval dates plot lower than Method II whilst regressive dates are nearly identical. However, the evidence for interval dates is ambiguous because of the lack of data.

The explanations for the differences of indicative meanings have been discussed in Chapter 6. Nevertheless, two points are worth reiterating. First, it was expected that the indicative ranges of Method II would be larger, primarily because they are estimated from a database consisting of 8 sites which have profoundly different physiographic conditions. The vertical range of foraminiferal species and their relationship to a reference water level differs from site to site depending on many marsh development factors (Scott and Medioli, 1980a; Scott and Leckie, 1990; Jennings and Nelson, 1992). Jennings and Nelson (1992) suggested that these results may differ by 20 to 40 cm from one transect to another because of tidal range variations. Furthermore, it is probable that the indicative ranges will fluctuate because over longer periods other environmental factors (such as intertidal zone topography) are likely to change (Horton, in press). In contrast, the indicative meanings of Method I were developed with the objective of reconstructing Holocene sea-level changes in the Fenland and, therefore, the ranges of these levels may be site-specific.

Second, the contrasting reference water levels between methods for transgressive and basis dates, and the homogeneity for regressive dates are associated with the training data of Method II. Previous research (Jelgersma, 1961; Tooley, 1978a; van de Plassche, 1982; Shennan, 1986; French 1989, 1991, 1993; French *et al.* 1995; Allen, 1995) has shown that the tide level of the *in situ* marsh drowning is lower than for marsh growth (approximately 29 cm for the SLIs of Chapter 6). On this basis it is assumed that the foraminiferal-predicted reference water levels (Method II) are dependent on the type of overlap under consideration. However, the training set does not possess any sites with a modern analogue of a retreating marsh. Therefore, the scatter plots of observed versus predicted SWLIs (Figures 5.8, 5.11 and 5.13) and the CCA and DCA ordination diagrams (Figures 5.2 and 5.3, respectively) show parity among the data, as opposed to subsets of retreating and advancing environments.

7.4.2 The indicative meaning and sea-level index points

The two methods of estimating the indicative meanings are applied to all SLIs of the Fenland from the radiocarbon databank (ERC) including those without foraminiferal data. The SLIs have been constructed using the indicative meanings shown in Table 7.2. The subsequent age-altitude graphs assess the importance of differences between methods with respect to other factors such as sediment compaction.

The altitudinal and calibrated data of all Fenland SLIs are summarised in Figure 7.5. A polynomial best-fit line is plotted through the SLIs to aid comparisons. The differences in the indicative range of Methods I and II are relatively minor compared to the scatter of the index points. Similarly, the differences between reference water levels for transgressive (Figure 7.6), regressive (Figure 7.7), basis (Figure 7.8) and interval dates (Figure 7.9) are relatively minor. Hence, the polynomial equations are near-identical. The divergence of reference water levels between the two methods are often incorporated within the indicative range of Method II. Only with close inspection of the data are the conclusions of Chapter 6 reflected in the age-altitude graphs. Furthermore, the differences in indicative meanings are modest compared to the potential errors resulting from tidal range variations or sediment compaction.

Numerous researchers (Scott and Greenberg, 1983; Tooley, 1985; Austin, 1991; Woodworth *et al.*, 1991; Hinton, 1992, 1995; Gehrels *et al.*, 1995) have suggested that tidal amplification is non-linear and probably exponential with time (Section 2.7.3) Therefore, in order to evaluate and predict relative sea-level changes for a particular location, it is important to identify changes in tidal range through time (Tooley, 1985).

In theory all sediments undergo compaction (Section 2.7.4) which may vary from 0 % to 90% (Jelgersma, 1961). An alternative approach to reduce the problem of sediment compaction is to date sequences of compaction-free basal peats. The contrasting influence of compaction between intercalated and basal peats is summarised in Figure 7.10. The age-altitude graph and polynomial equations show the basal SLIs to plot at a higher altitude than intercalated SLIs.

Nonetheless, the differences in indicative meanings have profound implications for reconstructing late Holocene sea-level changes from foraminiferal distributions (Thomas and Varekamp, 1991; Varekamp *et al.*, 1992; de Rijk, 1995a, 1995b; Nydick *et al.*, 1995; de Rijk and Troelstra, 1997; Edwards, in prep.). Such reconstructions have been calculated in North America (de Rijk, 1995a, 1995b; de Rijk and Troelstra, 1997) from the disequilibrium between marsh sedimentation and relative sea-level rise. This involves the use of foraminifera to determine reference water level changes within fossil sediment and, hence, reconstruct a sequence of marsh submergence and emergence. However, high-resolution reconstruction is impeded by the magnitude and uncertainty of age and altitude errors.

The 'marsh palaeoenvironmental curve' research of North America commonly uses the relative percentage of *J. macrescens* as proxies for flooding frequencies and, therefore, reference water levels (Thomas and Varekamp, 1991; Varekamp *et al.*, 1992; Nydick *et al.*, 1995). However, Method II uses the statistically reliable relationship between foraminiferal assemblages and SWLIs (which are direct functions of flooding frequency) to calibrate a transfer function. Therefore, this method has the potential to provide more reliable reference water level calculations with defined error margins.

7.4.3 The application of the indicative meaning to clastic sequences

The comparable indicative meanings of Method I and II for traditional peat dates imply that Method II is a reliable technique. On this basis it is assumed that reliable SLIs can also be reconstructed for all foraminiferal assemblages found within the training dataset including calcareous tidal flat assemblages.

Calcareous foraminiferal samples were selected from cores Theddlethorpe LM5b, Clenchwarton F13 and Spalding F19. The samples from LM5b were paired with *Hydrobia ulvae* samples. The subsequent age anomalies between the paired dates are relatively small and preferable to many previous studies (Heier-Nielsen *et al.*, 1995; Kristensen, *et al.*, 1995). More importantly, their indicative meanings are consistent with the transgressive, regressive and basis SLIs from the same area (Figure 6.17a).

The radiocarbon dates are not yet available for Cores F13 and F19. More importantly, MAT implies that their indicative meanings possess 'no close analogues' and should be ignored. The lack of 'good analogues' for clastic sequences is a major problem for Method II. The foraminiferal and environmental samples of the training set consist of 101 samples. However, only 15 of these have a SWLI less than 160. Consequently, there are only a limited number of tidal flat analogues.

Dated material	Method I		Method II	
	Indicative Range	Reference Water Level	Indicative Range	Reference Water Level
Phragmites or monocot peat:				
- directly above clastic saltmarsh deposit;	20 cm	[(MHWST + HAT)/2]-20 cm	12.09	208.20
- directly below clastic saltmarsh deposit;	20 cm	MHWST-20 cm	11.66	205.60
- middle of layer.	70 cm	MHWST	12.47	212.45
Basis peat:				
- directly below *Phragmites* or clastic saltmarsh deposit.	20 cm	MHWST	12.47	212.21

Table 7.2 Indicative range and reference water level for commonly dated materials using Methods I and II. The indicative ranges (given as a maximum) are the most probable vertical range in which the sample occurs. The reference water levels are given as a mathematical expression of tidal parameters. The reference water levels and indicative ranges of Method II are calculated using further SLIs collected by ERC and other LOIS partners. They are shown as SWLIs and should be back-transformed relative to OD and indicative range expressed in metres.

A second, more serious problem is the effect of dissolution of calcareous foraminifera on SWLI reconstructions. Seven of the fourteen fossil cores analysed in this thesis show smaller-than-expected SWLI changes between peat and clastic units (e.g. LM2: Figure 6.6) because of an absence or low abundance of calcareous foraminifera within clastic saltmarsh units. As a result calcareous foraminifera have been largely ignored in palaeoenvironmental reconstructions (Scott and Medioli, 1980a; Scott and Leckie, 1990; Jennings and Nelson, 1992; Alve and Murray, 1995). The potential influence for SWLI reconstructions is illustrated in Figure 7.11. The assemblage of sample 1363 cm from Teesside industrial estate T2 is transformed using a dissolution index:

$$X_i = O_i - (O_i * D) \qquad (7)$$

where X_i is the abundance of calcareous species i after dissolution; O_i is the original abundance of calcareous species i; and D is the dissolution index between 0 % and 100 %. The abundances are subsequently converted into percentages. For example, $X_i = 0$ if the dissolution index D = 100 %. Conversely, $X_i = O_i$ if the dissolution index $D = 0$ %.

The reference water levels for sample 1363 cm show a gradual increase from the original 1.83 ± 0.54 m OD (D is assumed to be 0 %) to 2.81 ± 0.54 m OD (D = 100 %). The approximate 1 m increase in reference water level is associated with a decrease in the abundance of calcareous taxa (e.g. *H. germanica*) and their consequent replacement by agglutinated taxa (e.g. *J. macrescens*) whose species optima are low and high in the tidal frame, respectively.

Unfortunately, there are no direct methods of identifying the pH of the environment of deposition and consequently no means of detecting erroneous reconstructed reference water levels. Indirect methods include identification of foraminiferal test linings (Alve and Murray, 1995) and/or agglutinated species whose optima are low in the tidal frame (e.g. *Trochammina ochracea* or *Reophax nana*). The presence of either of these constituents, in the absence of calcareous foraminifera, would suggest dissolution. However, neither are abundant in the fossil cores under investigation: *T. ochracea* is only present in two fossil cores (HMB2 and LM5b). Therefore, the most important indirect method is comparison with other lithostratigraphical and biostratigraphical techniques.

Reconstructed reference water levels from clastic tidal flat units are reliable and informative. Field observations have suggested that tidal flat environments are carbonate-rich and dissolution-free (no etching). The production of SLIs from such units have many potential applications because establishing reliable chronologies in Holocene sediments is a key theme in a number of special LOIS topics. For example, although four SLIs have been produced from Holkam Core NNC17, there is the potential to produce further index points from the upper and lower clastic units (Figure 7.12). There are sufficient calcareous foraminiferal tests for numerous AMS dates. Indeed, an AMS date of shell material already exists (NNC17/398). Furthermore, the indicative meanings for all but one of the levels possesses a 'good analogue'. The exception is 445 cm (dissimilarity coefficient of the MAT is 0.54).

Method II provides the means to produce SLIs from clastic sequences and potentially valuable in establishing continuous records of relative sea-level change or sedimentation from sequences of sediments downcore. For example, a conceptual age-altitude graph (Figure 7.13) is produced for Holkam NNC17 with each sample being used as a SLI (except sample 445 cm). The ages of samples which have not been radiocarbon dated are estimated assuming a constant sedimentation rate. The majority of SLIs show a general trend of rising sea-level. The exception is the oldest index point (NNC17/907). The graph also shows an oscillation in sea-level rise between 3 and 4 ka. cal. yrs. BP which would hitherto be undetected.

The chronology of sea-level studies is not dependent solely on the use of transgressive or regressive contacts. The biostratigraphical record clearly demonstrates that these contacts represent only one point in a time transgressive process of watertable and sea-level change (Tooley, 1978a; Long, 1992). Thus, any dating methodology concerned with the timing of sea-level events must consider both intra-deposit and inter-deposit changes.

7.5 Summary

(1) The foraminiferal death distributions of four field sites show a strong, statistically significant relationship with altitude which supports the conclusions of Scott and Medioli (1980a, 1986). This relationship is used to develop a vertical zonation for each marsh. The assemblages are very similar to those studied in other mid-latitude, cool-temperate intertidal zones. However, the dimensions and foraminiferal assemblages of the four field sites are shown to differ, illustrating the localised nature of some foraminiferal distributions. Furthermore, seasonal variations modify the patterns of contemporary foraminiferal distribution across the intertidal zone.

(2) This thesis presents an alternative method of estimating the indicative meaning (Method II) based upon the contemporary relationship among relative sea-level, environmental conditions and the succession and seasonal variations of foraminiferal assemblages. Method II provides the

means to quantify the precision and definition of the indicative meanings of Method I which are used in the majority of sea-level studies.

(3) The two methods of estimating the indicative meanings were used to produce thirty-three reliable new SLIs from a range of palaeoenvironments along the margin of the western North Sea. The results show the indicative ranges of Method II are consistently larger than Method I. Furthermore, the altitudes of transgressive, basis and interval dates for Method II are higher than Method I. Conversely, the reference water levels of Methods I and II for regressive dates are comparable. The differences of reference water levels are often incorporated within the increased indicative ranges of Method II.

(4) Method II is potentially valuable in establishing continuous records of sea-level changes and sedimentation in minerogenic sediments. For the first time, reliable and informative index points can be produced from clastic sequences.

Chapter Eight: Conclusions

8.1 Introduction

This chapter concludes the thesis by assessing the extent to which the initial research aims and objectives outlined in Chapter One have been met. The chapter concludes by considering future research avenues.

8.2 Summary of the thesis

(1) Four contemporary intertidal environments were selected from the margin of the western North Sea within the RACS area. They exhibit a wide range of physiographic conditions including macro-tidal and meso-tidal estuarine (Welwick and Cowpen marshes, respectively), macro-tidal open coast (Thornham Marsh) and macro-tidal back-barrier (Brancaster Marsh) environments.

(2) The contemporary fauna and flora were systematically assessed using a range of lithostratigraphical and biostratigraphical techniques. The analyses concentrated on foraminifera because of the potential to quantify the indicative meaning of a range of Holocene SLIs. Difficulties encountered when studying intertidal foraminifera were assessed through a pilot study of Cowpen Marsh. The pilot study results show that a wetsplitter can be used to produce reliable results that are indicative of foraminiferal assemblages from a particular site. The study also implies that the intertidal foraminifera of Cowpen Marsh live primarily in epifaunal habitats. The pilot study concludes that foraminiferal death assemblages provide the most reliable dataset for studying patterns of foraminifera distributions.

(3) The contemporary foraminiferal death assemblages were studied to elucidate the relationship between foraminiferal distributions and a series of environmental variables. More importantly, they were examined to identify the patterns of foraminiferal distribution across the intertidal zone that can be related to fossil deposits. The subsequent results (Chapters 4 and 5) show the distribution of foraminiferal species in the intertidal zone are usually direct functions of altitude. The other variables (organic content and grain size of the substrate, pH, salinity and vegetation cover) further influence the assemblages, though in most sites these other environmental variables also change along the altitudinal gradient of the intertidal zones

(4) The strong, statistically significant relationships of foraminiferal death distributions versus altitude were used to develop a vertical zonation for each marsh. The zonations show general and site-specific trends which are comparable with many other mid-latitude, cool-temperate intertidal zones. Cluster analysis and DCA separates the annual average foraminiferal death assemblages of each site into Zones I and II. Zone I is characterised by high percentages of *Jadammina macrescens* and in most areas *Miliammina fusca* and *Trochammina inflata*. Zone II is characterised by a high diversity of foraminifera and is dominated by calcareous species such as *Haynesina germanica, Ammonia beccarii* var. *limnetes, Elphidium williamsoni* and *Quinqueloculina* spp. Cowpen Marsh is the only site to exhibit two subzones of Zone I. Subzone Ia is similar to Zones I of Welwick, Brancaster and Thornham marshes. Subzone Ib is dominated by *J. macrescens* and *M. fusca*.

(5) The detailed biological and environmental data from each site were combined with data collected by other members of the ERC. The primary aim was to reconstruct indicative meanings as a function of foraminiferal data (Chapter 5). To facilitate such a function, the altitudinal data were expressed as a standardised water level index (SWLI). Two quantitative reconstruction techniques (known as Method II) were chosen: weighted averaging (WA) regression and calibration; and modern analogue technique (MAT). Statistical measures assessing the performance of these techniques suggest that precise reconstructions of former sea levels are possible.

(6) Method II was used in combination with the established technique (Method I) of Shennan (1982, 1986) to estimate the indicative meanings of thirty-five SLIs (Chapter 6). The index points were collected from chosen locations along the margin of the western North Sea from Warkworth (Northumberland) to Salthouse (North Norfolk), and from specific time periods during the Holocene. The index points used dated material from a range of palaeoenvironments including clastic tidal flat sediments. Uniquely, calcareous material from such sediments has been dated and the indicative meanings estimated using the AMS technique and Method II, respectively. The new index points provide a comprehensive database to validate the final runs of the LOIS crustal model before inputting to the tidal model.

(7) The results of the two methods differ with respect to the reference water level and indicative range (Chapters 6 and 7). The indicative ranges of Method I are consistently smaller than Method II and the differences between reference water levels are dependent on the type of datable material. These inferences are supported by data from the ERC and other LOIS

partners. Nevertheless, the differences of indicative meanings are minor with respect to potential errors as the result of tidal range variations or sediment compaction.

8.3 Research recommendations

This thesis represents an attempt to quantify the indicative meaning of a range of Holocene sea-level index points based upon the relationship among relative sea-level, environmental conditions and the contemporary distributions of one microfossil group (foraminifera). In this sense the initial research aims stated in Section 1.3 have been met. However, many issues concerning the definition and precision of the indicative meaning remain unresolved.

There is a need to expand the training set to include more samples from tidal flat environments and, more importantly, to include samples from transgressive coastlines. The training set consists of 101 samples from eight sites. However, only 15 % of samples have SWLIs less than 160. Consequently, the reconstructions of clastic samples F13/1486 and F19/1054 are invalid. Estimations of the indicative meaning using Method I are dependent on the type of stratigraphic contact under consideration. However, this is unfeasible with Method II because the training set is composed exclusively of regressive overlaps (i.e. samples from advancing or stable coastlines). Therefore, retreating coasts should be targeted for future sampling with equal weight given to tidal flat and saltmarsh environments.

An alternative approach would be to apply the methodology to another microfossil group such as diatoms. Nelson and Kashima (1993) studied diatom zonation in the southern Oregon Tidal Marshes relative to vascular plants, foraminifera and sea level. They concluded that the diatom assemblages showed a three-part vertical zonation which was similar to the foraminiferal zonation, though, the vertical range was large (approximately 0.7 m). Preliminary investigations into the application of Method II to diatom assemblages have begun (Zong and Horton, 1997). The results are very promising and suggest that the diatom assemblages will provide an independent dataset to validate the foraminiferal-predicted indicative meanings. Furthermore, it is hoped that the diatom and foraminiferal assemblages can be combined to form a more reliable training data set.

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