Holocene sea-level change at the Steart Peninsula, Somerset: Development and application of a multi-proxy sea-level transfer function for the Severn Estuary region

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Abstract

This thesis presents a multi-proxy reconstruction of Holocene sea-level change at the Steart Peninsula in Bridgwater Bay, Somerset. Single- and multi-proxy transfer functions were developed from diatom and foraminifera training data from two sites on the Severn Estuary coast. Constrained and partial constrained ordination estimated that 5.5% of the intertidal diatom variation and 11.4% of the intertidal foraminifera variation in the training sets was explained independently by elevation within the tidal frame.

Foraminifera provided more favourable transfer function prediction statistics but were low in abundance in parts of the intertidal zone, resulting in a smaller than optimal training set. The preferred transfer function combined diatom and foraminifera data to optimise prediction statistics and intertidal coverage.

An 11.22m fossil core was retrieved from the Steart Peninsula for stratigraphic and micropalaeontological analyses. Analogue matching revealed that combining the two proxies increased the number of fossil samples with good or fair modern analogues in relation to the single proxies separately. The preferred multi-proxy transfer function was applied to the fossil micropalaeontological data.

The sediment stratigraphy, biostratigraphy and transfer function-based estimates indicated an overall rise in relative sea-level of about 13m between 7,582-7,345 and 1,804-1,690 cal. years before present (cal. yr BP), beginning with an initial rapid phase of sea-level rise and silty clay deposition in a minerogenic saltmarsh environment. Between 6,188-6,007 and 3,942-3,759 cal. years BP three main fluctuations in marine influence occurred, allowing organic upper saltmarsh conditions to develop periodically, but the data scatter and large vertical error bars prevent a detailed interpretation of absolute sea-level change. Diatoms and foraminifera were sparse or absent between 4,053-3,869 and 1,927-1,806 cal. years BP. Finally, foraminifera assemblages indicated a possible tidal flat environment and increase in marine influence between 1,927-1,806 and 1,682-1,619 cal. years BP.

This research concludes that multi-proxy methods have the potential to improve the ac-

curacy and precision of relative sea-level reconstruction in an extremely macrotidal setting such as that of the Severn Estuary, but that a number of issues such as sediment autocompaction and possible Holocene tidal range changes need to be quantified in order for the broad sea-level history presented to be constrained further.

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List of Abbreviations

ACD Admiralty Chart Datum.

AMS Accelerator Mass Spectrometry.

BIIS British and Irish Ice Sheet.

BP before present.

CA correspondence analysis.

CCA canonical correspondence analysis.

DCA detrended correspondence analysis.

DNN Danish National Datum.

GCM global climate model / general circulation model.

GIA glacio-isostatic adjustment.

GISP2 Greenland Ice Sheet Project 2.

GMST global mean surface temperature.

GRIP Greenland Ice Core Project.

GSSP Global Stratotype Section and Point.

HAT highest astonomical tide.

HHT higher high tide.

HHW higher high water.

IGCP International Geoscience Programme.

IPCC Intergovernmental Panel on Climate Change.

LAT lowest astonomical tide.

LGM Last Glacial Maximum.

LLT lower low tide.

LOI loss on ignition.

MAT Modern Analogue Technique.

MHHW mean higher high water.

MHWST mean high water spring tide.

MIS Marine Isotope Stage.

MLHW mean lower high water.

MSL mean sea-level.

MTL mean tidal level.

NGRIP North Greenland Ice Core Project.

NMDS non-metric multidimensional scaling.

NNR National Nature Reserve.

OD Ordnance Datum.

ODN Ordnance Datum Newlyn.

PCA principal components analysis.

PCO principal coordinates analysis.

PCR principle components regression.

PLS partial least squares.

PPT parts per thousand.

RDA redundancy analysis.

RMSE root mean squared error.

RMSEP root mean squared error of prediction.

RSL relative sea-level.

RWL reference water level.

SD standard deviation.

SLF Somerset Levels Formation.

SLIP sea-level index point.

SSSI Site of Special Scientific Interest.

SWLI standardised water level index.

WA weighted averaging.

WA-PLS weighted averaging partial least squares.

WA-Tol weighted averaging with tolerance downweighting.

WCRP World Climate Research Programme.

Chapter 1

Introduction

1.1 The significance of Holocene sea-level research

The Holocene is the second epoch of the Quaternary period and is the most recent geological interval in Earth's history. The commencement of the Holocene is defined by Walker *et al.* (2009) as 11,700 calendar years before AD 2000, based on a clear and precise record of the Pleistocene-Holocene boundary contained in the North Greenland Ice Core Project (NGRIP) ice core. The majority of cultural changes, like the domestication of animals and the emergence of agriculture, have taken place during the Holocene (Roberts, 1998) and the human population has increased exponentially from an estimated few million 10,000 years ago to 7 billion in 2011 (UN Department of Economic and Social Affairs, 2013).

The global climate and environment of the Holocene has been, and continues to be, of great significance to the growth and development of the human race. By the mid-21st century climatic changes related to the increased concentrations of greenhouse gases in the atmosphere have the potential to permanently displace 200 million people; the three main drivers of environmental migration are likely to be increased drought, heavier flooding and rising sea-levels (Stern, 2007).

Significant and often vulnerable populations live along highly developed coastal fringes and on low-lying islands throughout the world and ongoing sea-level rise is a major socio-economic hazard associated with global warming (Milne *et al.*, 2009). The Stern Review estimates that a 3-4°C rise in mean global temperature would lead to serious risks and increased pressures for coastal defences and critical infrastructure in Southeast Asia, small islands in the Caribbean and the Pacific and large, economically important cities such as Tokyo, London and New York (Stern, 2007). Consequently there is a great deal of interest in monitoring current sea-level trends and modelling future scenarios (IPCC, 2013; Lambeck *et al.*, 2010).

Sea-level change also influences the evolution of coastal environments, determines the base

level of continental erosion by fluvial and other erosive processes, and affects the amount and type of sediments deposited in coastal environments (Mastronuzzi *et al.*, 2005).

Efforts to directly measure contemporary sea-level change across the Earth have increased and improved since the mid-19th century. The longest tide gauge record in the world is from Brest in France, where relative sea-level has been measured continuously since 1807 (Mitchum *et al.*, 2010). Geographical coverage of tide gauge stations is relatively poor, particularly in the southern hemisphere, and while satellites now record water levels with global coverage, this newer system of recording sea-level has only existed since 1992 (Church and White, 2006). We currently have a good understanding of small scale, short term coastal processes, but a greater understanding of the complex causes and effects of sea-level change on decadal to centennial scales is critical for coastal management and future planning (de Groot, 1999). Sea-level researchers study sedimentary and palaeoenvironmental archives to identify past analogues for modern coastlines (Woodroffe and Murray-Wallace, 2012) and to improve understanding of sea-level change over a broader range of timescales than we currently have instrumental data for (Church *et al.*, 2008; Lambeck *et al.*, 2010). A longer time perspective is often valuable because the effects of environmental changes can take time to become apparent (Oldfield, 2005).

Glacio-isostatic adjustment (GIA), the deformation of the lithosphere in response to ice and water mass redistribution, is a major contributor to sea-level change (Whitehouse, 2009). The Earth's crust is compressed under the weight of glacial ice during glacial stages to an extent that is proportional to the weight of the ice, and when that ice is redistributed to the oceans the crust rebounds. The effects of GIA continue after ice volumes have stabilised (Lambeck *et al.*, 2010).

As mantle material moves from under the ocean into previously glaciated continental regions and meltwater increases the volume, and therefore weight, of water in the ocean, the ocean basin volume may increase, in addition to the forebulge subsidence that occurs outside of the margins of ice sheet melting (Wilson *et al.*, 2000). In areas experiencing ocean volume increase due to GIA the contribution of ice melting and steric effects to sea-level rise may be underestimated as their impact on relative sea-level is mitigated by the increase in ocean basin volume as water is redistributed, ensuring that the oceans' surfaces remain in gravitational equilibrium (Peltier, 1999). Present-day observations of mean tidal levels by tide gauges and satellite altimetry must therefore be corrected for GIA (Whitehouse, 2009).

High quality palaeo-sea-level data is used to test and refine GIA models and the British Isles form a particularly useful case study due to the combination of contrasting relative

sea-level changes between the north and south of the islands (Shennan *et al.*, 2009). For example, Peltier *et al.* (2002) used radiocarbon dated SLIPs from 55 locations in the British Isles to test their GIA model ICE-4G (VM2). The SLIPs for the Severn Estuary and Bristol Channel region are from Heyworth and Kidson (1982), highlighting an opportunity for this study to provide recent data using more sophisticated analytical techniques and improved radiocarbon dating than was available in the 1970s and 1980s.

The Intergovernmental Panel on Climate Change (IPCC) is the leading international organisation for the assessment and reporting of climate change and its environmental and socio-economic impacts (IPCC, 2015). The fifth assessment report recognises the significant progress that has been made in the accounting of GIA since the fourth assessment report published in 2007, and uses research on the geological record of sea-level change to summarise constraints on sea-level in the Middle Pliocene, Marine Isotope Stage (MIS) 11, MIS 3 and the late Holocene, emphasising the importance of the insights provided by past sea-level estimates (Church *et al.*, 2013).

Gehrels (2010) highlights the relevance of past sea-level knowledge in understanding and validating present and future sea-level estimates, and acknowledges the perception of the IPCC's fourth assessment report (Bindoff *et al.*, 2007; Jansen *et al.*, 2007) by parts of the sea-level community as excluding Quaternary sea-level specialists and providing the material on sea-level in a way that is not cohesive. The fifth assessment report presents the sea-level research in a central chapter and devotes more space to the field of palaeo-sea-level research (Church *et al.*, 2013), reflecting the increasing value of the discipline.

Successive International Geoscience Programme (IGCP)[1] projects have focussed on late Quaternary sea-level, coastal evolution, records of rapid coastal change and sea-level high-stands, and Quaternary land-ocean interactions. IGCP588, "Preparing for Coastal Change" builds on the outcomes of those earlier projects and focusses on the impacts of humans on coastal landscapes at different time scales, and on the reactions of human populations to coastal change, such that the past can help to guide the future (Woodroffe and Murray-Wallace, 2012). Regionality is a particularly important element of the goals of IGCP588.

Rovere *et al.* (2012) and Lloyd *et al.* (2013) propose that further large, regional sets of Holocene relative sea-level (RSL) data points should be compiled, to help to reduce discrepancies between reconstructions and models, and to recognise thresholds in coastal ecosystems and habitats.

One of the main research recommendations resulting from the World Climate Research

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[1]previously known as the International Geological Correlation Programme

Programme (WCRP) workshop on sea-level rise and variability in 2006 is for better spatial coverage of data of RSL variability over the past 8,000 years. The main motivations for this research recommendation are 1) the need for better knowledge about the extent to which sea-level changes in the Holocene were global, regional or local, and 2) to constrain estimates of the contributions of terrestrial ice melting since the Last Glacial Maximum (LGM) (WCRP, 2006).

Siddall *et al.* (2009) and the Paleo Sea Level Working Group (PALSEA, 2009) propose that, while past Quaternary interglacials such as MIS 5 and MIS 11 may prove to be useful analogues for various aspects of the Holocene climate (Mastronuzzi *et al.*, 2005), it is vital to study the Holocene itself in detail. If we can understand and quantify the response of sea-level, both globally and regionally, to climatic warming and ice sheet melting in the Holocene, we can place limits on any predictions of future sea-level rise, based on (a) our best prediction scenarios of future warming, (b) our understanding of ice sheet dynamics and thermal expansion, and (c) the volume of ice that remains on the land (Grinsted *et al.*, 2010; Kemp *et al.*, 2011; Siddall and Milne, 2012).

A recent move towards quantitative studies of coastal ecology and palaeoecology has led to the use of sea-level transfer functions, based on the present-day assemblages of microfauna that inhabit intertidal sediments and their fossil equivalents that are preserved in deeper coastal sediments, to produce sea-level reconstructions from biostratigraphic data that are potentially more robust than reconstructions generated from previous methods, as discussed later in Sections 2.3 and 2.4 of Chapter 2, and for which statistical estimations of error can be calculated (Gehrels, 2000; Horton *et al.*, 1999a; Horton and Edwards, 2006; Leorri *et al.*, 2011).

The sea-level literature presents many instances of Holocene sea-level reconstruction based on single-proxy transfer functions, using foraminifera (Horton and Edwards, 2005; Massey *et al.*, 2006a), diatoms (Woodroffe and Long, 2010; Zong and Horton, 1999) or testate amoebae (Charman *et al.*, 2010) to make hindcast predictions of former sea-levels. Research with multi-proxy sea-level transfer functions, to test for the relative accuracy and precision of using more than one sea-level indicator, is in its relative infancy, with just three examples of the development of a multi-proxy sea-level transfer function in the literature (Gehrels *et al.*, 2001; Kemp *et al.*, 2009a; Patterson *et al.*, 2005), and no instances of the application of a multi-proxy transfer function to fossil data in order to reconstruct former sea-level change. This thesis presents the first application of a multi-proxy sea-level function to fossil assemblage data and the subsequent Holocene sea-level reconstruction derived from that application,

and makes recommendations for the future use of multi-proxy transfer functions in Holocene sea-level studies.

Transfer function-based study of sea-level in macrotidal settings is also relatively scarce (Hill *et al.*, 2007; Horton and Edwards, 2000). This research contributes to our understanding of Holocene sea-level change in the Somerset Levels area of the Severn Estuary region, whose mean tidal range is the second largest in the world, with 14.85 metres between lowest astonomical tide (LAT) and highest astonomical tide (HAT) at Avonmouth (Proudman Oceanographic Laboratory, 2012a).

1.2 Sea-level change at the Steart Peninsula and the wider Somerset Levels

The Steart[2] Peninsula lies on the coastal fringe of the Somerset Levels (Figure 1.1), which form an eight to ten kilometre wide belt of Holocene marine and estuarine clays, intercalated in places with peats, lying to the west and seaward side of the lower lying fen and raised bog peats of the Somerset Moors (Williams and Williams, 1992). Together with the North Somerset Levels, the Avon Levels and the Gwent Levels, the Somerset Levels are part of the extensive system of buried river valleys bordering the Severn Estuary (Allen and Haslett, 2002; Williams and Williams, 1992). Holocene sea-level in the Somerset Levels, and the wider Severn Estuary/Bristol Channel region, is broadly understood to have risen rapidly in the early Holocene in response to global ice melting after the LGM, slowing from around 5,000 cal. yr before present (BP) to the rate of ~1mm/yr that occurs today (Kidson and Heyworth, 1976; Shennan and Horton, 2002), as shown in Figure 1.2.

Allen (2000c) argues that this broad, smooth curve is a misleading representation of Holocene sea-level change in the region, depicting only the underlying behaviour of sea-level and potentially masking the existence of centennial scale, decimetre to metre-scale variation in the record. Subsequent work at Gordano by Hill *et al.* (2007) reveals that marine influence in this part of the Severn Estuary was not uniform throughout the Holocene, but it is not possible to infer whether such changes in marine influence were due to sea-level changes given the magnitude of error in the chronolgical and geological records.

Heyworth and Kidson (1982) argued that any possible oscillations in sea-level would probably be of a lesser magnitude than the vertical errors associated with studies of RSL change. However, improved knowledge and more robust and precise methods may now mean

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[2]Note the two spellings of Steart/Stert for *Steart* village, *Steart* Peninsula, *Stert* Flats, *Stert* Point and *Stert* Drove.
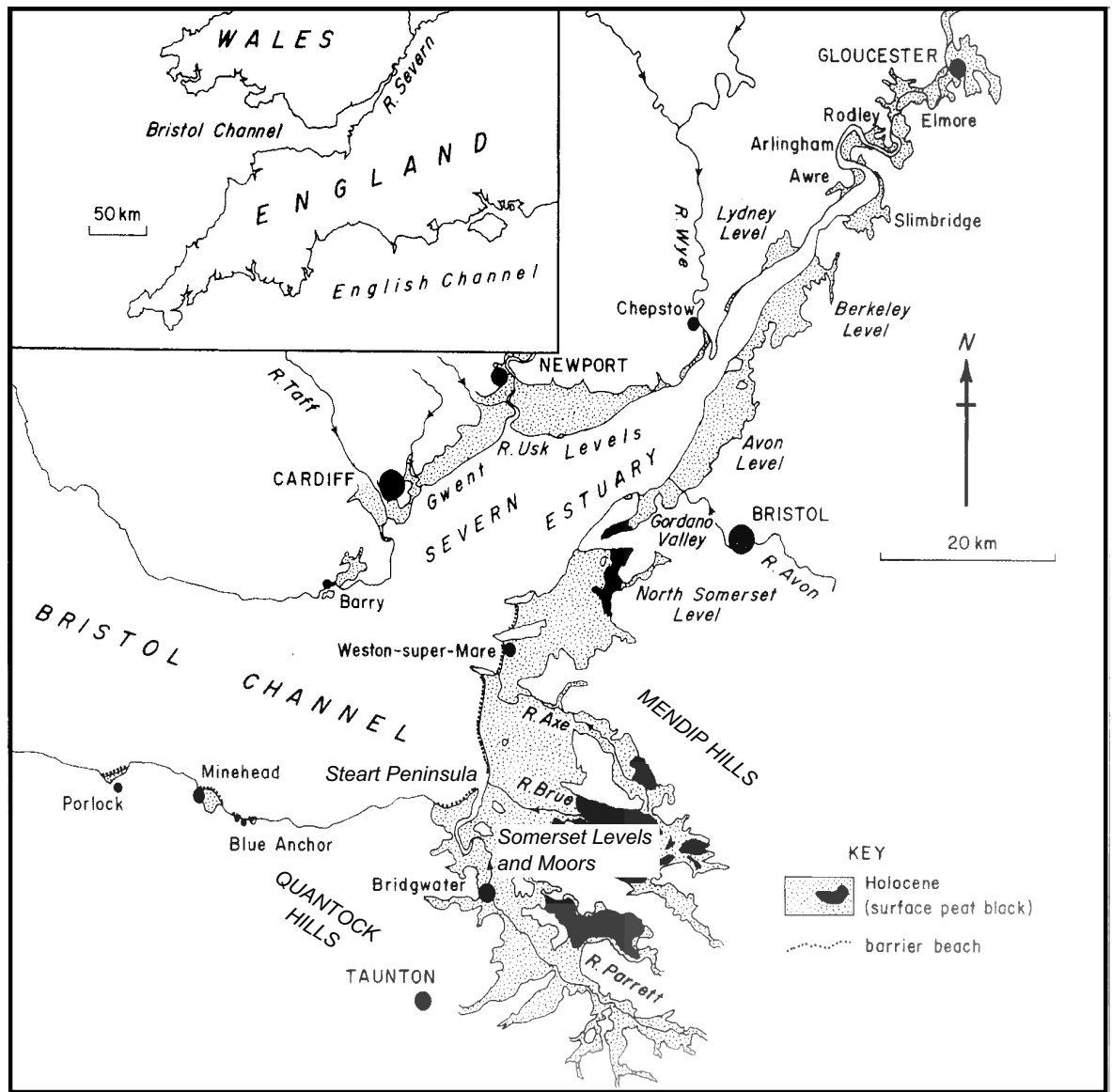
Figure 1.1: Map of the Severn Estuary levels, showing places mentioned in the text. Adapted from Allen and Haslett (2002) with permission from SAGE Publications.

that fluctuations in the direction and rate of Holocene sea-level change can be reflected in the reconstruction of regional RSL.

Many of the data points in Kidson and Heyworth's sea-level curve for the Bristol Channel region are from Bridgwater Bay (Kidson and Heyworth, 1976). While this research is significant and has been influential, it is of its time. The methods used to compile the sea-level curve are not sufficiently rigorous by the research standards of the present day, and have since been criticised by Allen (2000c) and Haslett *et al.* (1998). These criticisms are based around a lack of acknowledgement that the relationships between the peat units selected for SLIPs and past sea-levels are unknown. These data points have been used in a meta-analysis of relative land/sea-level change in the British Isles by Shennan and Horton (2002) without full acknowledgement of their limitations.
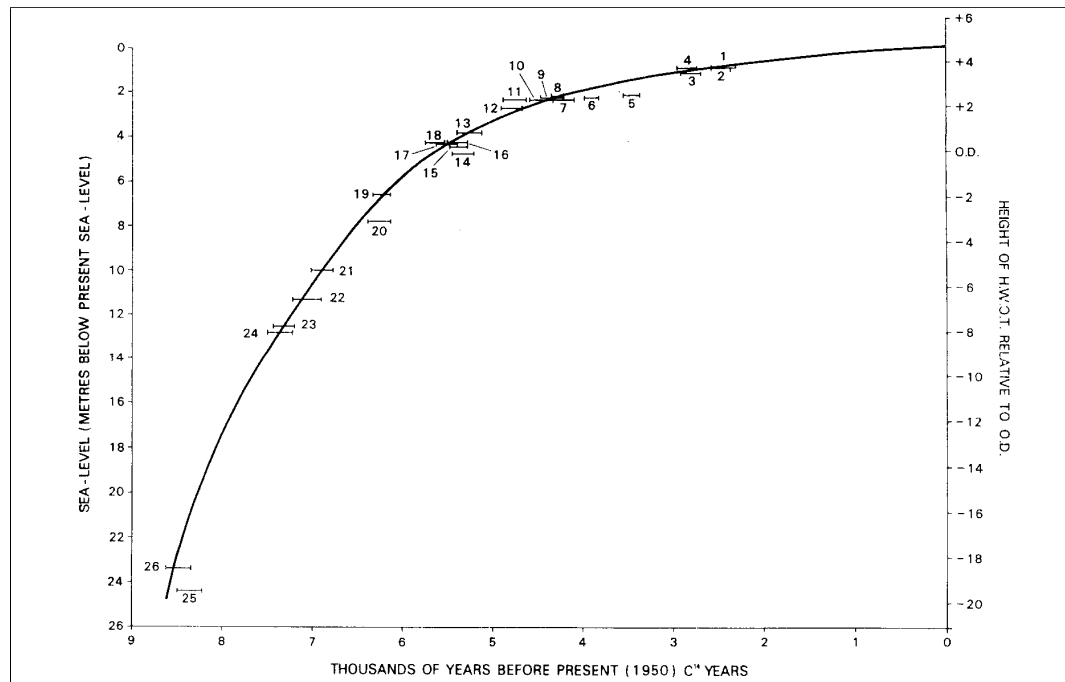
Figure 1.2: Holocene sea-level rise in the Bristol Channel, from Kidson and Heyworth (1976). Dates are in ^{14}C years and numbers on the plot refer to sea-level index points presented in the publication. Reproduced with permission from The Geological Society of London.

This thesis presents a transfer-function derived sea-level history for the Steart Peninsula, examines the relative merits of single- and multi-proxy transfer functions, and places this new sea-level reconstruction in the context of Holocene sea-level and environmental change in the wider and Severn Estuary region.

1.3 Thesis aims and objectives

The aims of this thesis, and the objectives set out in order to address those aims, are as follows:

Aim 1: To develop single- and multi-proxy sea-level transfer functions for the macrotidal Severn Estuary region

(a) To establish the key environmental factors affecting the presence and species abundance of surface-dwelling intertidal diatoms and foraminifera in the contemporary Severn Estuary intertidal zone.

(b) To develop single- and multi-proxy sea-level transfer functions based on the relationships between species and mean tidal level (MTL).

(c) To evaluate the transfer functions in terms of the potential success of their application to fossil sequences from the Steart Peninsula.

Aim 2: To reconstruct Holocene sea-level at the Steart Peninsula, Somerset.

(a) To apply the preferred sea-level transfer function to fossil microfaunal assemblages from a dated sediment sequence from the Steart Peninsula.

(b) To integrate the transfer function-derived sea-level history into the existing understanding of Holocene sea-level and environmental change in Bridgwater Bay and the wider Severn Estuary region.

Aim 3: To provide a critical reflection of the quantitative methodology used and make methodological recommendations for the use of multi-proxy transfer functions in the discipline.

Chapter 2

Sea-Level Variability and Reconstruction

This chapter provides reviews of the literature on Holocene sea-level change and reconstruction, with a particular focus on biological sea-level indicators and quantitative methods, and explores the evolution of methods since the mid-twentieth century.

Following a brief introduction to Quaternary science and sea-level research, some key terms used in sea-level studies are defined, and literature on sea-level indicators, qualitative and quantitative sea-level reconstruction and the particular problems posed by macrotidal estuaries are considered in order to inform the thesis aims and objectives. Literature specific to the geographical region of this study can be found in Chapter 3.

2.1 Quaternary climate and sea-level variability

The total global volume of ocean water (O) is a function of the total water in the Earth system and the various stores of water on-land. Rearranging the equation for the global hydrological balance of Pirazzoli (1996, p. 6) for O gives the following:

$$O = K - A - L - R - M - B - S - U - I \tag{2.1}$$

Where:

- O = oceans and seas

- K= global water (constant)

- A = atmospheric water

- L = lakes and reservoirs

- R = rivers and channels

- M = soil moisture

- B = biological water

- S = swamps

- U = ground water

- I = frozen water

Pirazzoli (1996) estimates that A, R, S, B and M together represent only 24cm of global sea-level, implicating lakes, reservoirs, ground water and land-based ice as the greatest potential contributors to ocean water volume. Indeed, the main factor influencing global sea-level during the Quaternary period has been the climatic forcing that causes contintenal ice sheets to increase and decrease in volume according to changes in insolation (Wilson *et al.*, 2000).

The Quaternary period began approximately 2.6 million years BP and continues today (Mascarelli, 2009). Broadly speaking, the Quaternary climate has oscillated between long glacial (90,000 to 100,000 years) and shorter interglacial (10,000 to 15,000 years) episodes with a c. 100,000 year periodicity controlled by astronomical forcing. The present interglacial, in which the human population has expanded significantly, is the Holocene. A 100,000 year cycle is more prominent in records of the last one million years (Bradley, 1999), perhaps suggesting that variation in the eccentricity of the earth's orbit around the sun is an important climate forcer during this time. However, Milankovitch theory (Hays *et al.*, 1976) indicates a shift away from the prominence of eccentricity at a 100,000 year periodicity in the last one million years, and an increase in variance at lower frequencies (~400,000 years). It is probable that the observed 100,000 year periodicity results from feedbacks within the climate system, amplifying the underlying orbital pacemaker of eccentricity (Bradley, 1999).

When ice sheets expand during glacials ocean water is enriched in the heavier stable oxygen isotope ^{18}O. This enrichment is recorded in the preserved calcium carbonate ($CaCO_3$) tests of benthic marine microorganisms such as foraminifera. The glacial and interglacial periods in the Earth's climatic history are thus referred to as marine isotope stages (MIS), based on the stable oxygen isotope record (δ^{18}O) obtained from deep sea cores (Emiliani, 1955). The Holocene is MIS 1 and the last glacial is MIS 2. The preceding Quaternary glacial cycles are numbered chronologically in this way, with odd numbers denoting interglacials and even numbers representing glacials (see Figure 2.1).
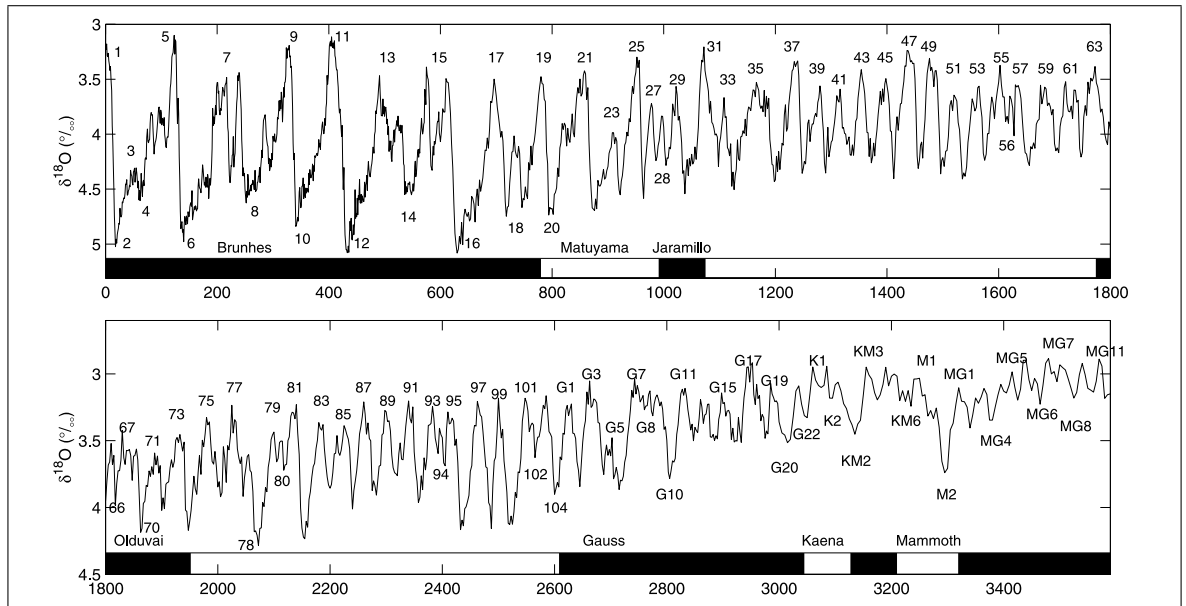
Figure 2.1: Stacked Quaternary δ^{18}O record for the last 3.6 million years constructed by the graphic correlation of 57 globally distributed, individual benthic δ^{18}O records. The horizontal axis is time in thousands of years. Note that the scale of the vertical axis changes across the panels. Adapted from Lisiecki and Raymo (2005) with permission from John Wiley and Sons.

Since the δ^{18}O record relates closely to the volume of water that is locked up in continental ice, it follows that that same record should have a relationship with global sea-level. However, Chappell and Shackleton (1986) and Shackleton (1987) have shown that the relationship between δ^{18}O record and sea-level is complex and may not have been constant over time. The δ^{18}O of benthic foraminifera may not only have been influenced by oceanic δ^{18}O over the Quaternary, but also by deep ocean temperature and salinity (Wilson *et al.*, 2000). If either one of these has varied during the Quaternary the ability of the δ^{18}O record to produce a reliable global sea-level record is compromised. However, a comparison of the δ^{18}O record with a eustatic sea-level curve derived from a series of raised coral terraces on the Huon Peninsula, New Guinea (see Figure 2.2) indicates that δ^{18}O is still a good general proxy-indicator of Quaternary sea-level (Masselink and Hughes, 2003).

The coral terrace-derived sea-level curve from the Huon Peninsula (Figure 2.2) demonstrates the magnitude of the vertical change in sea-level that occurs from interglacial to glacial periods. For example, the LGM was accompanied by a sea-level lowstand of ~140m below present mean sea-level (MSL) (Chappell and Shackleton, 1986), providing the base level dictating the lower limit of the occurrence of subaerial erosion processes such as fluvial erosion. The rivers of the Severn Estuary region cut deep valleys into the land surface when Pleistocene sea-level was low, and these valleys were later infilled with Holocene sediments under an interglacial transgressive regime (Case, 2013). The landscape and Holocene environmental
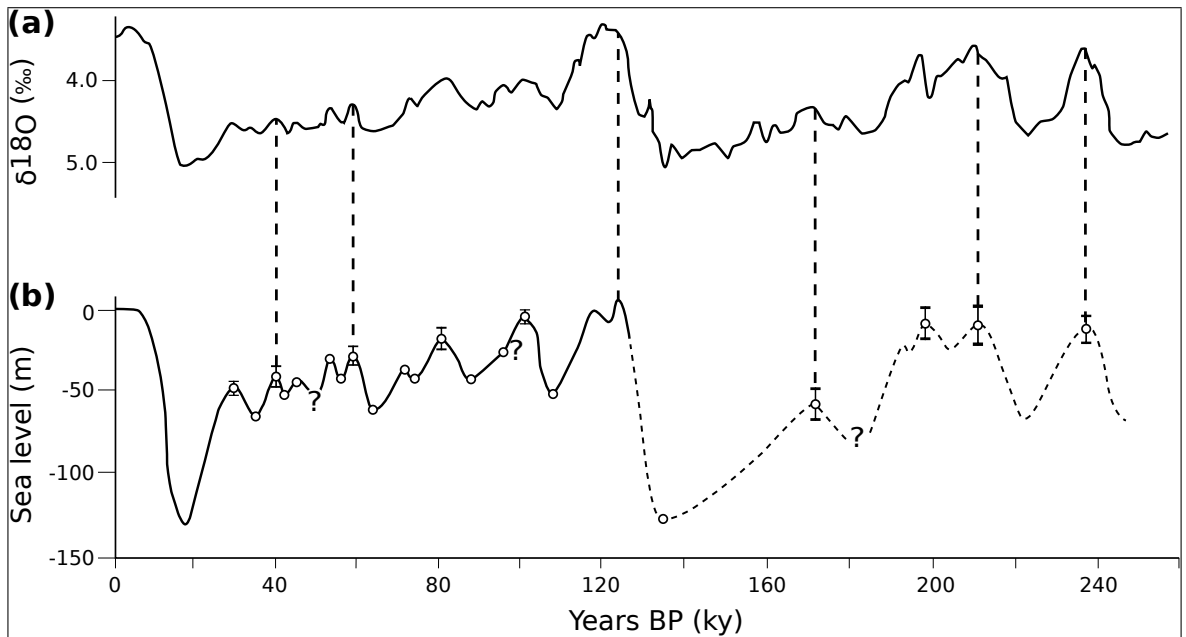
Figure 2.2: Correspondence between (a) $\delta^{18}O$ record from east equatorial core V19-30, from measurements of benthic *Uvigerina senticosa* and (b) eustatic sea-level curve for the Huon Peninsula, New Guinea, over the last 250,000 years. Adapted from Chappell and Shackleton (1986) by Masselink and Hughes (2003). Reproduced with permission from Taylor & Francis.

history of the Severn Estuary region is discussed further in Chapter 3.

2.2 Holocene climate and sea-level variability

The Holocene epoch denotes the Earth's current interglacial climate. The LGM of the British and Irish Ice Sheet (BIIS) occurred about 22,000 years BP, based on recent evidence from ^{36}Cl surface-exposure dating, amino acid geochronology of marine shells in glacial deposits and AMS radiocarbon dating (Bowen *et al.*, 2002). The termination of the most recent glacial (MIS2), in which glacial conditions gave way to Holocene climate, began around 14,500 years BP (Walker *et al.*, 2009).

The transition of the Earth's climatic mode from the LGM to the start of the Holocene is well-studied. This LGM-Holocene period is relatively recent, with respect to the wider Quaternary period and the rest of the Earth's history, and much evidence for environmental change is readily available in sedimentary, archaeological, marine and other records. This period represents a 'case-study' of large, centennial-scale changes in global climate, and more specifically of the rising global mean surface temperature (GMST) (Oldfield, 2005; PALSEA, 2009). Sea-level researchers are interested in this post-LGM period of warming, because improving our understanding of the responses of ice sheets, glaciers and thermal expansion of the oceans to warming during this time will help to constrain the likely contribution of these sources to sea-level rise in the twenty-first century (Siddall *et al.*, 2009).

The most recent proposal for the official date of the onset of the Holocene comes from the NGRIP and is defined in the ice core record as the horizon which shows the clearest signal of climatic warming, marked by a step change in deuterium values (Walker *et al.*, 2009). Walker *et al.* (2009) proposed 11,700 years BP as the new Global Stratotype Section and Point (GSSP) for the Pleistocene-Holocene boundary. The transition from glacial to interglacial climate in the Northern Hemisphere was not continuous or uni-directional and was interrupted initially between 12,900 and 11,500 years BP by a short-lived cold event known as the Younger Dryas or Greenland Stadial 1.

There is evidence for a further oscillation in climatic warming in the North Atlantic at around 8,200 years BP that lasted about 160 years (Schmidt and Jansen, 2006). This sudden cold event is known as the '8.2kyr event' and has been identified in the δ^{18}O record from the Greenland Ice Sheet Project 2 (GISP2), the Greenland Ice Core Project (GRIP) and NGRIP ice cores (Rohling and Palike, 2005), and in other proxy records (Nesje and Dahl, 2001). The cooling event is attributed to a slowdown in the North Atlantic Deep Water formation following an outflow of meltwater into the North Atlantic from the Lakes Agassiz and Ojibway (Kendall *et al.*, 2008). This rapid meltwater pulse raised global sea-level abruptly and recent research in the Netherlands supports a possible multi-staged lake drainage and, given the distance of the study site from the Laurentide proglacial lakes, a global sea-level event of greater magnitude than previous estimates (3.0 ± 1.2m versus 0.4-1.4m) (Hijma and Cohen, 2010)

The post-glacial contraction of continental ice sheet coverage caused rapid global sea-level rise of about 130m between the LGM and ~6,000 years BP. Since then, about 10m of global sea-level rise has occurred, representing relative stability in global sea-level since the mid-Holocene (Haslett, 2000).

The term 'eustatic' is often used to refer to absolute sea-level change, or global change, such as an increase or decrease in ocean water volume, that is independent of regional variation. In the 1960s researchers attempted to compile a global Holocene eustatic sea-level curve based on work by Godwin *et al.* (1958) on low-lying parts of the British Isles and work by Fairbridge (1961) in other parts of the world. It was at this point, when the 'eustatic' sea-level curve appeared to contain many sequences of oscillations, that it became apparent to the sea-level community that the pattern and timing of Holocene sea-level change was not uniform across the planet. There is little controversy around the broad shape of postglacial sea-level rise, with most of the sea-level community agreeing on something like the curve published by Fairbanks (1989) (Figure 2.3). However, the detail is still far from well established

(Masselink and Hughes, 2003). The term 'ice-equivalent' is now more often used in place of 'eustastic', which is itself now more a concept than an observable entity (Gehrels, 2010).

Gehrels (2010) outlines a debate over the timing of the final contribution of ice melt to the oceans in the mid- to late-Holocene, with estimates ranging from 6,000 years BP (Bassett *et al.*, 2005; Morhange and Pirazzoli, 2005) to 5,000 years BP (Milne *et al.*, 2005), 4,000 years BP (Peltier, 1998, 2002; Peltier *et al.*, 2002) and as recent as 1,000 years BP (Fleming *et al.*, 1998). The IPCC's Fifth Assessment Report concludes that it is likely that the global ocean water volume increased by 2 to 3m between 7,000 and 3,000 yearsBP (Masson-Delmotte *et al.*, 2013) and that in the last 2,000 years global MSL has not fluctuated by more than ±0.25m over timescales of several hundreds of years (Church *et al.*, 2013). The exact timing of the end of ice-melt contribution to the global oceans has still not been resolved, but significant progress has been made since the IPCC's fourth assessment report (Church *et al.*, 2013).
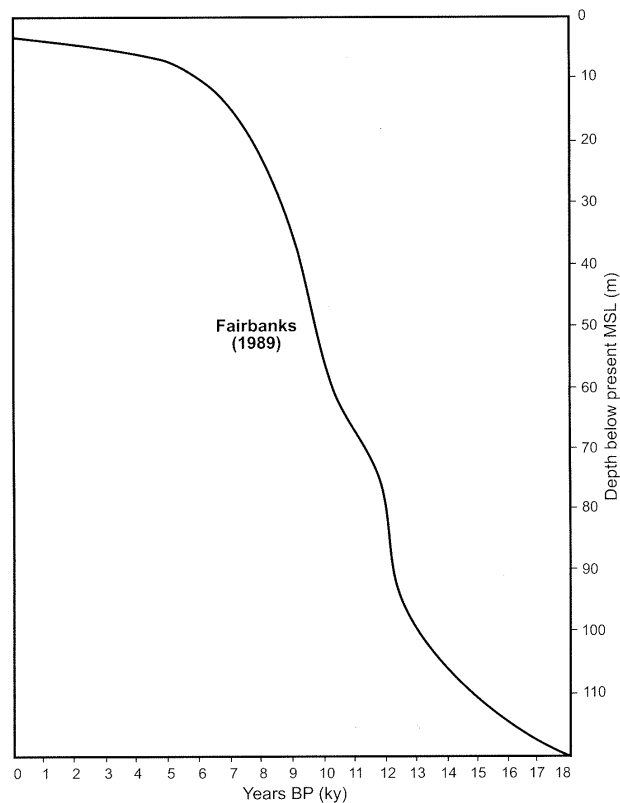
Figure 2.3: Eustatic sea-level curve for the Holocene, adapted from Fairbanks (1989) by Masselink and Hughes (2003) and reproduced with permission from Taylor & Francis.

Relative sea-level refers to the level of the sea relative to the land on a regional scale, and change can be due to a combination of ocean water volume variation and vertical land movement (Masselink and Hughes, 2003). Glacio-isostatic adjustment in and close to deglacial regions has played a prominent part in Holocene evolution of European coastlines (Roberts,

1998). In the British Isles, while eustatic change over the Holocene has been one of sea-level rise, the isostatic effects following the termination of the last glacial mean that the Northern part of the British Isles is experiencing slight relative sea-level fall where rebound occurs from the former loading of the BIIS, while relative sea-level is rising in the South as the glacial forebulge collapses (Peltier, 1998; Shennan and Horton, 2002).

Pethick (1984) argues that we should be most concerned with relative sea-level change, since that is what ultimately affects coastal areas, ecological habitats and human populations, and because the effect in terms of coastal morphology is similar whether a sea-level rise is the result of an isostatic fall in the level of the land or an eustatic rise in sea-level. However the Woodroffe and Murray-Wallace (2012) highlight the importance of the detection of a global, eustatic element to sea-level change, in order to quantify that which is attributable to thermal expansion and additional meltwater to the oceans, resulting from the greenhouse effec. The IPCC's Fifth Assessment report emphasises progress in monitoring *global* MSL rise in the 21st century as well as developments in observing regional sea-level changes (Church *et al.*, 2013) and in the use of palaeoclimatic archives in modelling climatic warming and establishing a Holocene baseline for the discussion of anthropogenic contributions to climatic and sea-level change (Masson-Delmotte *et al.*, 2013).

2.3   Sea-level indicators

Many sedimentary and geological records contain evidence of former sea-levels, some of which can be dated, providing the information with which to construct regional sea-level histories. The modern coastal environment and the behaviours of the waves, tides and coastal sediments and biota that we can study today provide a wealth of information that can be used to infer meaning from fossil sedimentary deposits, archaeological remains and erosional features (Pirazzoli, 1996). Kemp *et al.* (2012, p. 26) define a sea-level indicator as "...a physical, biological or chemical feature possessing a systematic and quantifiable relationship to elevation in the tidal frame". This section discusses some of the methods used to infer meaning from sea-level indicators in the following three categories: geomorphological, archaeological and biological. Sea-level indicators in these categories are often used in combination with one another in studies of former sea-level change (Faivre *et al.*, 2013).

2.3.1   Geomorphological sea-level indicators

Geomorphological indicators of sea-level can be erosional or depositional features (Haslett, 2000). Examples of the former might include exposed notches, arches or platforms preserved

in hard rock (Pirazzoli, 1996), while depositional indicators include features such as fossil beaches, saltmarshes and tidal flats (Lambeck *et al.*, 2010). A good understanding of the processes by which morphological features have been formed is a key factor in using them as sea-level indicators (Pirazzoli, 1996).

An important example of a depositional geomorphological sea-level indicator in the Severn Estuary region is the Burtle Formation, which includes shelly marine sands and gravels of the Kenn Church Member (formerly the Burtle Beds of Bulleid and Jackson (1937)) (Campbell *et al.*, 1999). These mostly marine shelly sands are raised in the order of tens of metres above the alluvial deposits of the Somerset Levels and are thought to relate to at least two interglacials, MIS 5e and MIS 7 (Campbell *et al.*, 1999). The Burtle Beds provide an example of a landform that is composed of more than one type of sea-level indicator. While the raised beds themselves would be classed as depositional indicators, the bivalve shells and foraminifera and ostracod tests found within them provide biological evidence for the former sea-levels (Hunt, 2006).

Depositional features indicating lower former sea-levels include fossil saltmarsh peats, buried by marine or estuarine silts and clays under a transgressive sea-level regime (Masselink and Hughes, 2003). Peats are organic and can be dated using radiometric dating techniques such as ^{14}C for sediments up to ~60,000 years old and ^{210}Pb for peats deposited in the last ~100 years (Gehrels, 2000; Leorri *et al.*, 2006). Kidson and Heyworth (1976) used buried peats as sea-level indicators to produce their Holocene sea-level curve for Bridgwater Bay. Today it is standard practice to combine stratigraphic work such as this with the study of the biological indicators (for example pollen, diatoms and foraminifera) preserved within the peats. This approach is discussed in more detail below, following a brief discussion of archaeological sea-level indicators.

2.3.2 Archaeological sea-level indicators

Effective examples of archaeological evidence for sea-level change can be found in various locations around the world, but most commonly in the Mediterranean, where human activity is recorded as far back as the LGM (Lambeck *et al.*, 2010). Archaeological evidence of to sea-level changes will generally be one of two types; structures with no specific former relationship with sea-level, such as dwellings built on the land and since flooded by the sea, and those such as slipways, fish tanks and harbours that were constructed in the past specifically in order to exploit a particular relationship with tidal-level and might no longer function today due to a sea-level change (Haslett, 2000). For example, Anzidei *et al.* (2013) combined archaeological

evidence in the form of fish tanks with modern data on tidal levels to estimate changes in sea-level at the Tyrrhenian coast of Calabria in Italy from 1,806 years BP onwards.

The one clear limitation of archaeological evidence is its location-specific nature. A piece of archaeological evidence found and studied in isolation can only offer insight into a change in sea-level in a strictly local context. Other limitations include the exclusion of structures built on unstable land surfaces, the uncertain use of some ancient structures, and the uncertain relationship that many structures have with sea-level (Lambeck *et al.*, 2010). The submerged remains of a dwelling clearly indicate a marine incursion but do not necessarily indicate the magnitude of sea-level rise. Archaeological evidence can therefore lack accuracy and precision (Pirazzoli, 2005). However, archaeological evidence may be used in conjunction with other categories of sea-level indicator. For example, there may be biological organisms preserved upon the surface of an ancient structure that can be cross-referenced with modern equivalents with reference to elevation relative to mean sea-level (Morhange *et al.*, 2001). Investigating two lines of enquiry can often increase the reliability of a reconstruction. Archaeological indicators may also be used in combination with historical data. Although historical accounts of past events or environments will not meet the rigorous modern criteria of scientific measurement, qualitative information can certainly contribute to the reconstruction of regional sea-level change over previous decades and centuries (Pirazzoli, 1996). For example, ancient writers such as Columella explained how marine fishtanks were constructed in the Mediterranean in the first century AD, and what their relationships with tidal levels were (Pirazzoli, 1988).

Researchers have been conducting an extensive programme of archaeolgical investigation of the Severn Estuary Levels since the 1980s (Bell, 1993, 1994; Bell and Neumann, 1997; Bell *et al.*, 2003; Walker *et al.*, 1998). Finds have included human and animal footprints, human skulls, remains of buildings, wooden trackways, pottery and wooden posts, dating from the Mesolithic to post-Medieval times. Of particular relevance to sea-level research are the Somerset Levels trackways, likely to have been constructed to sustain contact across communities in wet areas (Bell and Neumann, 1997), a line of stakes thought to be fish traps at Gore Sand (Nayling, 2002), and fossilised drainage channels along with mid-3rd century pottery that suggests that extensive drainage took place at an eroded Roman settlement on the Wentlooge Levels in South Wales (Allen and Fulford, 1986; Fulford *et al.*, 1994). Discussion of the wooden trackways and of the debates around the possibility of a marine transgression in the Roman Era can be found later in Section 3.5 of Chapter 3.

Robust interpretation of sea-level indicators relies on detailed understanding of their mod-

ern characteristics, but this is not always possible with archaeological indicators. Furthermore, while it might be possible to date an artefact and infer something about its use, its relationship with sea-level might not be clear, and nor may it be possible to know whether an item was buried, and if so, how deep, or if it was transported post-deposition (Nayling, 2002). Nevertheless, archaeological indicators contribute important information to studies of Quaternary sea-level and one of the aims of IGCP588 (Preparing for Coastal Change) is to embrace interdisciplinary research so that archaeology in coastal areas might contribute more to sea-level research as well as to our understanding of the social and cultural aspects of past societies (Switzer *et al.*, 2012).

2.3.3 Biological sea-level indicators

Living organisms that exist at known tidal ranges, and that can become stranded or buried by changes in sea-level, often occupy narrow vertical ranges (Lambeck *et al.*, 2010) and can be used to document these changes. Biological sea-level indicators are some of the most accurate, and organisms can include those, like barnacles and mussels, that adhere to hard surfaces such as rocky cliffs and sea walls, and those that inhabit intertidal sediments (Masselink and Hughes, 2003). The latter tends to consist of microscopic organisms that are often fossilised in coastal sediments, as well as fossil pollen and plant macrofossils produced by coastal vegetation, that can indicate former changes in salinity and thus the position of the local water level (Pirazzoli, 1996).

In tropical waters the rates of growth in coral reefs are known to be governed mainly by water temperature and water depth, the latter often being directly related to MSL, and some species produce annual or seasonal bands that have allowed, in some cases, for detailed sea-level histories and marine conditions to be documented (Lowe and Walker, 1997).

The geographical research focus is dominated by a large estuary whose waters have deposited an archive of Holocene sediments upon the land over the past ~12,000 years (Allen and Rae, 1987). The tidally-dominated estuary is characterised by the prevalence of salt-marshes and tidal flats whose sediments are inhabited by tide-dependent microorganisms (see Chapter 3). For this reason, the focus of the remainder of this section is on the biological indicators that inhabit contemporary intertidal sediments and are preserved in the region's Holocene sedimentary sequences.

i Foraminifera as sea-level indicators

Forming the order Foraminiferida in the phylum Protista, a foraminifer is described by Loeblich and Tappan (1987, p. 7) as "...a cytoplasmic body enclosed in a test or shell of one or

more interconnected chambers." Foraminifera are single-celled organisms, and each of the c. 10,000 modern species can be classified by its form and test composition. Benthic forms live on the sea floor (Murray, 1991a) while planktonic species live within the water column (Murray, 1991b). Tests may be agglutinated (made of detrital sediment particles held together with cement), porcellaneous (calcareous with translucent walls) or hyaline (calcareous with glassy, transparent shells) (Murray, 2002).

All intertidal foraminifera that are used as sea-level indicators are benthic, living in or just below the sediment surface (Gehrels, 2002). Saltmarsh foraminifera are mainly agglutinated and are able to withstand the relatively acidic saltmarsh conditions, while tidal flat and tidal creek taxa are mainly those with calcareous tests (Gehrels, 2002).

Foraminifera are effective tidal indicators for a number of reasons. They exhibit strong correlation with elevation above mean sea-level (Scott and Medioli, 1978), are well preserved and straightforward to detect in accumulated saltmarsh sediments and often occur in large quantities (Horton and Edwards, 2006).

Pioneering work by Scott (1976) and Scott and Medioli (1978, 1980, 1986) changed the way that sea-level reconstruction has been attempted in recent decades. Scott (1976) and Scott and Medioli (1978) showed that foraminifera are organised into well defined zones in the modern intertidal sediments in Southern California, USA and Chezzetcook Inlet in Nova Scotia, Canada, meaning that rather than continuing to arbitrarily equate fossil saltmarsh sediments to a fixed altitude, it became common practice to subdivide fossil deposits into these zones, thereby increasing the potential vertical resolution of sea-level reconstructions. The authors found that the east and west coasts of the North American continent showed similar foraminifera zonation, with the high saltmarsh above higher high water (HHW) containing no or very few foraminifera, and with two distinct faunal zones sitting between HHW and MSL. However, the species composition of those two zones differed markedly between the two sites, and the zonation at Chezzetcook could be subdivided further than at the Southern Californian site (see Figure 2.4). Based on such differences, Scott and Medioli (1986) recommend that if a survey of the modern species has not previously been carried out at a site where foraminifera are to be used as sea-level indicators, this ought to be done.

Scott and Medioli (1980) carried out a more detailed study of the saltmarshes of Nova Scotia, taking in five distinct sites with varying tidal ranges. They found the distribution of the dominant species of foraminifera to be similar across the five sites, with low and high marsh zones emerging, and sometimes sub-zones within them also present, as observed at the initial Chezzetcook site. Scott and Medioli (1980) recognised that narrower foraminifera

zones could result in higher accuracy in Holocene sea-level reconstruction than those that are wider; the lowest zone in particular was indistinguishable from a typical tidal flat assemblage. Conversely, at the upper end of the zonation Scott and Medioli (1980) found that a marked decline in the number of tests present above HHW occurred at all five sites, and surmised that this feature would be advantageous in subsequent work using the modern foraminiera zonation to assist in Holocene sea-level reconstruction, serving as a distinctive and reliable datum.
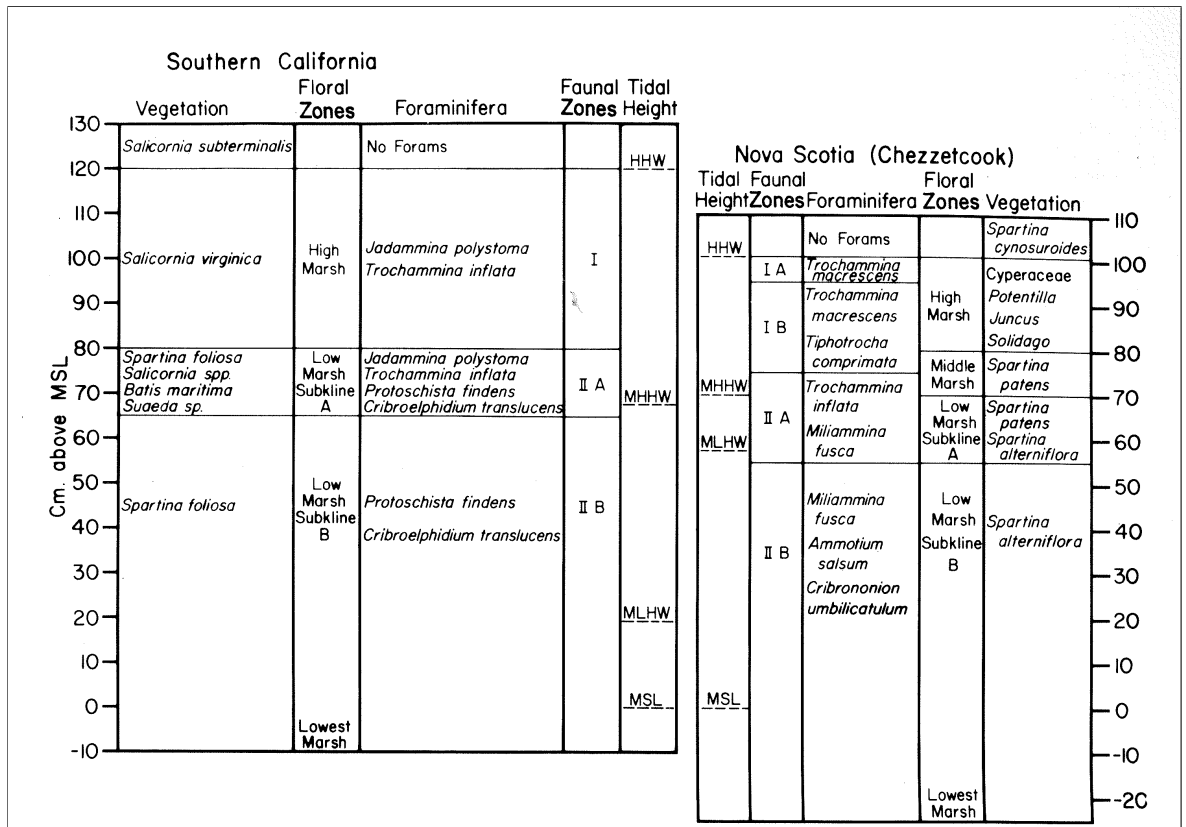
Figure 2.4: Floral and microfaunal zones of sites in Southern California and Chezzetcook Inlet, Nova Scotia, shown against tidal levels HHW, MHHW, MLHW and MSL. Reproduced from Scott and Medioli (1978) with permission from Nature Publishing Group.

ii Diatoms as sea-level indicators

Diatoms are unicellular, microscopic algae (Kennington, 2002) that inhabit various aquatic environments, such as rivers and lakes, wetted surfaces and soils, as well as the marine and coastal habitats that foraminifera are restricted to. Frustules can be planktonic (floating within the water column), epiphytic (attached to aquatic plants), epibiontic (attached to other organisms), epipsammic (attached to sediment particles), epipelic (attached to, or living in sediment) or epilithic (attached to rock surfaces; Kennington (2002)). Diatom taxa can also be categorised by their tolerances to salinity (Patrick and Reimer, 1975), as follows:

- *Polyhalobian:* marine; greater than 30 parts per thousand (PPT) salinity.

- *Mesohalobian:* brackish; 2-30 PPT salinity.

- *Oligohalobian:* fresh water; less than 2 PPT salinity.

- *Halophobes:* true fresh water forms intolerant of any salt.

Palmer and Abbott (1986) note that diatoms have been used in sea-level studies since the 1940s, citing diatomists such as Cleve-Euler (1944) and Florin (1944). Palmer and Abbott (1986) divide the coastal sedimentary environment into three main zones where different diatom groups may be found: the subtidal zone from lower low tide (LLT) downwards, the intertidal zone where the most highly varied diatom communities can be found, and the supratidal zone above higher high tide (HHT) where euryhaline taxa (those that can adapt to a range of salinities) can be found. In the 1990s research by Nelson and Kashima (1993), Hemphill-Haley (1996), Shennan *et al.* (1995, 1996) and Zong (1997) further investigated intertidal diatom variation in the UK and North America, finding a strong zonation of taxa with respect to tidal submergence.

Using fossil diatom assemblages found in sediment cores Palmer and Abbott (1986) suggest grouping taxa by their halobian categories (salinity tolerances) and visually presenting frequency versus depth for each of these categories. Figure 2.5 shows this approach in some early work by Kjemperud (1981) for a site in Norway. The graph signifies a marine regression, as the top of the core is dominated by oligohalobous forms, giving way to mesohalobous and polyhalobous taxa further down, indicating that the water level dropped over time, so the coring site that was once marine later became a more brackish environment.

iii   Testate amoebae as sea-level indicators

Testate amoebae, also referred to as thecamoebians (Charman *et al.*, 2010) are test forming, unicellular protists occurring in various moist to aquatic environments, ranging from estuaries, lakes and rivers to soils and mosses (Mitchell *et al.*, 2008). Test construction falls into two basic groups; autogenous (formed by the secretion of pre-formed siliceous plates), and xenogenous (agglutinated test constructed from the surrounding substrate) (Charman *et al.*, 2000).

Testate amoebae are strong palaeoenvironmental indicators, resonding quickly to environmental changes. Charman (2001) described the use of testate amoebae in sea-level studies to be very much in its infancy, with testate amoebae traditionally employed in the study of palaeohydrology (Warner and Charman, 1994; Woodland *et al.*, 1998) and palaeolimnology
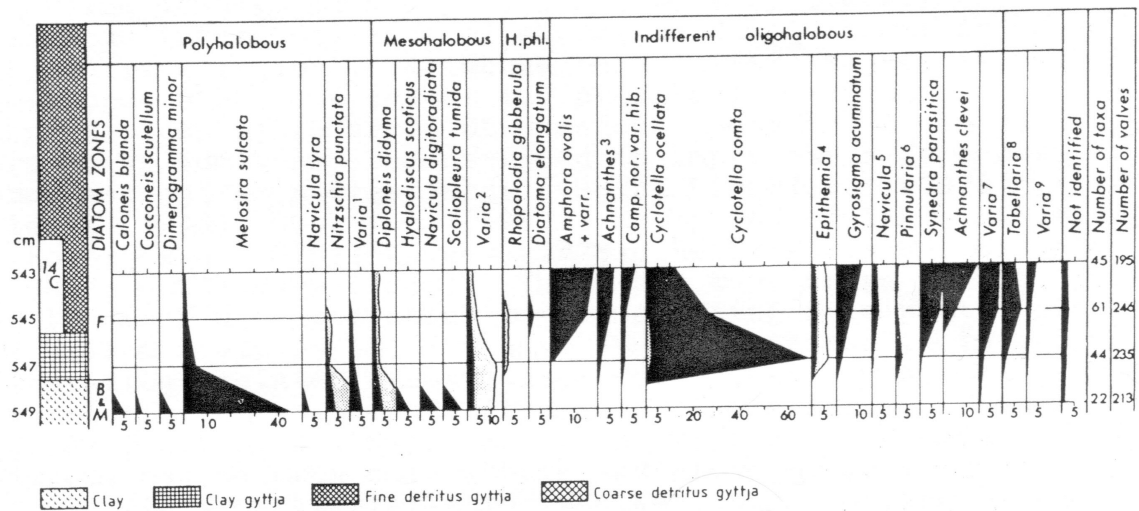
Figure 2.5: Fossil diatom zonation based on salinity preferences from Frosta, Nord-Trøndelag, Norway. A freshwater zone (F) overlies a brackish-marine zone (B&M). Adapted from Kjemperud (1981) by Palmer and Abbott (1986) and reproduced here with kind permission from Springer Science+Business Media and John Wiley and Sons.

(Medioli and Scott, 1988; Reinhardt *et al.*, 1998). This is in part because testate amoebae are principally restricted to freshwater settings and only relatively recently have they been found to display a very strong and distinctive zonation in the upper saltmarsh and supra-tidal coastal environments. In a study from the Taf Estuary in south Wales, Charman *et al.* (1998) also found that while saltmarsh testate amoebae had previously been analysed along with foraminifera in the 63–500μm fraction of intertidal sediment samples, a greater abundance and diversity of tests can be identified in the <63μm size fraction, thus increasing the potential of testate amoebae as successful tidal indicators. However, using this smaller size fraction did pose problems with detritus on the microscope slides, making it very time consuming to reach the total of 150 individuals normally counted per sample in freshwater peatland studies (Charman *et al.*, 1998).

Charman (2001) confirms that testate amoebae have been found in fossil form in various types of coastal sediments, but that the method of applying testate amoebae-based transfer functions to fossil data is still very much in its early stages, with further work needed on techniques to concentrate together fossil tests in order to yield high enough numbers for significant results. Additionally, factors affecting the differential preservation of species are not yet fully understood; a potential source of error in the application of testate amoebae in sea-level studies (Charman, 2001). However, they do offer the opportunity to extend the range of sea-level indicates in the high supra-tidal freshwater marsh environment Charman *et al.* (1998).

2.4 Sea-level reconstruction

The sea-level history for low energy sedimentary environments such as estuaries can be established by creating a sea-level curve composed of several data points known as SLIPs. A SLIP is a dated sample of sediment with a known contemporary altitude in relation to OD that contains within it preserved sea-level indicators such as pollen or diatoms (Shennan and Horton, 2002). For a dated horizon the former sea-level may be estimated by subtracting the reference water level (RWL), inferred from knowledge of the preferred habitat of the preserved indicators, from the present day altitude of the sampling point (Engelhart and Horton, 2012). The RWL is a numerical representation of the indicative meaning at the particular site in question, *i.e.* mean high water spring tide (MHWST) in the Severn Estuary will not be the same altitude above OD as MHWST at a site on the south coast of England, due to differences in tidal ranges, so MHWST at these two sites will have differing RWLs. The indicative meaning is a qualitative desciption of a tidal level within the intertidal zone (*e.g.* MHWST), whereas a RWL is a numerical representation of that indicative meaning at a particular site (*e.g.* 1.2m above MSL).

A hypothetical worked example takes a peat-silt stratigraphic boundary estimated by radiocarbon dating to have been deposited 3,000 years BP, at former MHWST, inferred from diatom analysis. The sample is currently situated at 2m OD and the current level of MHWST is 5m OD. Subtracting the RWL of the SLIP (5m OD) from its present day altitude (2m OD) puts the RSL at that site at -3m OD 3,000 years BP.

There are a number of attributes that must be established for each data point in order for it to qualify as a SLIP (Shennan *et al.*, 1994):

- *Age:* ascertained by a dating technique such as radiocarbon dating

- *Altitude:* levelled to a local benchmark

- *Indicative meaning:* referring to the position that the SLIP occupied in the tidal frame when the sediment was deposited or formed, such as HAT

- *Indicative range:* referring to any uncertainty either side of the assigned indicative meaning

- *Sea-level tendency:* referring to the direction of sea-level change

Early research into sea-level change produced sea-level curves constructed from SLIPs for which only age and altitude was referred to (Hawkins, 1971a,b; Heyworth and Kidson, 1982),

resulting in very general sea-level trends with unknown vertical errors associated with the data points.

Later work (Shennan, 1982, 1986a,b) incorporated indicative meaning and range and sea-level tendency into SLIPs, achieved by using the biological indicators that are restricted to particular tidal levels, as referred to previously in Section 2.3. Sea-level tendency can be established by examining the sediment just beneath the SLIP. If biological remains indicate an increase in marine influence then a positive tendency is assigned; a negative tendency if a decrease in marine influence is indicated (Shennan *et al.*, 1983). Analysis of fossil foraminifera, diatoms, testate amoebae, pollen or other indicators preserved in Holocene coastal sediments, with some knowledge of the modern tolerances of the taxa found, can resolve the indicative meaning of the SLIP (Haslett *et al.*, 1997, 1998). SLIPs are then presented with respect to present-day MSL, and RSL curves produced. A greater degree of accuracy is implied in comparison with earlier studies.

In a study of Holocene sea-level change in west Cornwall Healy (1995) acknowledges that previous research, such as that of Heyworth and Kidson (1982), arguably places too much emphasis on radiocarbon dated points that have an unknown and possibly rather tenuous relationship with sea-level. In the study at Marazion Marsh, Healy (1995) presents a series of radiocarbon dates plotted against altitude, as well as pollen and diatom analyses. Changes in the salinity classes of the diatom taxa are examined in conjunction with the pollen data and a transition from freshwater to brackish water conditions is inferred from the sequences, signifying a marine transgression at around 4,500 years BP. Healy (1995) concludes that some of the organic deposits formed in isolation from direct marine influence.

Selby and Smith (2007) present the results of a study of sea-level at three sites on the Isle of Skye. Sixteen samples from cores taken at the three sites were radiocarbon dated and pollen and diatom analyses were carried out throughout the cores. From this data eight dated SLIPs were assigned indicative meanings and ranges and sea-level tendencies, based on the diatom assemblages identified. Selby and Smith (2007) were then able to infer a sequence of sea-level changes from the end of the Devensian to ~3,200 years BP in which sea-level, from its lowest point around 12,400 years BP in the Younger Dryas, rose markedly up to 8,800 years BP, fell from then until 7,500 years BP, before rising one final time to 4,300 years BP, and staying relatively stable until 3,200 years BP when a fall towards the present-day level began.

Similarly, Roberts *et al.* (2011) conducted a study of sea-level change in North Wales and with 33 dated SLIPs, each with sea-level tendency, indicative meaning and indicative range

inferred from fossil foraminifera, incorporated their own results into existing data to present a relative sea-level curve for North Wales (see Figure 2.6). Roberts *et al.* (2011) were careful to distinguish between 'true' SLIPs and those termed 'limiting points' due to their absence of foraminifera as indicators.

Index Point	Calib. 14C age (a BP, ± 2σ range)	IP inferred altitude of MSL or LP original altitude (m) OD
IP 1	11230-10790	-24.19
IP 2	10670-10270	-24.03
IP 3	10670-10270	-20.34
IP 4	10670-10287	-20.26
IP 5	9680-9490	-16.47
IP 6	9890-9550	-16.37
IP 7	9400-9030	-10.19
IP 8	8580-8390	-10.07
IP 9	9250-8780	-8.98
IP 10	9260-9010	-8.93
LP 1	11900-11220	-23.37
LP 2	11630-11200	-23.08
LP 3	11550-10890	-23.37
LP 4	11550-11120	-23.08
LP 5	15700-14340	-28.21
LP 6	13820-13160	-28.14
LP 7	12950-12360	-25.83
LP 8	12350-11660	-15.86
LP 9	12110-11260	-15.72
LP 10	8540-8340	-4.68
IP 11	5590-5310	-1.22
IP 12	9400-9000	-12.65
IP 13	9690-9330	-12.77
IP 14	5440-4520	-1.78
IP 15	5730-4870	-1.95
IP 16	7240-6320	-2.38
IP 17	8180-7620	-6.13
IP 18	4830-4250	-1.1
IP 19	8350-7790	-6.21
IP 20	7470-6910	-3.37
IP 21	8600-7840	-6.06
IP 22	7250-5490	-4.58

Figure 2.6: Relative mean sea-level curve for North Wales, incorporating data from Heyworth and Kidson (1982), Prince (1988), Bedlington (1994) and Roberts *et al.* (2011). IP = Index Point. LP = Limiting Point. Reproduced from Roberts *et al.* (2011) with permission from John Wiley and Sons.

Other examples include Gehrels *et al.* (2006c) who expanded on the information gained from 23 radiocarbon dated index points from cores at Ho Bugt in Denmark by analysing the foraminifera and diatoms preserved in the sediments and assigning each index point with an indicative meaning. The indicative meanings were based on surveys of modern intertidal floral zones and the foraminifera and diatoms identified in these zones. For example, the freshwater assemblage was found 2.30±0.40m above Danish National Datum (DNN) and the saltmarsh to freshwater marsh transition was found 1.90±0.20m DNN. Gehrels *et al.* (2006c) differentiated between basal and non-basal SLIPs, highlighting a source of complexity and error in Holocene sea-level studies. In the context of Holocene sea-level, a basal SLIP is one that is from the base of a Holocene sedimentary sequence, lying directly on a hard substrate (Gehrels *et al.*, 2011).

2.5 Quantitative environmental reconstruction

The next development in terms of the progression of sea-level research was the quantification of relationships between sea-level indicators in the modern environment, so that predictive hindcasts of past sea-level change could have some statistical rigour. Researchers began to take this step in the late 1990s (Zong and Horton, 1999; Gehrels, 1999, 2000), borrowing techniques from other areas of ecology and palaeoecology, and continuing to develop numerical techniques of reconstructing sea-level change today. By statistically modelling the relationship between many species of sea-level indicators and tidal levels, researchers can now make more accurate and precise predictions of past sea-levels than those discussed above that were based on the vertical position of three or four broad assemblage or salinity zones. This section outlines the development of quantitative palaeocological techniques and their use in sea-level studies.

Birks *et al.* (2010) describe an increasing demand for quantification in palaeoecology, and give several reasons for this, including the need for data to validate hindcasts produced by Earth system models, to give insights into the rates of past changes in variables such as temperature and precipitation, and to integrate past climatic reconstructions with past societal changes such as migration and population growth.

There are three basic approaches commonly used by palaeoecologists to reconstruct past environmental change; the indicator species approach, the assemblage/analogue approach and the multivariate calibration-function (hereafter referred to as the 'transfer function') approach.

2.5.1 The indicator species approach

The indicator species approach is the simplest of the three approaches listed above. Almost exclusively applied to temperature indicators, the technique is based upon preserved occurrences of a species with quantified environmental tolerances which enable a reconstruction of the past environment or a past environmental variable (Birks, 1981). For example, Zagwijn (1994) used the first occurrences in the Holocene of *Hedera* (ivy), *Ilex* (holly) and *Viscum* (mistletoe) as temperature indicators, to compare Holocene and Eemian interglacial temperatures in the Netherlands.

The main weaknesses of this approach are that abundance data, even where available, are not often used, and that the assumption that a taxon has an equal probability of occurring anywhere within its climatic tolerance range is unlikely to be valid (Horne and Mezquita, 2008). This approach has been more-or-less superseded by more sophisticated techniques that

rely on abundance data rather than the mere presence or absence of a taxon, but remains useful in studies that use organisms whose past abundance is not likely to be reflected in the fossil assemblage, such as plant macrofossils (Birks *et al.*, 2010).

Following an extensive literature search, the author is not aware of any studies that use the indicator species approach to reconstruct former sea-levels.

2.5.2 The assemblage approach

The assemblage approach considers the fossil assemblage as a whole, and therefore the relative abundance of all fossil taxa (Birks and Birks, 1980). Traditionally, data tended to be interpreted intuitively, rather than numerically, as in some earlier sea-level studies where species assemblages of sea-level indicators were arbitrarily ascribed to tidal levels (Healy, 1995; Zong, 1998). However, more recently the assemblage approach has been used in a quantitative manner (Birks *et al.*, 2010).

The Modern Analogue Technique (MAT) is a common specific quantitative method based on the assemblage approach that uses a statistical measure of dissimilarity assemblages of flora or fauna in modern and fossil samples and infers variation in a past environmental variable or variables based on the composition of the fossil assmeblages (Overpeck *et al.*, 1985). A reconstruction that uses the MAT is based on the modern samples that most closely match the fossil assemblages (Lytle and Wahl, 2005). For example, Pflaumann *et al.* (1996) used the MAT to model the relationships between planktonic foraminifera assemblages and sea surface temperature in the eastern North and South Atlantic Oceans, and Jianga *et al.* (2006) used the MAT to reconstruct temperature and precipitation in Mongolia from a high resolution pollen record.

The response surfaces technique is a form of the MAT that uses smoothed modern data rather than individual assemblages as a database of potential modern analogues for the fossil assemblages (Birks *et al.*, 2010). For example, Gonzales *et al.* (2009) used a response surfaces technique to extend existing interpretations of late-glacial to early-Holocene temperature and precipitation from pollen data, where previous interpretations suffered from a lack of modern analogues for some fossil assemblages. Huntley *et al.* (1995) used the response surface technique on a larger scale, using climate and vegetation data across the whole of Europe to make predictions about potential future shifts in the geographic ranges of several plant species.

The assemblage approach appears to be more sophisticated than the indicator species approach but it is not without weaknesses. For example, fossil assemblages may contain taxa

that respond to different environmental variables to their closest modern counterparts, or may have no modern analogue, or several modern analogues that imply differing climatic or environmental conditions (Birks *et al.*, 2010).

Delacourt and Delacourt (1991) evaluate the concept of the modern analogue. One major issue is that of defining what a modern analogue is. With respect to vegetation, researchers in the United States use several different definitions: 1) all communities that exist today, 2) natural vegetation as it existed in pre-settlement times and 3) natural vegetation that existed in the late Holocene (~500 years ago). Modern analogues used on the basis of the third definition would themselves have to be constructed from fossil data.

The second issue discussed by Delacourt and Delacourt (1991) is that which is alluded to by Birks *et al.* (2010) above; not all fossil assemblages will have perfect modern analogues. Figure 2.7 shows the five different ways in which modern and past assemblages can be related to one another. A brief description of each type of relationship follows:

(a) the past assemblage has an excellent modern analogue

(b) the past and modern assemblages only partially overlap

(c) the past assemblage has no modern analogue

(d) the modern assemblage represents only a subset of the past assemblage

(e) the past assemblage may be included as a subset of all modern analogues

Any one attempt at reconstructing a palaeoenvironment using the assemblage approach may encounter any combination of these relationships. The researcher then risks the possibility of fossil assemblages being matched up with modern assemblages that do not make good analogues for them.

Finally, the MAT and other related techniques have no underlying statistical model and so it is not possible to properly evaluate the performance of a particular reconstruction in the way that the performance of a regression model would be assessed using specific prediction statistics (Hayward *et al.*, 2004; Birks *et al.*, 2010). MAT is used more often by palynologists (Wahl, 2004) and palaeoceanographers (Pflaumann *et al.*, 1996) than it is by sea-level researchers (Birks, 1998), though a handful of studies in New Zealand (Hayward *et al.*, 2004; Southall *et al.*, 2006), North America (Charman *et al.*, 2010) and the British Isles (Allen, 2010) have used this approach with success.

Hayward *et al.* (2004) chose to use the MAT, based on its success in other areas such as sea surface temperature reconstruction from foraminifera assemblages, to reconstruct tidal
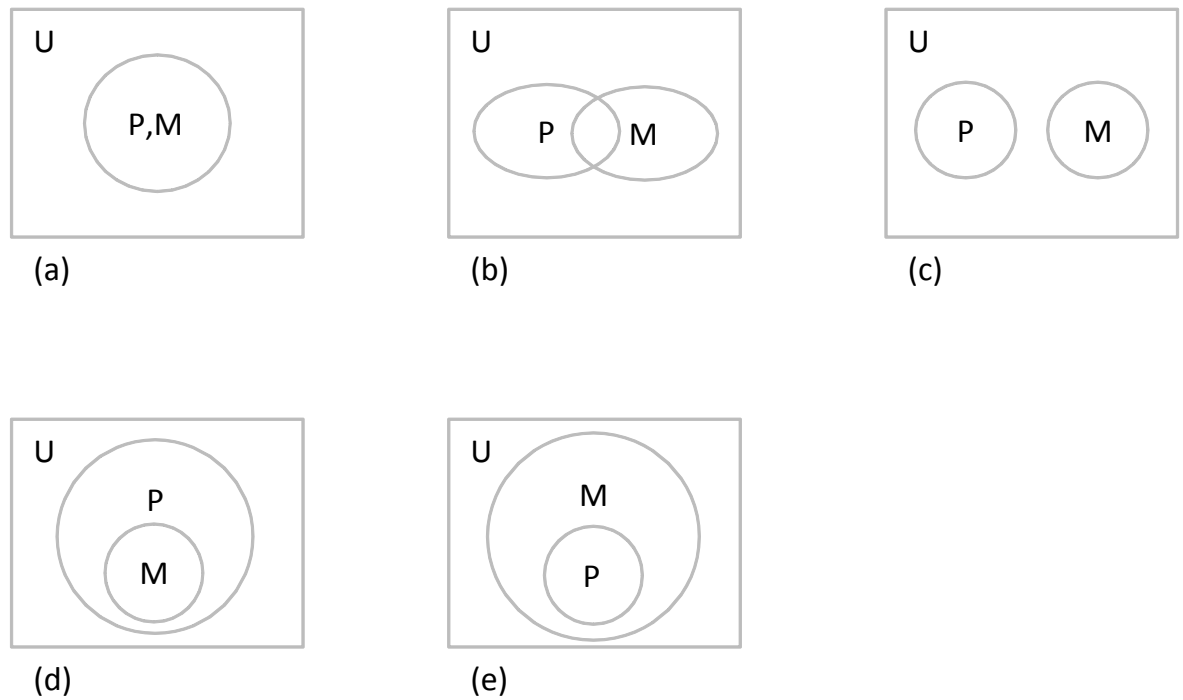
Figure 2.7: Venn diagrams illustrating the concept of different analogue situations. 'U' represents the universe of all possible assemblages, 'P' represents the subset of past assemblages and 'M' represents the subset of modern assemblages. Adapted from Delacourt and Delacourt (1991) with kind permission from Springer Science+Business Media B.V.

height at two sites in the North Island of New Zealand from 281 modern foraminifera samples. They found that MAT estimates for sheltered harbour or tidal inlet environments were more precise than those given for lower-salinity estuarine settings, citing the collection of a larger modern estuarine foraminifera data set as a potential way of improving MAT performance in reconstructing water levels of estuarine environments in New Zealand.

Charman *et al.* (2010) used the MAT on modern and fossil testate amoebae assemblages to reconstruct recent sea-level change in Maine, USA and Nova Scotia, Canada. When compared to transfer function models (see Section 2.5.3) the MAT approach was less successful, with cross validation (see Section 2.5.3) showing the MAT method to over-predict low elevation samples and under-predict those with higher elevations.

In contrast, in a study of the environmental controls on saltmarsh foraminifera in Devon, Allen (2010) found the MAT to perform better than a regression-based approach (transfer function).

2.5.3 The transfer function approach

Sachs *et al.* (1977, p. 159) define transfer functions as "...empirically derived equations for calculating quantitative estimates of past atmospheric or oceanic conditions from paleontological data". The contemporary responses of taxa that are both extant today and present

in fossil forms, to a suitable environmental variable or variables, can be modelled numerically by appropriate regression methods. A modern dataset is referred to as a 'calibration set' or 'training set' (Birks *et al.*, 2010), composed of species abundance data Y_m and corresponding values of the environmental variable(s) X_m. The resulting transfer function is used to transform the fossil assemblages (Y_f) into statistical estimates of the past environmental variable(s) (X_f). Birks *et al.* (2010) illustrate this sequence of steps in a simple diagram, replicated here in Figure 2.8.

The transfer function approach was first applied to palaeoenvironmental reconstruction in the early 1970s when computational power became sufficiently advanced to handle the large, multivariate datasets involved. Although the transfer function approach to climatic reconstruction is often attributed to Imbrie and Kipp (1971), three groups of researchers actually produced the first quantitative palaeoenvironmental reconstructions based on linear regression independently (Fritts *et al.*, 1971; Imbrie and Kipp, 1971; Webb III and Bryson, 1972).
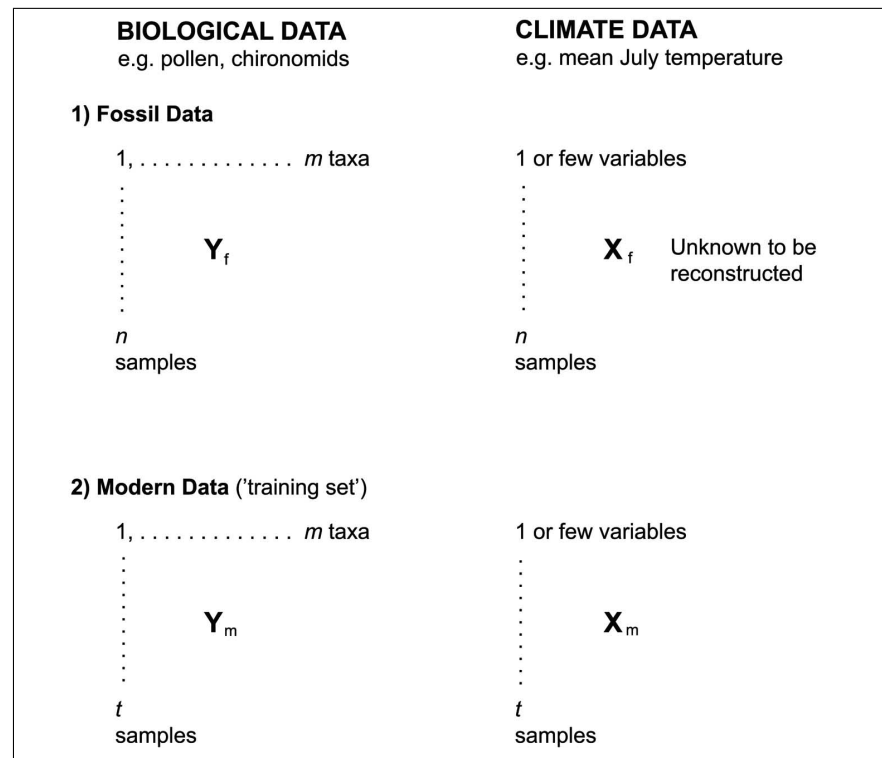
Figure 2.8: The principle parts of quantitative palaeoenvironmental reconstruction, showing $\mathbf{X}_f$, the unknown past environmental variable (*e.g.* mean sea-level) to be reconstructed from fossil assemblages $\mathbf{Y}_f$ and the important role of modern biological data (*e.g.* species assemblages), $\mathbf{Y}_m$ and associated environmental data ($\mathbf{X}_m$) n refers to a number of fossil data samples and t refers to a number of contemporary training samples. Reproduced from Birks *et al.* (2010) with permission from Bentham Science Publishers.

There are four important regression statistics produced when a transfer function is developed. These are commonly used in the studies discussed in the remainder of this chapter,

and are defined below.

The r^2 value is a coefficient of determination and refers to the strength of the transfer function, based on its ability to predict each observed occurrence of the variable being modelled (Szkornik *et al.*, 2006). r^2 will always be between 0 and 1, with values closer to 1 indicating closer correlation between the observed and predicted values.

Most researchers use some kind of cross-validation method to test the strength of a transfer function further, which include various ways of leaving samples out of the regression and recording the ability of the transfer function, based on the remaining samples, to predict the environmental variable from the missing samples' species data. There are several methods available, and the two most common in sea-level studies are jackknifing and bootstrapping. The resulting r^2 from the cross-validation exercise may be denoted as r^2_{jack} or r^2_{boot}, for example, and will normally be lower than the basic r^2 that is based on every sample in the training set.

Jackknifing is also known as the leave-one-out method, using regression of N-1 samples to estimate the environmental variable for the excluded sample (Quenouille, 1949). This process is repeated N times, so that each sample in the training set is left out in turn.

Bootstrapping uses random sampling to select subsamples from the training set with which to predict excluded samples (Efron, 1979). Each subsample actually contains the same number of samples as the original training set (N) but some samples will appear more than once per iteration, while others are left out. This is known as picking from a data set 'with replacement', and so a sample has the same probability of being picked whether or not it has been picked before. Bootstrapping can offer greater precision because the process can be repeated thousands of times, with thousands of different combinations of the samples, whereas jackknifing is a special case of bootstrapping for which only N iterations is ever possible (Lanyon, 1987).

The root mean squared error (RMSE) refers to the differences between the observed values of the environmental variable and those predicted by the transfer function, when the sample whose associated variable being predicted remains in the training set, and is an indicator of precision (Kemp *et al.*, 2009a). RMSE is given in the units of the environmental variable being modelled, so for sea-level RMSE is usually expressed in metres or centimetres. Root mean squared error of prediction (RMSEP) is the corresponding measure of precision from the cross-validation, so will inevitably be slightly higher relative to the RMSE for most models.

A number of multivariate regression methods are available to palaeoeologists aiming to reconstruct unknown past occurrences of an environmental variable from known species data,

and each of these is introduced fully in Chapter 4 (Methodology). Each method falls into one of two categories; those that are based on the assumption that species respond linearly to the variable in question, and those that assume unimodal (bell-shaped) responses. As references are made to specific methods in the following review of the quantitative sea-level litertaure, a brief description of each method is given in Table 2.1, prior to the lengthier explanations given in Chapter 4.

Table 2.1: Description of the four multiple regression models commonly used in sea-level studies.

Regression model	Linear or unimodal?	Description
Partial least squares (PLS)	Linear	Combines features from ordination method principal components analysis (PCA - see Section 4.2) and multiple linear regression to reduce the number of dimensions in the species data down into a smaller number of components, then performs linear regression on those components and the environmental variable (Yeniay and Göktaş, 2002).
Weighted averaging (WA)	Unimodal	Multivariate regression based on the assumption that a species with a particular optimum of an environmental variable will be most abundant when that variable is close to that optimum (Ter Braak and van Dam, 1989).
Weighted averaging with tolerance downweighting (WA-Tol)	Unimodal	Similar to WA but gives more weight to species with narrower tolerance ranges (Gehrels, 2000).
Weighted averaging partial least squares (WA-PLS)	Unimodal	Similar to WA but uses the interactions between predictive variables (species) to improve predictions (Ter Braak and Juggins, 1993).
Stepwise multiple linear regression (SMLR)	Linear	Species are selected that have the best predictive correlation with the variable being reconstructed and the next best predictors added continually until the result (*i.e.* the r^2) stops improving (Hair *et al.*, 1998; Patterson *et al.*, 2005).

2.6 Implementation of the transfer function approach in sea-level studies

The development of quantitative ecological and palaeoecological techniques in sea-level studies broadly parallels the same development in other areas such as palaeolimnology and palynology. Initially modern intertidal ecological zones were determined subjectively and matched

up with fossil assemblages (Devoy, 1982; Funnell and Pearson, 1989; Long and Tooley, 1995; Haslett *et al.*, 1997). Statistical elements were added to this qualitative approach when researchers began to use cluster analysis to define modern assemblage zones (De Rijk, 1995; Horton, 1999; Patterson *et al.*, 2000) and when Jennings and Nelson (1992) used discriminant analysis (a multivariate classification technique) to assign fossil samples to qualitatively selected contemporary assemblages zones.

The previous section discussed how the apparent zonation of microfaunal assemblages in the intertidal zone was first used to validate SLIPs in studies of Holocene sea-level change. This early work enabled researchers to take this approach a step further and use quantitative tools to develop more accurate sea-level histories. The earliest sea-level transfer functions were developed in the late 1990s and are detailed in Table 2.2 (Guilbault *et al.*, 1996; Gehrels, 1999; Horton *et al.*, 1999b; Zong and Horton, 1999; Edwards and Horton, 2000).

A review of Holocene sea-level research that uses the transfer function approach follows below, beginning with single-proxy transfer functions, then studies using two or more proxies are discussed, followed by a review of the work done in macrotidal estuaries. A review of research based specifically in the Severn Estuary region can be found in Chapter 3.

2.6.1 Foraminifera-based sea-level transfer functions

Gehrels (1999) used a modern data set of surface-dwelling intertidal foraminifera to develop a sea-level transfer function for Eastern Maine, USA, and reconstructed Holocene sea-level at Machiasport. This 6,000 year reconstruction can be seen plotted together with SLIPs obtained by the more traditional methods in Figure 2.9, revealing multi-decadal to century scale fluctuations within the long term sea-level trend. From this study Gehrels (1999) noted that rapid sea-level rise (2.2mm/yr) began before industrial times, suggesting that at least some of the increase in the rate of sea-level rise since the industrial revolution is probably part of some natural oscillation.

Leorri *et al.* (2010) analysed the distribution of intertidal foraminifera along the Atlantic coast of south western Europe, sampling across 14 transects at four sites. The four sites in Britanny (France), the Basque Coast (Spain), the Minho and Lima estuaries (Portugal) and the Sado estuary (Portugal) are all close to tide gauge locations with continuous records of at least 50 years (Brest, Santander, La Coruña and Cascais respectively). They found that the composition of the foraminifera zones at the four sites was different enough to justify studying them separately. At each of the four sites they developed three transfer function models, as follows:

Table 2.2: Details of the earliest sea-level transfer functions published. N is the number of modern samples analysed. MTR is the mean tidal range at the sampling site.

Study location	Citation	Microorganism group	N	MTR	Period of reconsruction
Vancouver Island, Canada	Guilbault *et al.* (1996)	Foraminifera	18	2.8m	180-1,140 years BP
Machiasport, Maine, USA	Gehrels (1999)	Foraminifera	68	3.6m	5,500 years BP to present
Various, UK	Horton *et al.* (1999b)	Foraminifera	Not given	N/A	Not applied
Various, UK	Zong and Horton (1999)	Diatoms	88	N/A	1,553-1,090 years BP
Various, UK	Edwards and Horton (2000)	Foraminifera	Not given	N/A	3,460-60 years BP (at Poole, Dorset, UK)
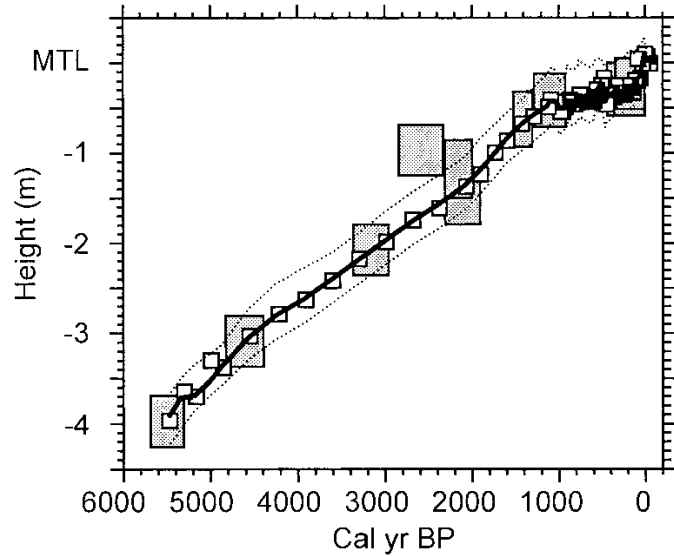
Figure 2.9: Relative changes in MTL at Machiasport during the past 6,000 years. The solid line is a 5 point moving average on data points given by the transfer function (small squares). The grey boxes are basal SLIPs from Gehrels *et al.* (1996) and Gehrels (1999). The dotted lines reflect the statistical uncertainty of the transfer function. Reproduced from Gehrels (1999) with permission from Elsevier.

1. Unscreened data.

2. Samples above a certain SWLI[1] (Britanny: SWLI >180, Basque Coast: SWLI >160, Minho and Lima: SWLI >160, Sado: SWLI >180).

3. As 2, but with foraminifera data expressed as concentrations rather than percentages.

When converting foraminifera counts in percentages, there is a risk that artificial correlations among species can be created, known as matrix closure (Mekik and Loubere, 1999). This effect should be considered when carrying out quantitative reconstructions. However, Leorri *et al.* (2010) found that for the four sites studied, using concentrations instead of percentages did not seem to affect model performance. Instead the greatest difference in performance appears to be based on the sampling strategy. Model 2 always showed significantly greater precision than model 1, suggesting that high marsh foraminifera are more precise sea-level indicators. Woodroffe (2009) attributes this effect to species inhabiting the lower part of the tidal frame generally having wider tolerance ranges. The authors' main recommendation is that modern transects are sampled from the same environment being reconstructed, to include at least 50 samples that mainly come from the high marsh where just a few resistant species dominate (Leorri *et al.*, 2010, 2011).

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[1]SWLI=Standardised Water Level Index; a measure to account for different tide ranges at the four sites. See Section 4.1.1 of Chapter 4 for a more detailed description.

In conjunction with tephra anlaysis, geochemistry, ^{14}C and ^{210}Pb dating Gehrels *et al.* (2006b) used a foraminfera-based transfer function to reconstruct MSL at Vidarhálmi in Iceland since AD 100. The study shows that relative sea-level has risen on the west coast of Iceland by 1.3m since AD 100, including 0.65m of isostatic subsidence per 1,000 years. The younger part of the sea-level reconstruction corresponds well with the Reykjavik tide gauge records (1957 to 2004), and shows a clear acceleration to the present rate of 2.3±0.5mm/yr between 1800 and 1840 (see Figure 2.10). The regression model used was weighted averaging with tolerance downweighting (WA-Tol), chosen because although less precise than the weighted averaging partial least squares (WA-PLS) model (WA-Tol RMSEP = 0.20, WA-PLS RMSEP = 0.14), the WA-Tol r^2 statistic indicated greated accuracy (Gehrels *et al.*, 2006b).
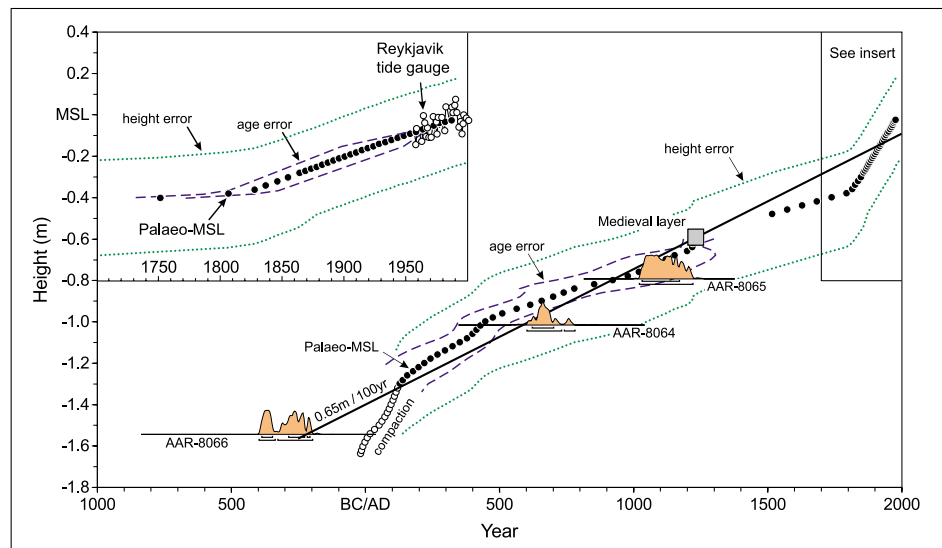
Figure 2.10: Relative sea-level changes at Vidarhálmi, Iceland. Solid circles present reconstructed sea-level positions. The trend line shows a long-term sea-level rise of 0.65m per 1000 years. The 2-σ calibrated probability distribution of each radiocarbon date is represented by an orange curve. The inset graph shows correspondence with twentieth century sea-level observations at Reykjavik. Reproduced from Gehrels *et al.* (2006b) with permission from SAGE Publications.

There are relatively few studies that use foraminifera as quantitative sea-level indicators in the southern hemisphere. One of these studies, by Southall *et al.* (2006) at Pounawea on the south island of New Zealand, found that foraminifera showed a very strong vertical zonation. The RMSEP for a weighted averaging (WA) transfer function was 0.467, meaning that the foraminifera are potentially capable of predicting former sea-levels with precision of ±5cm or better. The low tidal range of the Catlins River estuary will mean that the species assemblages will be more tightly banded vertically than at sites with bigger tidal ranges but even when RMSEP is expressed as a proportion of the tidal range (1.5m), precision is better than several studies from North Atlantic (*e.g.* Gehrels (2000), Gehrels and Newman (2004),

Edwards *et al.* (2004)). See Table 2.3 for the results of key studies, including the RMSEP presented as a proportion of the tidal range, to account for those studies that do not convert elevation to a SWLI.

Some studies use sea-level transfer functions to extend sea-level records back several centuries from the present day, in detail, effectively extending tide gauge records further back in order to establish whether any inflection or acceleration in the records can be identified, in the context of the industrial revolution and increased fossil fuel consumption. Comparing transfer function-predicted recent sea-level records with real, instrumental records also provides a method of confirming the validity of the transfer function approach to studying Holocene sea-level.

In Tasmania, Australia, Callard *et al.* (2011) investigated the zonation of foraminifera in two saltmarshes. Port Arthur in southeastern Tasmania is the home of one of the oldest tidal bench marks in the world, cut into the rocks in 1841 (Hunter *et al.*, 2003), which is partly why sea-level here is of particular interest to researchers. Callard *et al.* (2011) were looking to develop a transfer function accurate and precise enough to extend back the instrumental record of sea-level change in Tasmania. The resulting partial least squares (PLS) sea-level transfer function, composed of modern data from both sites, while strong (r^2_{jack}=0.68, RMSEP=0.094), was not quite as accurate or precise as the Pounawea transfer function (Southall *et al.*, 2006), even when RMSEP was expressed as a proportion of the very small tidal range of 0.6m. The results were still very much comparable with studies from the North Atlantic, however.

Some published studies focus solely on the development of the modern training set and transfer function, leaving the actual reconstruction of sea-level for later work. In fact, Birks (1998) expresses surprise at the amount of effort that has gone into the development of modern training sets but that have not been used to reconstruct past environments, as they were developed to do. However, many such studies offer very useful insights into more specific aspects of quantitative reconstruction. For example, Horton (1999) monitored the foraminifera content and five environmental variables (flooding frequency, salinity, substrate, pH and vegetation cover) at Cowpen Marsh on the Tees estuary, UK. Every two weeks for a period of 12 months surface sediment samples were taken at 32 sampling stations across the intetidal zone.

The live, dead and total foraminifera assemblages in every sample taken were recorded to address the often-contested question of which assemblage most accurately represents that which will be preserved in fossil form and so will be the best analogue for fossil assemblages.

Table 2.3: Results of modern foraminifera training sets from selected studies. N is the number of samples in the training set. r_X^2 is the cross-validated r^2. MTR = mean tidal range. The data from the Gehrels *et al.* (2005) is taken from Scott and Medioli (1980). C11=Callard *et al.* (2011), So06=Southall *et al.* (2006), G01=Gehrels *et al.* (2001), M06=Massey *et al.* (2006a), L10=Leorri *et al.* (2010), G et al 05=Gehrels *et al.* (2005), G00=Gehrels (2000), E04=Edwards *et al.* (2004), K12c=Kemp *et al.* (2012), K09c=Kemp *et al.* (2009c), H10=Hawkes *et al.* (2010).

Site	N	Model	r_X^2	RMSEP (m)	MTR	RMSEP/ MTR (%)	Citation
Tasmania	43	WA-PLS	0.68	0.09	0.60	16.7	C11
Pounawea, NZ	31	WA-Tol	0.49	0.05	1.50	3.1	So06
UK (average of 3 sites)	90	PLS	0.29	0.08	Not given	Unknown	G01
Southwest England	85	WA-PLS	0.93	0.29	3.45	8.3	M06
Brittany, France	43	PLS	0.52	0.12	3.50	3.4	L10
Northern Spain	59	WA-PLS	0.77	0.13	2.25	5.8	L10
Northern Portugal	52	WA-PLS	0.39	0.42	1.80	23.4	L10
Southern Portugal	22	PLS	0.22	0.14	2.00	7.1	L10
Nova Scotia	46	WA-Tol	0.46	0.06	1.50	3.7	G05
Maine	68	WA-PLS	0.76	0.08	3.11	1.0	G00
Connecticut	86	WA-PLS	0.72	0.14	1.36	10.3	E04
New Jersey	56	WA-PLS	0.79	0.14	1.20	11.7	K12c
North Carolina	46	WA-PLS	0.74	0.04	0.27	14.8	K09c
Oregon	91	WA-PLS	0.82	0.20	1.81	11.0	H10

Horton (1999) found that despite clear seasonal fluctuations in the life assemblage, the dead assemblage remained relatively stable over the course of the year (see Figure 2.11).
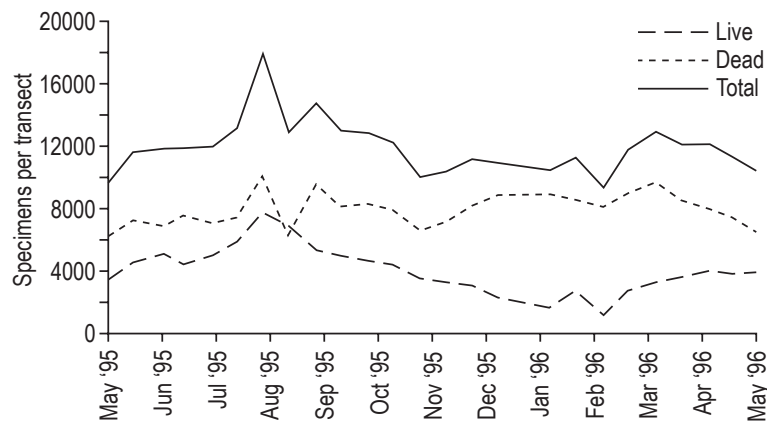
Figure 2.11: Number of live, dead and total foraminifera specimens for all species from Cowpen Marsh, between 1 May 1995 and 3 May 1996. From Horton and Edwards (2006). This figure uses the data collected by Horton (1999). Reproduced with permission from the authors.

When compared with subsurface assemblages (all dead), Horton (1999) found that the death assemblages, which are removed from most seasonal fluctuations in the life assemblages, accurately represent the sub-surface assemblages that are the focus of palaeoenvironmental

studies.

2.6.2   Diatom-based sea-level transfer functions

Early work by Shennan *et al.* (1995), Zong and Tooley (1996) and others first investigated the vertical zonation of diatom species in coastal saltmarshes, relative to the tidal frame. Like foraminifera, diatoms were initially used in sea-level studies to validate SLIPs, rather than to reconstruct past sea-levels explicitly (Zong and Horton, 1999).

Zong and Horton (1999) compiled a training set of diatom assemblages for the UK, containing data from a wide range of contemporary coastal environments. The relationships between diatom species and altitude were explored statistically. As data from several sites fed into the transfer function, altitude was converted to SWLI so that the sites would be directly comparable. CCA (see Chapter 4 (Methodology) for a discussion of CCA and other multivariate techniques) showed that of SWLI, organic content of the substrate and substrate grain size, SWLI accounted for most of the explained variance in the diatom data (23.3%). However, 78.4% of the total variation in the data remained unexplained.

Nevertheless, Zong and Horton (1999) used their training set to develop a predictive transfer function and used this to estimate the indicative meaning of the radiocarbon dated core samples from Kentra Bay in the Scottish Highlands. The WA-Tol model (r^2=0.72, RMSEP=21.38[2]) performed slightly better than the WA model (r^2=0.65, RMSEP=23.58). When corrected for tidal range the prediction error of the transfer function is very low (see Table 2.4), but because the training set is composed of data from six sites with quite different tidal ranges (ranging from 0.98m to 4.70m) it is not particularly informative to express the RMSEP as a proportion of the tidal range.

Szkornik *et al.* (2006) developed a diatom-based transfer function for the Ho Bugt region of western Denmark and produced a significant r^2_{jack} value of 0.901 and a low RMSEP of 0.141m, using a WA-PLS regression model and jack-knifing for the cross-validation. Using CCA ordination they found that the three observed variables, elevation, salinity and pH, explained 37.9% of the variation in the diatom data, and that of that explained variation, 24% was attributed to elevation, compared to 1.4% explained by salinity and 9.2% explained by pH. However, the authors highlight the issue of positive spatial autocorrelation and how

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[2]While it was stated previously in section 2.5.3 that RMSEP in sea-level studies is normally given in metres, Zong and Horton (1999) standardised the tidal levels of their training set samples in order to combine together training data from six sites with different tidal ranges. Therefore, RMSEP of 21.38 does not indicate potential prediction precision of 21.38 metres, but 21.38 units of the standardised index used. The equation quoted is as follows: $X_{ab} = (((A_{ab} - MTL_b)/MHWST_b - MTL_b) \times 100) + 200)$, where X_{ab} is standardised water level of sampling station a at site b, A_{ab} is the measured altitude of sampling station a at site b, MTL_b is the mean tidal level at site b and MHWST$_b$ is the mean high water spring tide at site b. This approach differs slightly from that used in this study (see Chapter 4).

this may lead to over-optimistic estimation of transfer function errors (Telford and Birks, 2005). Positive spatial autocorrelation is "the tendency of sites close to each other to resemble one another more than randomly selected sites" (Telford and Birks, 2005, p.2173) and can be a particular problem in studies in which sampling takes place along line transects, as is common in sea-level studies (Szkornik *et al.*, 2006).

Table 2.4: Results of modern diatom training sets from selected studies. See Table 2.3 for an explanation of the column headings. ZH99=Zong and Horton (1999), G01=Gehrels *et al.* (2001), WL1=Woodroffe and Long (2010), Sz06=Szkornik *et al.* (2006), H07=Hill *et al.* (2007), K09=Kemp *et al.* (2009a), NS03=Ng and Sin (2003).

Site	N	Model	r_X^2	RMSEP (m)	MTR	RMSEP/ MTR (%)	Citation
UK (average of 6 sites)	88	WA-Tol	0.72	0.12	n/a	Unknown	ZH99
UK (average of 3 sites)	94	WA-PLS	0.75	0.05	Not given	Unknown	G01
West Greenland	135	WA-PLS	0.90	0.10	1.88	5.32	WL10
West Denmark	40	WA-PLS	0.90	0.14	1.5	9.33	Sz06
Severn Estuary	61	WA-Tol	0.85	0.88	14.65	6.01	H07
North Carolina (average of 3 sites)	46	WA-PLS	0.76	0.04	n/a	Unknown	K09
Double Haven (Hong Kong)	25	WA	0.73	0.39	1.7	22.94	NS03

A Hong Kong study by Ng and Sin (2003) examined the relationship between intertidal diatom assemblages and 14 environmental variables using CCA, before developing a sea-level transfer function for the Double Haven embayment in North East Hong Kong. Many authors tend to focus on just three or four environmental variables (*e.g.* pH, organic content, salinity, elevation), but of the fourteen studied by Ng and Sin (2003), water depth (linked to elevation above MSL) was still identified as the most important variable influencing the diatom distribution in Double Haven. Of the various transfer function models produced, the WA-Tol model performed best (r_{boot}^2=0.805, RMSEP=0.399) and has the potential to infer Holocene sea-level changes on the Hong Kong coast, where studies using microorganisms as quantitative sea-level indicators are not very common. A minor criticism of the study is that only 25 points were sampled across the intertidal zone. Leorri *et al.* (2010) suggest that at least 50 samples should be collected, and many other authors base their training sets on between 30 and 100 samples, which implies that 25 is a relatively low number of samples. This seems particularly unfortunate because of the effort made to measure and analyse the microfaunal relationships with such a large number of other variables. Table 2.6 provides a summary of the microorganisms groups and environmental variables measured by Ng and Sin (2003) and other researchers.

2.6.3 Testate amoebae-based sea-level transfer functions

The use of testate amoebae in sea-level transfer functions is relatively recent and has thus far only been applied to sea-level change in the past ~100 years due to methodological constraints (Charman *et al.*, 1998, 2010). As the focus of this thesis is on the entire Holocene, only a short discussion of testate amoebae as quantitative sea-level indicators follows. The key results of the studies can be found in Table 2.5.

Charman *et al.* (2002) analysed the variation in testate amoebae across the intertidal zone at three sites in the UK, along with salinity, pH, LOI, total organic carbon and grain size (proportions of sand, silt and clay). Flooding duration was calculated from the elevation of each sampling site and the tidal range. For the three sites combined elevation was the most influential of the variables measured in terms of species composition (10.5% of total variation in species composition, or 25.4% of the *explained* variation). Salinity and pH respectively were the second and third most important factors. The elevation data were normalised to SWLI so that the three sites could be combined, and compared directly. They explored the relationship between the testate amoebae assemblages and the environmental parameters using CCA. Charman *et al.* (2002) found that of all of the environmental variables measured, SWLI and flooding frequency had the strongest relationships with the species data, and went on to use this data in a study of multiple sea-level indicators (Gehrels *et al.*, 2001), and to develop a transfer function. The testate amoebae-based transfer function gave a fairly low RMSEP value of 0.076, meaning that any eventual reconstruction using the transfer function could potentially be precise to the nearest 7.6cm. However, the low r^2_{jack} value of 0.44 presents the question of whether a sea-level reconstruction that has the potential to be very precise is valuable if the data points are not known to be accurate in the first place. As discussed previously, foraminifera-based transfer functions have given higher prediction r^2 values of 0.68 and above.

A recent study in North America investigated the potential for testate amoebae to produce a detailed reconstruction of recent sea-level change that would highlight the occurrence of any marked acceleration in sea-level rise in the nineteenth or twentieth century. Charman *et al.* (2010) developed a testate amoebae-based transfer function that produced a sea-level curve for Maine, USA and Nova Scotia, Canada, that is in general agreement with both tide gauge data and a sea-level curve based on foraminifera. The best model gave a high r^2_{jack} of 0.85 and low RMSEP of 0.054. Furthermore, and in stark contrast to the study mentioned above, they found that a UK testate amoebae training set could be used to predict modern elevations from modern US and Canadian testate amoebae assemblages in Maine

and Nova Scotia with exceptional accuracy (r^2_{jack}=0.99, RMSEP=0.012). Such consistency of zonation across a large geographical region has not been seen in studies of intertidal foraminifera or diatoms. However, as Mitchell *et al.* (2008) mention in a paper that calls for a taxonomic revision of testate amoebae, it is possible that a given morphological species may conceal several genetically distinct species that differ in terms of geographical distribution or ecological requirements; a warning against the potential overestimation of accuracy.

Table 2.5: Results of modern testate amoebae training sets from selected studies. See Table 2.3 for an explanation of the column headings. *This r^2 value does not result from cross validation. G06a=Gehrels *et al.* (2006a), C10=Charman *et al.* (2010), G01=Gehrels *et al.* (2001).

Site	N	Model	r^2_X	RMSEP (m)	MTR	RMSEP/ MTR (%)	Citation
North America (average of 3 sites)	38	WA	0.87*	0.09	n/a	Unknown	G06a
North America (average of 2 sites)	29	WA	0.85	0.054	2.18	2.48	C10
UK (average of 3 sites)	52	WA-Tol	0.44	0.08	Not given	Unknown	G01

Ooms *et al.* (2011) have also published a preliminary study investigating the potential for using testate amoebae to reconstruct water levels in the inland, freshwater tidal zones of estuaries. Based on a training set containing 54 modern testate amoebae samples from the estuarine part of the Scheldt estuary in south-west Netherlands, the best transfer function developed to predict elevation used a weighted averaging (WA) regression model and gave r^2_{jack} and RMSEP values of 0.70 and 0.05 respectively.

Table 2.6: A summary of the microorganism groups used and the environmental variables measured in studies of quantitative sea-level reconstruction. ◇ = microorganisms group used, ● = environmental variable measured and its relationship with microfaunal assemblage variation analysed, ○ = environmental variable noted but no analysis of its relaionship with the microorganism group carried out.

Citation	Diatoms	Foraminifera	Testate amoebae	CaCO₃ content	Clay-silt fraction	Distance to coast	Gradient	Mean grain size	Mode grain size	LOI	Salinity	Sediment pH	Sediment redox	Sediment uniformity	Vegetation cover	Water content	Water depth	Wind fetch
Callard *et al.* (2011)		◇													○			
Cearreta *et al.* (2008)		◇																
Charman *et al.* (2010)			◇															
Charman *et al.* (2002)			◇	●				●		●	●	●						
Edwards *et al.* (2004)		◇													○			
Gehrels (2000)		◇																
Gehrels *et al.* (2006a)			◇															
Gehrels and Newman (2004)		◇									●	●			○			
Gehrels *et al.* (2001)	◇	◇	◇												○			
Hawkes *et al.* (2010)		◇			●						●	●	●		●			
Hill *et al.* (2007)	◇							●		●								
Horton and Edwards (2005)		◇																
Horton *et al.* (2003)		◇						●			●	●						
Horton *et al.* (1999b)		◇									●							
Kemp *et al.* (2012)		◇																
Kemp *et al.* (2009b)		◇																
Kemp *et al.* (2009a)	◇	◇																
Leorri *et al.* (2010)		◇																
Leorri *et al.* (2008)		◇													○			
Massey *et al.* (2006a)		◇													○			
Ng and Sin (2003)	◇			●		●	●	●	●	●	●	●	●	●		●	●	●

Citation	Diatoms	Foraminifera	Testate amoebae	CaCO₃ content	Clay-silt fraction	Distance to coast	Gradient	Mean grain size	Mode grain size	LOI	Salinity	Sediment pH	Sediment redox	Sediment uniformity	Vegetation cover	Water content	Water depth	Wind fetch
Patterson *et al.* (2004)		◇																
Rossi *et al.* (2011)		◇																
Southall *et al.* (2006)		◇																
Szkornik *et al.* (2006)	◇										●	●						
Woodroffe and Long (2010)	◇							●		●								
Zong and Horton (1999)	◇							●		●					○			

2.6.4 Multi-proxy quantitative sea-level reconstruction

In most studies involving sea-level reconstruction using transfer functions only one microorganism group is used (*e.g.* diatoms). Using two or more proxies has been shown in other areas of environmental change research to give more robust results (Roberts, 1998; Di Rita *et al.*, 2011). However, only a very small number of researchers have applied this approach to quantitative sea-level reconstruction and used combined training sets of more than one microorganism group to develop sea-level transfer functions.

Kemp *et al.* (2009a) investigated the performance of a combined diatom and foraminifera-based transfer function for a site in North Carolina, USA, by comparing it with the performance of separate diatom- and foraminifera-based models. All three transfer functions showed strong relationships between the observed and predicted elevations of the contemporary samples in the training set (the cross validation r^2), but the multi-proxy model slightly out-performed the other two in terms of predictive power (the RMSEP). The study found that many core samples did not have good modern analogues for diatom assemblages in the training set, and therefore a sea-level reconstruction was produced using only the foraminifera-based transfer function. The performance of the combined transfer function is comparable to results reported by others using just one sea-level indicator (Gehrels, 2000; Patterson *et al.*, 2004; Massey *et al.*, 2006a; Ng and Sin, 2003; Szkornik *et al.*, 2006). Kemp *et al.* (2009a) also compared the palaeo-marsh elevations estimated by the two single proxy transfer functions and found that in only three of the 18 samples did the two models give significantly different results, the greatest being a 0.13m difference. However, in the upper section of the core the diatoms estimated higher palaeo-marsh elevations, while foraminifera produced higher values for the lower core section, and this effect could not be explained.

Table 2.7: Results of multiproxy training sets from selected studies. See Table 2.3 for an explanation of the column headings. SMLR = stepwise multiple linear regression. *This r^2 value does not result from cross validation. G01=Gehrels *et al.* (2001), K09a=Kemp *et al.* (2009a), P05=Patterson *et al.* (2005).

Site	N	Model	r^2_X	RMSEP (m)	MTR	RMSEP/ MTR (%)	Citation
UK (average of 3 sites)	99	WA-PLS	0.82	0.05	Not given	Unknown	G01
North Carolina (average of 3 sites)	46	WA-PLS	0.83	0.04	0.27	12.96	K09a
British Columbia, Canada	38	SMLR	0.96*	not given	-	-	P05

When Horton and Edwards (2000) carried out a study of modern foraminifera at ten intertidal sites, and diatoms at 6 of those sites, they found, through CCA analysis a large

difference between the amount of variation explained by the environmental variables measured in the foraminifera data (49%) compared with the diatom data (22%). However, the amount of the explained variation accounted for by SWLI was comparable between the two microfossil groups (19% and 23% respectively; see Figure 2.12). The authors attributed this effect to an unmeasured parameter or a large amount of stochastic (random) variation, but could not say which.
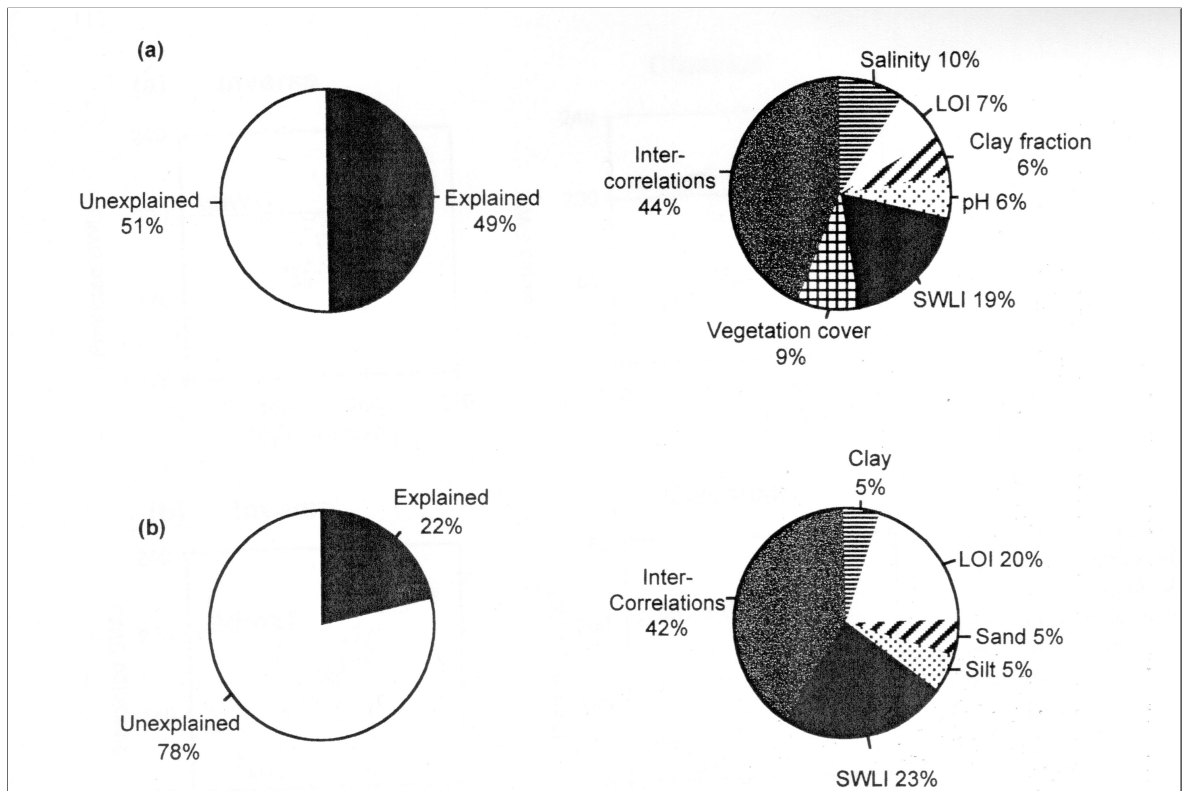
Figure 2.12: Pie charts showing the total variation of the Horton and Edwards (2000) (a) foraminifera and (b) diatom training sets in explained and unexplained portions, and components representing the unique contributions of SWLI, salinity, loss on ignition, vegetation cover, pH, grain size and inter-correlations among gradients. Reproduced with permission from the Severn Estuary Levels Research Committee (SELRC) and the authors.

Even though almost 80% of the diatom variation and 50% of the foraminifera variation remained unexplained, Horton and Edwards (2000) developed foraminifera- and diatom-based single-proxy transfer functions using the data from the ten sites, with measurable success. The r^2 was 0.75 for the foraminifera-based transfer function and 0.72 for the diatom-based transfer function. RMSEP values are not presented, and nor is any cross validation method such as jack-knifing or bootstrapping mentioned. The foraminifera-based transfer function was used in the study to reconstruct sea-level from a sediment sequence from Holkham, North Norfolk (see Figure 2.13). The diatom-based transfer function was used in another study (Zong and Horton, 1999). This was not truly "multi-proxy", but more of a comparative study as the data for the two microfossil groups were not combined together to form one transfer function.

The study does highlight some interesting differences between the behaviour of foraminifera and diatoms across several of the same sites, however.
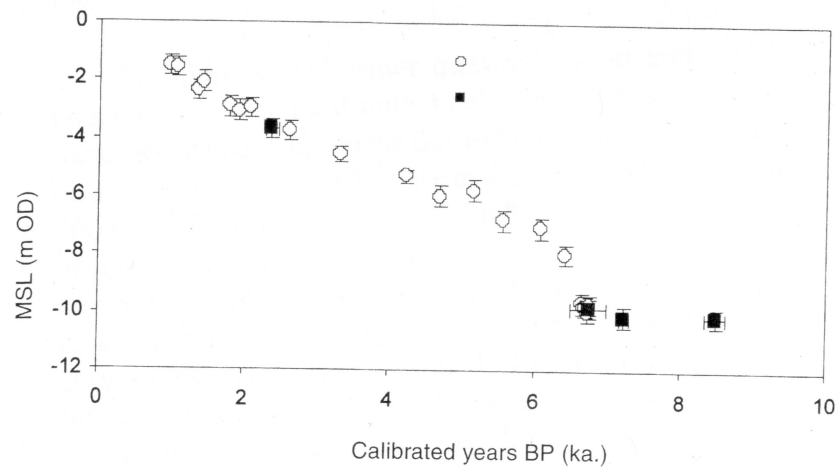
Figure 2.13: Age-altitude graph of SLIP at Holkham, North Norfolk using the Horton and Edwards (2000) foraminifera-based transfer function. The altitude of each SLIP has been corrected from SWLI to OD. Radiocarbon dates SLIPs are shown by black squares. The ages of samples not radiocarbon dated are estimated assuming a constant sedimentation rate, and are represented by white circles. Reproduced with permission from the SELRC and the authors.

Gehrels *et al.* (2001) analysed various combinations of three different sea-level indicators (foraminifera, diatoms and testate amoebae) to test the hypothesis that the combination of these three groups of microorganisms into a transfer function is more accurate and precise than a single proxy transfer function. They included combinations of live, dead and total foraminifera in their analyses, to give a total of eleven different permutations of their transfer function. They discovered that testate amoebae were most abundant in the uppermost marshes while foraminifera and diatoms were encountered along the entire range of the sampled transects, both exhibiting four main zones, identified by cluster analysis. In terms of accuracy, the regression analysis revealed that diatoms are more accurate than foraminifera based on cross validation r^2 values, and that while testate amoebae span a shorter range of the intertidal zone, RMSEP values show them to be the most precise tidal indicators. The version of the transfer function that gave the best results was that which used the training set of diatoms, testate amoebae and both live and dead foraminifera (see Table 2.7 for the results). Gehrels *et al.* (2001) did conclude that the accuracy and precision gained in using three sea-level indicator groups might be disproportionate to the amount of time invested in analysing them, but that the main advantage of the approach was that when one group of microorganisms might be sparsely represented in the modern or fossil data, another might be more abundant and offer useful data where there might otherwise have been none.

While Gehrels *et al.* (2001) and Kemp *et al.* (2009a) have developed multi-proxy sea-level transfer functions from modern intertidal data and explored the relative benefits of doing so, a multi-proxy sea-level transfer function has not yet been applied to fossil data to reconstruct former sea-levels. This thesis addresses this current gap in sea-level research.

2.6.5 Macrotidal estuaries

There is little documented use of transfer functions in the reconstruction of sea-level in macrotidal environments, perhaps because the precision offered by the vertical ranges of biological indicators decreases on coasts with larger tidal ranges (Lambeck *et al.*, 2010).

Of the ten UK sites studied by Horton and Edwards (2000), five of them have macro-tidal spring tidal ranges, the greatest being 8m at Thornham and Brancaster Marshes in Norfolk. A transfer function was developed using samples from all ten study sites combined. Local sea-level change was reconstructed from a core taken from Holkham, North Norfolk; a site close to Thornham and Brancaster Marshes. But, by developing and using a regional transfer function and combining training sets from ten UK sites, Horton and Edwards (2000) do not demonstrate whether or not a local transfer function based on data from a macro-tidal site would be effective at reconstructing sea-level in that same setting.

Hill *et al.* (2007) developed a diatom-based transfer function for the Gordano Valley, North Somerset. CCA indicated that altitude and flooding duration had a strong influence on assemblage variability. The transfer function was developed using WA-Tol regression, which gives more weight to species with narrow ranges, since they are more precise indicators (Gehrels, 2000). This regression model gave the lowest RMSEP of all the regression models tested. An RMSEP value of ±0.877m was deemed to be acceptable in the extremely macrotidal environment of the Severn Estuary. The predictive power of the transfer function was supported by a strong correlation between observed and predicted values for the modern training set of diatoms from which the transfer function was derived ($r^2_{jack} = 0.847$). Thirtynine positions of MSL were predicted by the transfer function from diatom samples, five of which were described as SLIPs because the sediments were radiocarbon dated, as well as satisfying all of the other criteria to be SLIPs. The study therefore confirmed that a diatom-based transfer function can be developed and applied successfully in a macro-tidal UK estuary. The research presented in this thesis explores the relative benefit of basing a sea-level transfer function in a macro-tidal environment on more than one sea-level indicator or proxy.

Recent work by (Mills *et al.*, 2013) at the Mersey Estuary, which has a spring tidal range

of 8.4m, has shown that there is a strong potential for foraminifera-based sea-level transfer functions to be developed at and applied to sites with large tidal ranges. (Mills *et al.*, 2013) demonstrated elevation to be an important control of foraminifera assemblages at two sites in the estuary, with prediction statistics of $r^2_{jack} = 0.55$ and RMSEP$_{jack}$=0.17m, improved to $r^2_{jack} = 0.79$ and RMSEP$_{jack}$=0.13m when only agglutinated species of foraminifera were used and statistical outliers were pruned from the dataset. These results are comparable with studies of sites with smaller tidal ranges (see Table 2.3), and this outcome provides support for this study in the Severn Estuary.

2.7 Vertical and horizontal sources of error

There are a number of factors that introduce error into estimates of past sea-level. There are vertical errors which relate to the estimate of change in MTL with respect to OD and horizontal errors related to the chronology. Those which are relevant to this study are discussed here.

In the vertical dimension error may be introduced initially in the collection of modern sediment samples and sediment cores, dependent on the accuracy and precision of the levelling equipment used, the reliability of local benchmarks, the degree of human error when levelling and the angle of the borehole when coring. Next, in the preparation of samples for microfaunal analysis the choice of sample preparation techniques may introduce unwanted bias into the results and the experimenter's own knowledge and expertise will govern the extent to which taxa are identified and recorded accurately.

The derivation of a transfer function is dependent on the vertical tolerance ranges of the microfauna, which are likely to be wider in a macrotidal environment such as the Severn Estuary, and the strength of their relationship with MTL. The macrotidal issue is central to this study and is discussed throughout, but is recognised here as a significant contribution to the overall vertical error margins. In addition, the tidal range across the Severn Estuary region is likely to have changed over the course of th Holocene, such that inferences of former MTL from palaeoenvironmental evidence may be affected.

Gehrels *et al.* (1995) estimate that the average M$_2$ tidal range (the principal lunar, semi-diurnal component of the tide) across the Bay of Fundy may have been only 54-59% as large as it is today 7,000 years ago. As the Severn Estuary/Bristol Channel is similarly funnel-shaped and fronted by a wide and shallow shelf (Tooley, 1985; Haslett, 2000), it is possible that a similar amplification of the tidal range since the early Holocene has occurred. In contrast, Shennan *et al.* (2000a) developed palaeogeographic models of northwestern Europe

that suggested that while tidal ranges would have been smaller in the early Holocene, only very minor changes have occurred since 6,000 cal. years BP.

SLIPs are derived from core samples that are usually at peat-clay boundaries. A SLIP that does not sit directly on a non-deformable surface is extremely likely to have been vertically displaced over time by sediment compaction, lying below its original elevation (Shennan *et al.*, 2006). Engelhart and Horton (2012) differentiate between basal SLIPs which, derived from from basal peats, are sampled from within 5cm of the underlying solid substrate, and base of basal SLIPs taken from immediately above the substrate. They argue that this distinction is important because while the base of basal samples will produce the best quality SLIPs, those taken from within 5cm of the substrate will have undergone some consolidation since deposition, but substantially less than that of intercalated samples. Most authors simply refer to basal and non-basal SLIPs, however. It can be difficult to compare the results of different studies of sea-level when some authors ignore the potential for SLIPs to be affected by autocompaction, while some mention autocompaction as a limiting factor and others attempt to correct for it.

Sediment autocompaction potentially leads to the underestimation of former sea-level altitudes and overestimation of the long-term rate of relative sea-level rise (Edwards, 2006). Older sediments will usually experience more compaction than younger sediments, resulting in a non-linear pattern of vertical displacement in any given Holocene sequence.

Edwards (2006) investigated the effect of sediment compaction on the correct placing of SLIPs, with the view to explaining some of the observed discrepancies between model estimates and geological reconstructions of sea-level change. The study site, Llanrhidian Marshes on the Loughor Estuary in West Glamorgan, south Wales, was characterised by fine grained, minerogenic and dateable organic deposits (Edwards, 2006). The study found that both the thickness of the underlying sediment and the sediment overburden at a SLIP correlated with the difference between modelled and reconstructed MSL. The strongest correlation was with sediment overburden (r^2=0.8).

While it is possible to use compaction-free data from sequences where peat sits immediately above a non-deformable basement, this effectively discounts any number of potentially useful sites. Edwards (2006) concludes by arguing that compaction-free data will be spatially and temporally restricted and that a correction ought to be applied for the amount of compaction, based on the thickness of sediment resting upon and underlying a SLIP, in future sea-level studies.

Edwards (2001) advises that the mainly minerogenic Holocene transgressive sequences of

the British Isles are unlikely to have undergone as much compaction as the highly organic sequences of North America, where Holocene deposits have been estimated to have been displaced by one metre or more (Gehrels, 1999). However, in a study based on the south coast of England Massey *et al.* (2006b) used a model described by Paul and Barras (1998) to estimate the maximum autocompaction of 10-15m-thick Holocene peat and clay sequences from the estimated stress experienced by 0.1 to 0.2m vertical increments of sediment. They measured the plastic and liquid limits of the sediments, particle size and pore water pressure and from these parameters calculated the effective stress for each increment. They estimated that a maximum of 2.2m of vertical displacement occurred in the deepest organic-rich sediments, and a maximum of 1.1m at the contact between peats and minerogenic sediments.

Shennan and Horton (2002) present an analysis of a database of Holocene SLIPs held at the University of Durham. In total there are 1,097 SLIPs from 52 coastal sites in Great Britain and of these, 265 are from basal peats. In addition, 180 are 'limiting points' (sometimes refered to as 'limiting dates') that are either from freshwater peats with no direct relationship with sea-level, or from peats that have not had relationships with sea-level estimated using biological indicators. Figure 2.14 illustrates the difference in spread between all of the data points and only the basal data points, alongside Holocene sea-level changes based on the GIA models of Lambeck (1995) and Peltier *et al.* (2002).

Previous research by Shennan *et al.* (2000b) shows that the type of sediment overlying and underlying the SLIP is an important factor in the potential for autocompaction, in addition to the thickness of those sediments. They found that sediment with a large sand fraction is rarely compacted, while peats may be reduced from their original volume by 90% by the process of autocompaction. In such a large dataset of SLIPs from Great Britain, where different authors will have made different allowances for autocompaction, it would be impractical to meaningfully compare all of the different non-basal SLIPs, so instead Shennan and Horton (2002) were able to focus on subsets of SLIPs from thin basal peats overlying bedrock or Pleistocene sands. Intercalated index points were still considered and included in the presentation of the the data for different regions in Great Britain, but a clear distinction was made between basal index points, intercalated index points and limiting points. An example of this distinction is shown in Figure 2.15 for southern England and Wales.

More recently Brain *et al.* (2011, 2012) have attempted to develop a framework which might allow the 'decompation' of Holocene intertidal stratigraphic sequences without the need for complex geotechnical experiments (eg Paul and Barras (1998)). The research is concentrated on UK intertidal sites where sea-level research has previously taken place and
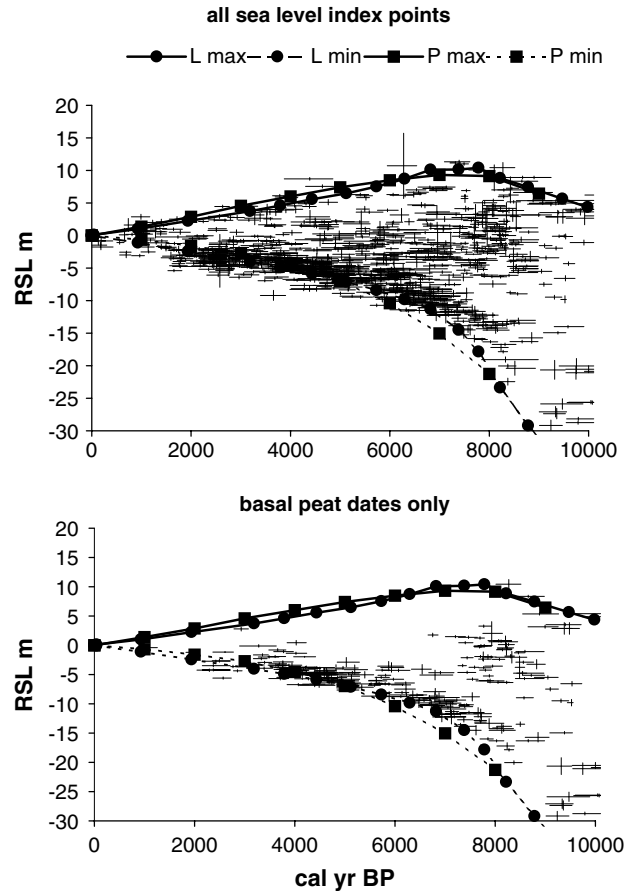
Figure 2.14: Plots of (a) all validated SLIPs and (b) SLIPs from basal peats, from 52 sites in Great Britain, for the past 10,000 years, compared with the ranges of relative sea-level changes from the models of Lambeck (1995) - L_{max} and L_{min}, and Peltier *et al.* (2002) - P_{max} and P_{min}. Reproduced from Shennan and Horton (2002) with permission from John Wiley and Sons.

where sediments are typically less than 50% organic by LOI and targets mechanical/physical compaction specifically.

By measuring LOI, particle size, moisture content, specific gravity, bulk density, voids ratio by Height of Solids and One-dimensional K_0 (zero lateral strain) compression of bulk samples from the upper 0.2m of the sediment column from various eco-sedimentological zones at three different UK sites Brain *et al.* (2012) showed that LOI, initial voids ratio and two derived compression indices covaried significantly with SWLI[3] and LOI, suggesting that organic matter content is important, and with high marsh sediments show to be the most compressible.

It is already well-known that organic sediment is more susceptible to compression than minerogenic sediment because high organic content generally means there has been growth of vascular plants which create well-aerated, highly porous sediment structures (Delaune *et al.*,

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[3]SWLI=Standardised Water Level Index; a measure to account for different tide ranges at the four sites. See Section 4.1.1 of Chapter 4 for a more detailed description.
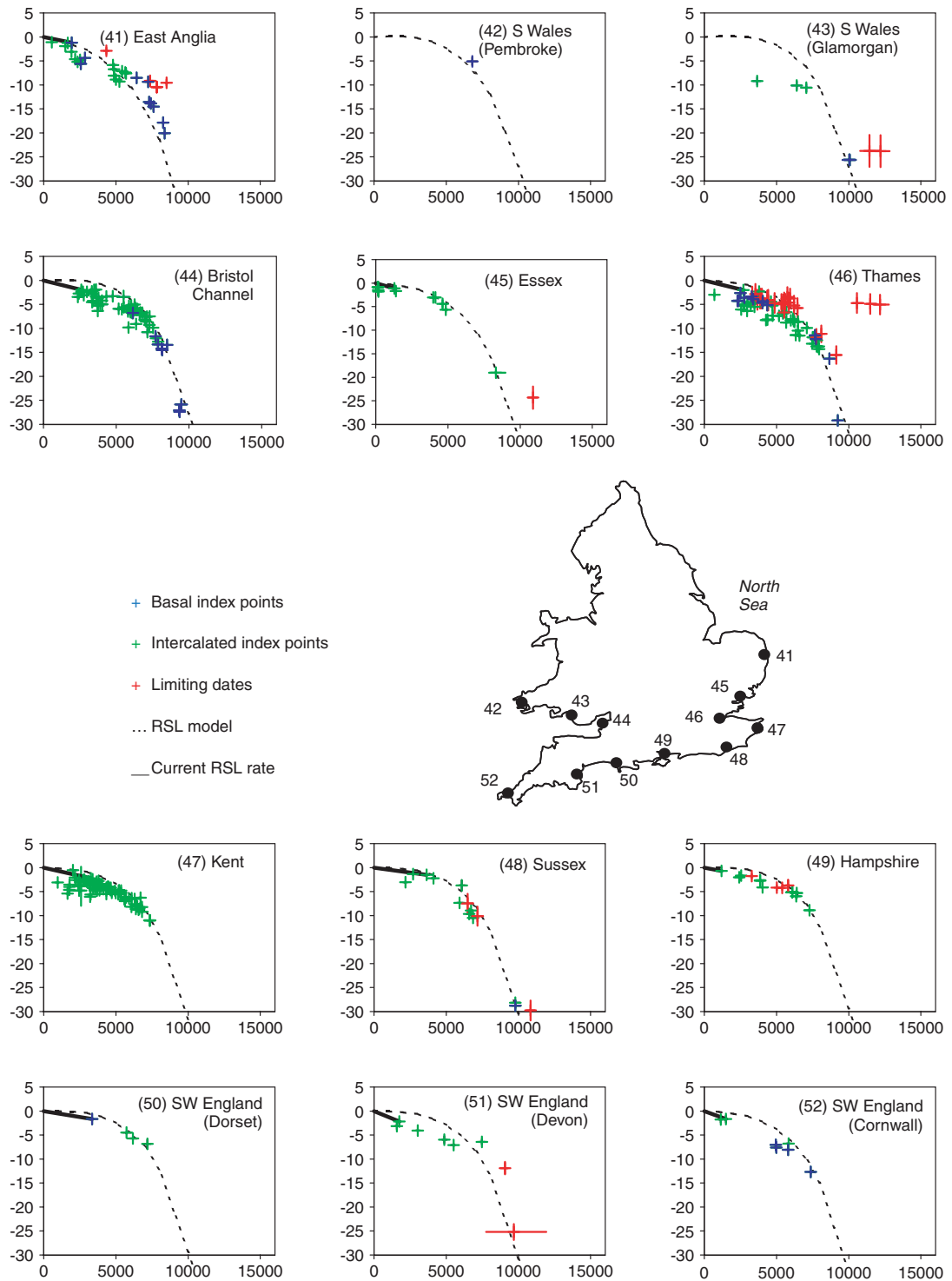
Figure 2.15: SLIPs for sites in southern England and Wales plotted as calibrated age against change in sea-level relative to present (m). The RSL model, shown by a dashed line in each graph, is from Peltier *et al.* (2002). Where available, horizontal and vertical cross hairs represent temporal and vertical uncertainty, but simple + symbols are used where these data are not available. Reproduced from Shennan and Horton (2002) with permission from John Wiley and Sons.

1994) and that the frictional drag on saltmarshes caused by vegetation creates more open micro-strucures (Leonard and Luther, 1995) compared to tidal flats (Burland, 1990).

However, by making a statistical link between variables that are already routinely measured in sea-level studies (SWLI and LOI) Brain *et al.* (2012) have demonstrated that in the future it may be possible to decompact intertidal sediments routinely in Holocene sea-level studies.

Models presented in Brain *et al.* (2012) decompact a set of synthetic stratigraphic successions and show that in the late Holocene/twentieth century compression has likely contributed to the sea-level acceleration observed in studies such as Gehrels *et al.* (2005) and Gehrels *et al.* (2002), but not been the sole cause of it. Brain *et al.* (2012) estimated that only subtle differences in lithology are prone to variations in twentieth century acceleration of 0.1-0.2mm/yr. Future research in this area will concentrate on more organic-rich saltmarshes and the role of processes other than sediment overburden, such as biodegradation which is known to be important in freshwater peats and delta environments but poorly understood in saltmarshes.

While there have been various attempts to 'decompact' Holocene sequences (Kaye and Barghoorn, 1964; Allen, 2000a; Haslett *et al.*, 1998; Paul and Barras, 1998), sea-level researchers are still without a well established, rigorous method of doing so. However, mechanical compression must be noted as a potentially significant source of vertical error for this study, particularly for thick, organic-rich sediments.

Horizontal sources of error are mainly related to dating methods. Depending on the time period studied, various radiometric and geochemical dating methods are available to researchers but this section will focus on radiocarbon dating as it the most relevant to Holocene sea-level research.

During sampling and radiocarbon dating there are chances for material to become contaminated with older or younger carbon. Such errors can be mitigated by laboratory pretreatments and careful sampling, but not eliminated entirely (Lowe and Walker, 1997). The radiocarbon dating technique itself has uncertainty associated with interpreting radioactive decay as an age. Additionally, radiocarbon ages have to be calibrated against a chronology of calendar years ('cal. years BP' where the present is taken to be 1950) to account for temporal variations in atmospheric ^{14}C during the Holocene (Lowe and Walker, 1997). The calibration curves used don't provide a one-to-one matching of ^{14}C years and cal. years BP, introducing more uncertainty. Finally, not all material can be dated, usually due to a combination of methodological and financial constraints, so researchers have to interpolate between dated samples, necessarily making assumptions about rates of deposition and the occurence

of between samples.

All of the issues described in this section are recognised as having some relevance to this study and have been quantified where possible.

2.8   Chapter Summary

This literature review has traced the developments in Holocene sea-level research in tide-dominated coastal environments from the early use of microscopic biological indicators in North America (Scott, 1976; Scott and Medioli, 1978, 1980, 1986), to the palaeoenvironment-led notion of establishing SLIPs formed of measurements of age, altitude, sea-level tendency, indicative meaning and indicative range (Shennan *et al.*, 1983) from the 1980s onwards (Gehrels *et al.*, 2006c; Haslett *et al.*, 1998; Selby and Smith, 2007), through to the increased use of quantitative approaches in the 1990s and the early 21st century (Gehrels *et al.*, 2006b; Zong and Horton, 1999). A number of philosophical and intellectual challenges emerge from this review, which inform the aims and objectives of this study.

The empiricist ontological perspective of scientific enquiry places value on evidence-based research, where observations and experiments are the primary routes to gaining knowledge. Empiricism states that there is a true, external reality than can be observed and measured and that all of our concepts are derived from sensory experience (Ladyman, 2002; Russell, 2004).

A particular challenge for palaeoenvironmental research is that the past is not directly accessible to us, and the external, objective reality that is available for study is the present day world in which only preserved evidence of past change can be observed. Combined with the study of present-day phenomena and their causes and interactions, archives of geological, sedimentary, archaeological and biological evidence may be used to study past environments, but not without at least some degree of reasoning, inference and interpretation.

In many other disciplines researchers will seek to conduct experiments in which some variables can be controlled while others are measured directly. In palaeoenvironmental studies researchers instead attempt to verify their findings using independent lines of evidence. However, caution is generally required due to the difficulty in having certainty that the scenario described to explain the existence and nature of the evidence observed is the correct, or indeed only, interpretation. Even when two or more distinct lines of evidence are used to infer changes in the palaeoenvironment, certain assumptions are inevitably made about the independence of such observations.

In addressing an opportunity to extend the current methodology used in Holocene sea-level studies and exploring the benefits of employing multi-proxy quantitative techniques, this study also employs such a verification method, whereby separate lines of enquiry (sedimentological and biological, with more than one tidal proxy) are considered both separately and together in order to gain assurance that any particular scenario is a likely or unlikely explanation for the palaeoenvironmental evidence observed. In doing so the question of whether the additional time spent using different types of evidence, and in particular in using multiple biological sea-level proxies, is justified based on the benefits gained from doing so, can also be addressed.

The literature review has identified that little research into sea-level indicators has taken place in macrotidal settings such as that of the Severn Estuary (Horton and Edwards, 2000; Hill *et al.*, 2007; Mills *et al.*, 2013) where it is more difficult to constrain sea-level variability due to the larger vertical ranges of intertidal habitats and species tolerances. Gehrels *et al.* (2001) have shown that using more than one biological sea-level proxy can improve model precision and accuracy in mesotidal environments and this study attempts to show whether this holds true in a severely macrotidal setting, before going on to actually apply an optimised transfer function to fossil data from the Steart Peninsula.

Finally, the issue of reliably establishing good modern analogues for fossil samples was identified in this chapter. Some researchers do routinely address this issue, but not all. The methodological approach, presented and discussed in Chapter 4 (Methodology) includes an attempt to optimise the modern sampling in order to find good modern analogues for the fossil assemblages, and also address analytical issues around combining the data from two different proxies, measured in different ways, together. The results and subsequent discussion will explicitly state where good modern analogues were and were not available and explore what affect this may have on the interpretative value of those results.

The next chapter explores the literature on Holocene environmental and sea-level changes in the Somerset Levels region and identifies the ways in which quantitative analysis of sea-level indicators in the Bridgwater Bay and wider Severn Estuary regions, and the development of a new multi-proxy sea-level transfer function for the region, may contribute to our understanding of Holocene sea-level change in the region.

The Holocene Environmental History

of the Somerset Levels

3.1 The Somerset Levels

The area known as the Somerset Levels and Moors is an extensive system of buried valleys in the southwest of England (Williams and Williams, 1992). The buried valleys cover an area of approximately 650km^2 and are infilled with Holocene and earlier Quaternary sediments (Kidson and Heyworth, 1976). Numerous islands of sand and rock protrude from the low-lying moors (Coles and Orme, 1982), such as the Jurassic Blue Lias inlier Brent Knoll (English Nature, 1997).

The Moors are composed of very low-lying fen peats and raised peats that are often observed at the ground surface, but are overlain in some places by fluvial silts and clays (Williams and Williams, 1992). The levels lie to the west of the moors alongside the coast of the Bristol Channel and Severn Estuary, forming an eight to ten kilometre-wide belt of marine and estuarine clay, intercalated in places with peats. While the elevation of the Moors is around 3-5m OD, the The Levels are raised slightly above the Moors, with a typical altitude of 5-6m OD (Bryant and Haslett, 2004). The Quaternary sediments overlie a bedrock of Jurassic and Triassic ages, most commonly the Triassic Mercia Mudstone (formerly referred to as Keuper Marl), a calcareous clay deposited around 240 million years ago (Ruffell, 1990).

The Somerset Levels coast has been shaped by geomorphological processes since the Cretaceous period but more recently Quaternary processes such as fluvial incision, periglaciation and marine erosion have sculpted the landscape onto and into which Holocene marine and fluvial sediments are deposited (Case, 2013).

The Somerset Levels and Moors are bordered by the Mid Somerset Hills and the Mendip Hills to the east, the Avon Valleys and Ridges to the north and the Quantock Hills to the

southwest. To the west and northwest the Levels border the Severn Estuary and the Bristol Channel. The Somerset Levels form part of the broader system of levels that border the Severn Estuary, and are geographically distinct from the North Somerset Levels, located inland from Weston-super-Mare, the Avon Levels to the northeast of the Gordano Valley, and the Gwent Levels that border the opposite side of the Severn Estuary in south Wales (Figure 3.1). The estuary itself is extremely macrotidal and the sediment supply from the river catchments in the region is abundant (Allen, 2000b).
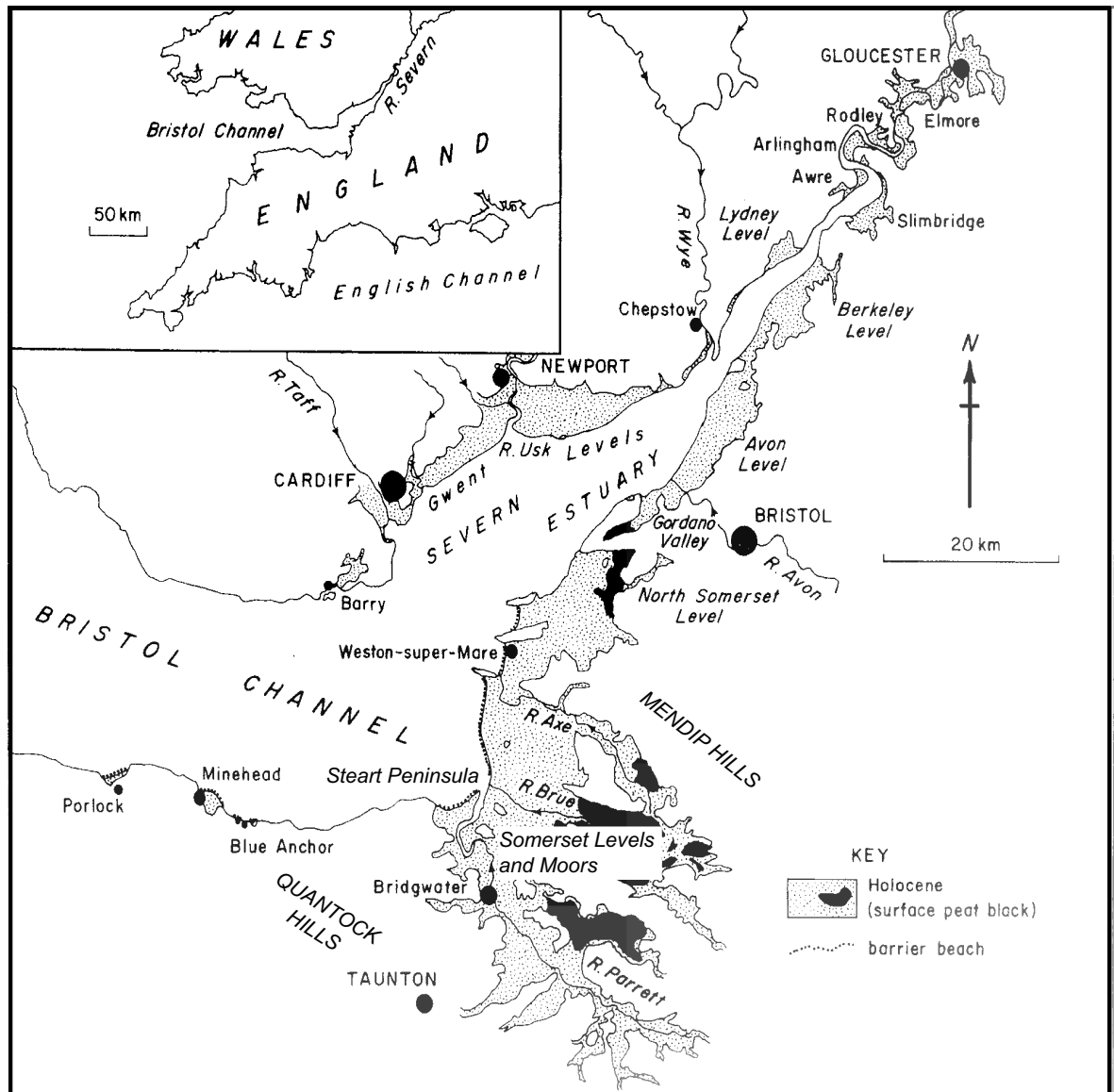
Figure 3.1: The Severn Estuary Levels, rivers and key settlements. Adapted from Allen and Haslett (2002) with permission from SAGE Publications.

At present the major land uses of the Somerset Levels and Moors include livestock and arable farming, orchards, tourism, recreation, floodwater storage and urban development (English Nature, 1997). Since the Roman Period peat has been extracted for burning as fuel. This practise occurred intensively until the 1990s, but now only takes place on a much

smaller scale in some parts of the Brue Valley (Natural England, 2012b), and is now more prominent in the making of composts than burning as fuel (Williams and Williams, 1992).

Due to the low elevation of the Levels and Moors, much of the area is prone to river flooding in winter as well as occassional marine inundation (Williams, 1970). Frequent flooding of the six main rivers (Kenn, Yeo, Axe, Brue, Parrett and Tone) has resulted in the formation of natural silt levees which ordinarily contain the rivers' flow, but are overtopped during periods of particularly high discharge (Williams, 1970).

During the Devensian glaciation (MIS 2), the most recent glacial period, ice sheets extended over large parts of Europe, including the British Isles. However, the southwest peninsula lay outside of the extent of ice cover for the majority of the Devensian (Bowen *et al.*, 2002) (see Figure 3.2). The area now known as the Somerset Levels and Moors therefore experienced mainly periglacial conditions and "head" deposits are widespread around the coast (Kidson, 1971), for example at Stolford, and often observed at exposed sections.

During more distant glacial periods the Somerset Levels were glaciated, most extensively around 620,000 years BP in MIS 15 (Hawkins and Kellaway, 1971; Hunt and Haslett, 2006). Some debate has arisen surrounding the possibility of glaciers and small ice caps during MIS 2 on Dartmoor and Exmoor, to the south west and west of the Somerset Levels respectively (Evans *et al.*, 2012, 2013; Straw, 2013). However, it is thought that if glaciation in the south west did occur during the last glacial, it is likely to have been only very localised on these uplands, and the consensus remains that the Somerset Levels were not under ice during MIS2(Bowen, 2005).

Evidence exists in the Somerset Levels and Moors for sea-level lowstands and highstands associated with the expansion and contraction of ice sheets during the Quaternary. Evidence for sea-levels lower than present MSL includes the drowned river channels and submerged forests, while high sea-levels are evidenced in the form of raised beaches and higher level erosion surfaces (Kidson, 1971). Mentioned previously in section 2.3 (Chapter 2), the MIS 7-age shelly marine sands and gravels found near Middlezoy and Kenn, known as the Burtle Formation or more formally the Kenn Church Member (Campbell *et al.*, 1999), are considered by geologists to be Pleistocene features of great importance. The typesite at Greylake was designated as a Site of Special Scientific Interest (SSSI) in 1987 (English Nature, 1997).

3.2 Holocene evolution of the moors

Following the onset of the global ice thaw at the end of the Pleistocene, the river valleys in the Somerset Levels and Moors were flooded by sea water and subsequently infilled with clays
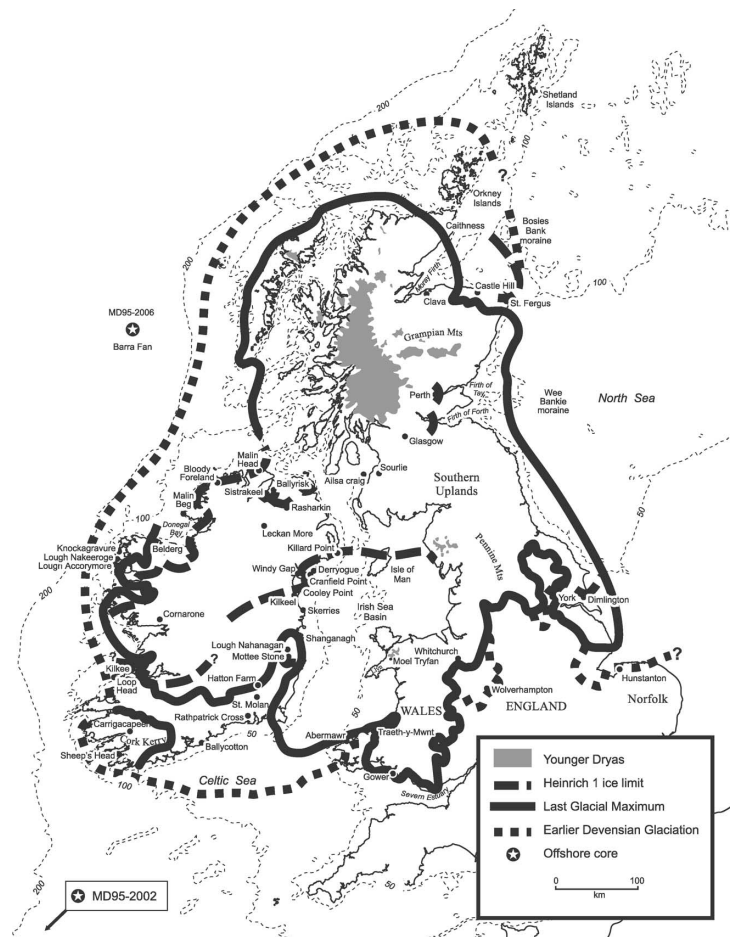
Figure 3.2: The extent of ice cover in the British Isles during the Devensian glacial. Reproduced from Bowen *et al.* (2002) with permission from Elsevier.

over a period of about five thousand years. *Betula* (birch) had begun to colonise the valley floors following climatic amelioration at the start of the Holocene, but once the rising sea-level reached the bottom of the valleys, water logging and peat formation prevented forests from becoming fully established (Kidson and Heyworth, 1976). Soft blue-grey estuarine clay therefore forms a base upon which the general pattern of succession from fen, to fenwood, to raised bog has developed on the Moors (Clapham and Godwin, 1948; Godwin, 1948; Dewar and Godwin, 1963).

The foundations of our understanding of environmental and vegetation change research in the Somerset Levels and Moors were laid down by the late Professor Sir Harold Godwin in the 1940s and 1950s (Godwin, 1941, 1948, 1955a,b). However, radiocarbon dating was only in the early stages of development at this time, so much of Godwin's work relies on dating by vegetation zones and human artefacts (Godwin, 1941, 1955b). Based on pollen analysis of samples from peat cores, Godwin (1941) describes the environmental history of the ombrotrophic bogs at Shapwick Heath, Meare Heath and Sharpham Heath. He highlights a sharp division between a lower, well humified *Sphagnum-Calluna-Eriophorum* (Sphagnum

moss-heather-cottongrass) peat that developed during the alder-mixed oak forest stage, overlain by a fresh *Sphagnum-Molinia* (Sphagnum moss-moor grass) peat that developed during vegetation zone VIII, when *Betula* increased and *Tilia* (lime) disappeared, regionally. Within the upper peat Godwin (1955b) also described two flooding events, typified by the growth of *Cladium* (fen-sedge) peat. Clapham and Godwin (1948) surmised that these flooding events were caused by calcareous water draining off the higher land of the Mendip and Polden Hills and flooding the bog surface.

Some two decades later, Beckett and Hibbert (1979) provided a chronology for the sequences and events described by Godwin. Based on correlations between sequences at three sites, Beckett and Hibbert (1979) deduced that the clay-fen peat interface occurred around 6,000 to 5,500 years BP. Coles (1978) suggests that the development of coastal dunes provided a seaward barrier, sealing the areas behind off from the influence of the sea, creating the reed swamp environment characterised by *Phragmites* (common reed). This freshwater fen gave way to fen woodland around 5,404-5,490 years BP or earlier across the three sites, depositing wood peat over the top of the herbaceous peat. Water levels would have been lower at this point, the fen woodland characterised by *Betula* and *Alnus* (alder) (Beckett and Hibbert, 1979). On top of this, the *Sphagnum* peat, reflected by the appearance of *Calluna* and *Eriophorum*, began to develop around 4,000 years BP (Birks and Birks, 1980). Coles (1978) suggests that rainfall may have increased around this time, providing the ideal conditions for raised bogs, that develop under the direct influence of local precipitation and evaporation. In particular, the Brue Valley was a site of major raised bog development at this time.

The two flooding episodes described by Clapham and Godwin (1948), characterised by occurrencess of *Cladium* peat, were dated to 2,544-2,854 years BP and 1,924-1,904 years BP by Beckett and Hibbert (1979). Clapham and Godwin (1948) had originally estimated these events to have taken place around 500-600 BC and AD 150 respectively, and the radiocarbon dates corroborate the original interpretation. Around AD 400 annual rainfall reduced, and along with drainage and land reclamation (see Section 3.4), contributed to the end of raised bog growth in the Somerset Moors (English Nature, 1997).

3.3 Holocene stratigraphy of the Somerset Levels

The Somerset Levels cover the region within 8km of the coast where the low moor fen peats are sandwiched stratigraphically between a lower blue-grey clay unit and an upper coastal

clay belt. Current understanding of the Holocene development of the Somerset Moors is generally greater than our knowledge of the Holocene history of the Levels.

The broad Holocene stratigraphic sequence seen throughout the fringes of the Severn Estuary was described by Allen (1987) and Allen and Rae (1987) as the Wentlooge Formation, after its typesite, the Wentlooge Level in South Wales.

The lower Wentlooge Formation is a unit of fine blue-grey silty clays, sitting above a base of bedrock, Quaternary gravels and head deposits, and traces of early Holocene soil and peat (Bell and Neumann, 1997; Bridle, 2012). The middle Wentlooge Formation consists of intercalated peats, organic rich beds and sandy to clayey silts (Allen and Pye, 1992). With distance inland from the estuary the organic units thicken and represent the various facies found on the Somerset Moors such as reedswamp and raised bog (Coles and Coles, 1986). The upper Wentlooge Formation sees the return to bluish to greenish grey sandy to clayey estuarine silts and very occassional thin peats (Allen, 2004).

Marsh reclamation, leading to the construction of sea defences and drainage systems during the past two thousand years, has resulted in a halting of the upper Wentlooge Formation development in all but a few locations (Allen and Scaife, 2010), and since then the Rumney, Awre and Northwick Formations have developed from the 17th, 19th and 20th centuries respectively (French, 1996). Figure 3.3 gives a schematic representation of the four marsh units. As the accretion of these three recent coastal formations parallels urban and industrial growth, the marsh sediments contain evidence of metal pollution and human artefacts, as well as being ideal for some radiometric dating techniques (French, 1996). These three younger formations are on the seaward side of the sea defences and are thus restricted to the coastal margins and estuarine fringes (Allen and Scaife, 2010).

Campbell *et al.* (1999) describe the Somerset Levels Formation (SLF) which is equivalent to the Wentlooge Formation for the Somerset Levels. Haslett *et al.* (2001a) then divide the sequence into the Lower, Middle and Upper SLFs. The lower SLF, of dark blue-grey silty clays, reflects the marine sedimentation that occurred due to rapid sea-level rise at the start of the Holocene. The Middle SLF peat accumulation resulted from the rate of sea-level rise falling to a level that was outpaced by organic sedimentation during parts of the mid-Holocene[1] (Allen, 1990b). The Upper SLF silt layer then signals a further marine transgressive sequence (Haslett *et al.*, 2000). The SLF is summarised in Table 3.1.

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[1]Any reference to the early-, mid- and late-Holocene in relation to the sequence stratigraphy of the Severn Estuary region is based on other authors' interpretations of sedimentary changes or boundaries, and not on any proposal to formally sub-divide the Holocene into stages, such as that of Walker *et al.* (2012) to sub-divide the Holocene based on significant climate events at 8,200 years BP and 4,200 years BP.

Table 3.1: Description of the Wentlooge and Somerset Levels Formations. Author's own.

	Wentlooge Formation, Severn Estuary (Allen and Rae, 1987)	**Somerset Levels Formation** (Campbell *et al.*, 1999) (Haslett *et al.*, 2001a)	**Sediment description** (Allen and Rae, 1987)
Late-Holocene	Upper Wentlooge Formation, 2,500 years BP onwards	Upper Somerset Levels Formation	Late Holocene period of further deposition of thick greenish grey marine, estuarine and fluvial silty clay, sometimes grading into green-brown mottled silts.
Mid-Holocene	Middle Wentlooge Formation, 6,500–2,800 years BP	Middle Somerset Levels Formation	Intercalated peats and greenish-grey sandy to clayey silts reflecting mid-Holocene decrease in the rate of sea-level rise.
Early-Holocene	Lower Wentlooge Formation, 7,500–6,500 years BP	Lower Somerset Levels Formation	Pale grey-green estuarine silty clays deposited during the early Holocene phase of rapidly rising sea-level. Basal peat resting on pre-Holocene basement (such as Pleistocene head), deposited prior to marine inundation. Peat and/or Pleistocene sediments sometimes absent.
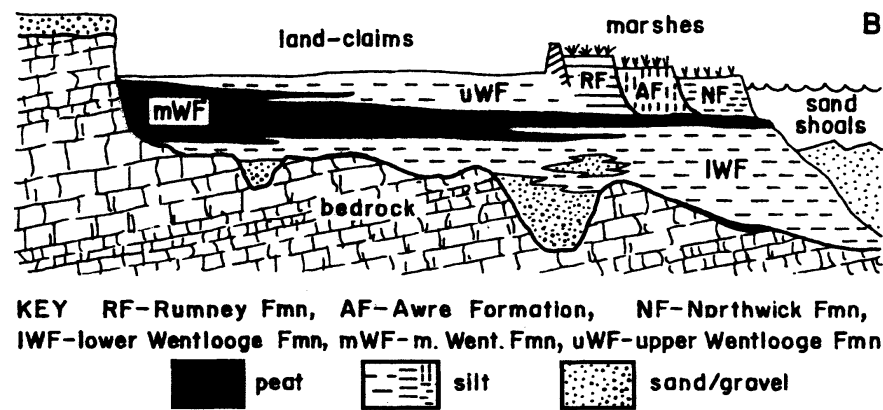
Figure 3.3: Cross section showing the typical morphology of the four marsh units in the Severn Estuary. Adapted from Allen (2004) with permission from SAGE Publicatinos.

3.4 Human occupation and the draining of the Somerset Levels and Moors

The arrival of the first farmers to the Somerset Moors can be dated to around 6,500 years BP, during the Neolithic, with evidence for deforestation represented by the regional vegetation in the pollen record (Kidson and Heyworth, 1976). In fact, several episodes of forest clearance can be seen in the pollen record through the Neolithic, Bronze Age and later. Each period of deforestation can be identified from a decline in the *Ulmus* (elm) and *Tilia* (lime) pollen and an increase in herbs and cereals (Beckett and Hibbert, 1979; Coles and Orme, 1982). By 6,000 years BP farming communities became established (Coles and Orme, 1982).

During the Neolithic early settlers to the Moors constructed wooden trackways on top of the fen wood peat, to allow them to traverse the waterlogged land (Birks and Birks, 1980). The trackways, made with posts of *Corylus* (hazel) and planks of *Fraxinus* (ash) and *Tilia* (Coles and Orme, 1982), were confirmed by radiocarbon dating to have been built between 4,800 and 4,000 years BP. This first period of track building coincides with the decline in *Ulmus*, dated around 5,000 years BP (Beckett and Hibbert, 1979), and the tracks were eventually buried by the humified bog peat that occurs directly above the fen wood peat (Birks and Birks, 1980).

A second phase of track building occurred in the Bronze Age, between 2,900 and 2,500 years BP, when surface wetness increased again. Parts of these upper tracks, built mainly from split *Quercus* (oak) trunks and pegs made from *Corylus*, *Alnus* (alder), *Ulmus*, *Fraxinus* and *Ilex* (holly) (Coles and Orme, 1982), are preserved in the fresh *Sphagnum* and *Cladium* peats that eventually submerged them (Birks and Birks, 1980). It is thought that flooding on the moors eventually became so severe, in magnitude and length during the year, that transportation by boat would have been easier to achieve (Coles, 1978), and indeed the remains of a boat, dated to the Iron Age, have been found at Shapwick (Birks and Birks,

1980).

During these times of widespread flooding a sharp decline in agricultural species such as cereals and their associated weeds can be recongnised in the pollen record (Godwin, 1955a). Around the time that the later trackways were being constructed, the two major early Iron Age settlements, the Meare and Glastonbury Lake Villages, were established (Brown, 2006). It is understood that rather than attempting to improve their environment by draining the land, the settlers here built timber huts on top of bracken and clay-filled wooden rafts in the marsh (Godwin, 1955b). However, these settlements were eventually abandoned around 2,050 years BP when the calcareous run-off waters flooded the land, causing the *Cladium* sedge fen development and increased wetness (Williams, 1970). No further human activity is recorded until the Roman reclamation of parts of the Somerset Levels and Moors, dated to 1,776 ± 46 years BP (AD 130-221) by Haslett *et al.* (1998). The Roman settlers occupied both the moors and the coastal clay Levels, but only sparsely, preferring the higher ground surrounding the Levels and Moors (Williams, 1970).

It is belived that the Romans made some attempts to drain the land, but records of widespread drainage begin in the 11th century, according to the Domesday Book (Williams and Williams, 1992). In the 12th century the early Celtic Christian monks of Glastonbury, Athelney and Muchelney began to drain the land around their monasteries (Williams, 1970). In the 13th century walls were built along parts of the River Parrett (Williams and Williams, 1992) and from this time onwards the levels and moors were progressively drained via narrow, artificial channels, known locally as "rhynes". From the 19th century the water was pumped by windmills and steam powered engines (Williams, 1970); now automatic electric pumps are used (Dunning, 2012). The rhynes are often also used as alternatives to hedgerows to demarcate field boundaries (Williams, 1970).

While storm surges and other exceptionally high tides have caused some short-lived flooding, when the clay belt has been overtopped, the tidal estuarine waters cause greater problems when fluvial water becomes backed up in the rivers during high tides in the estuaries. To ameleorate this type of flooding tidal sluices were constructed at the River Brue around 1485, King's Sedgemoor Drain in 1791, the River Axe in 1806 and the artificial Huntspill channel in 1944 (Williams, 1970). The River Parrett is still open to the tide and a combination of the large tidal range and the confined banks cause a small tidal bore to move up the river at each tide (Williams and Williams, 1992).

A high energy event documented in historical records on 30 January 1607 resulted in 2,000 recorded deaths as sea-water from the Severn Estuary inundated up to 22km inland from the

coast in some places (Bryant and Haslett, 2004, 2007). Sheets of sand appear in the Rumney Formation near Cardiff that coincide with this event, which Bryant and Haslett (2004), Bryant and Haslett (2007) and Haslett and Bryant (2004) attribute to a localised tsunami, based on descriptions of the event and its impacts. The tide was said to be low prior to the inundation, likened by Haslett and Bryant (2004) to the drawing back of the water before a tsunami, and that the event may have occurred during fair weather (Bryant and Haslett, 2004). Documentation of an earth tremor off the southern coast of Ireland contributes to the evidence for a possible tsunami, though this claim is disputed by researchers who argue that the east coast of England experienced similar flooding on the same day, suggesting a meteorological origin, and that a simulation of the event indicates a storm surge due to a southward displacement of the jet stream (Horsborough and Horritt, 2006).

3.5 Holocene sea-level change in the Somerset Levels and Severn Estuary

Early work by Hawkins (1971a,b) examines the Holocene sea-level history of the southwest of England. From bore holes drilled into the sediments of buried valleys in the southwest, including 18 sites in the Severn Estuary-Bristol Channel region, Hawkins (1971a) compiled a sea-level curve based on the depths of peat horizons. Hawkins (1971a) highlights the issue of sediment consolidation by drawing the sea-level curve through the lowest points where dated horizons closely overlie bedrock and points that represent the base of a peat horizon (Figure 3.4). The general shape of the curve indicates rapid sea-level rise between 9,000 years BP and 7,000 years BP, followed by a steady levelling off in the rate of relative sea-level rise to the present day. Hawkins (1971b) estimates that the mean rate of relative sea-level rise was 20mm per year in the early Holocene, dropping to 7mm per year between ~7,500 and 5,000 years BP, and gradually reducing to 1.2mm per year by the modern era. Hawkins' work (Hawkins, 1971a,b) did not include any micropalaeontolgical or palynological analysis of the peat horizons used as proxies for past MHWST.

In addition to his work on the ecological and environmental history of the Somerset Levels and Moors, Godwin also drew some conclusions about the Holocene sea-level history of the region (Godwin, 1943, 1948, 1955b, 1961). In particular, Godwin (1948) refers to evidence for a significant marine transgression during the Roman occupation that was implicit in the deposition of the coastal marine clay belt. Godwin (1948) bases this theory on the existence of Roman artefacts both above and below the clay belt, thus constraining it historically. Godwin (1955b) later estimated that the trangression occurred in the third century AD.

H.W.S.T.
Feet

Metres

-10

-20

-30

-40

-50

-60

-70

-80

-90

-100

-110

-120

-130

-140

-5

-10

-15

-20

-25

-30

-35

-40

-45

Co

A ·P
K ·I
·A A
·R
A P ·A W ·I KP
EB· ·A Pi
B·· MB·B· ·EB
FW T SH H I K W· ·A KP KP ·S
WH KT ·C K EB· ·A K
·S M·C·M ·KP ·M
M ·KP ·A
·S ·R
·A
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GB· ·S
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EB· ·S
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To

·K

PT ·PT ·PT ·PT

To
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To

To

To

To

A	AVONMOUTH
B	BREAN
Bu	BURNHAM
C	CLEVEDON
Co	COMBWICH
D	DUNBALL
EB	EAST BRENT
FW	FRESHWATER WEST
GB	GRAVEL BANKS
H	HIGHBRIDGE
I	I.C.I. SEVERNSIDE
K	KINGSTON SEYMOUR
KP	KENN PIER
M	MARGAM
MB	MOUNTS BAY
P	PORTBURY
Pi	PILNING
PT	PORT TALBOT
R	R.T.B. LLANWERN
S	STOLFORD
SH	SHAPWICK HEATH
T	TEALHAM MOOR
Tn	TEIGNMOUTH
To	TORBAY
W	WESTON-SUPER-MARE
WH	WESTWARD HO
—	POLLEN ANALYSIS

11   10   9   8   7   6   5   4   3   2   1   ,000 Yrs BP

| I | II | III | IV | V | a | b | c | | VIIa | | VIIb | | VIII | Pollen Zones |

LATE WEICHSELIAN   PRE-   B O R E A L   A T L A N T I C   S U B - B O R E A L   S U B - A T L A N T I C

Figure 3.4: Height/age Holocene sea-level curve for South West England. From Hawkins (1971a). Reproduced with kind permission from the author.

Research from the decades that followed revealed some strong evidence against Godwin's theory, with several researchers cautiously accepting the possibility of a Roman age for the coastal clay belt, but concluding that it has only regional significance and does not represent a wider, eustatic rapid rate of sea-level rise in the late Holocene (Hawkins, 1969, 1971a,b; Kidson and Heyworth, 1976).

Hawkins (1969) confirms that Roman remains can be found in the eastern Bristol Channel region both ~4m below the present surface and very close to the surface, but offers the possibilities of a break through of a coastal barrier, or a rapid phase of easterly tilting of the British Isles as alternatives to a sudden eustatic rise as a potential explanations. Hawkins (1971a) examines the concept of a sudden marine transgression during the Roman occupation and notes a number of inconsistencies, including the use of Roman evidence found on the foreshore where no depth or stratigraphic relationships can be reliably interpreted, the lack of existence of any 3rd or 4th century marine transgression elsewhere in the world and the absence of evidence for a buried soil horizon and therefore of the cultivation of the Levels by the Romans (Cunliffe, 1966).

In a separate publication Hawkins (1971b) acknowledges the evidence for the Roman habitation and cultivation of the Levels, but also recognises that a sudden marine transgression is unlikely, given that the upper clay is limited in south west England to the Gwent Levels, the Severnside Vale, the Gordano Valley and the Somerset Levels.

Hawkins (1971a) offer an alternative explanation for the presence of Roman artefacts at depths of up to 4 metres beneath those that were found buried closer to the surface, suggesting that those deeper remains may be items that were discarded or transported into tidal creeks rather than onto the more elevated ancient surfaces either side of them. Hawkins (1971a) cites work by Barnett (1961, p. 12), who recorded that artefacts were "grouped closely together ...embedded in glutinous estuarine clay ..." as evidence that the clay belt may have been deposited over a far longer period of time than the sudden transgression event that was proposed by Godwin (1943).

Based on the depth of radiocarbon-dated peat horizons from various locations throughout the Bristol Channel region, including the Somerset Levels and Moors, Kidson and Heyworth (1976) present a sea-level curve for the Holocene, showing sea-level rising rapidly from the start of the Holocene to ~5,500 years BP, when the rate began to level off. Kidson and Heyworth (1976) suggest that the rate of sea-level rise dropped considerably around 4,000 years BP, with little appreciable rise since then (see Figure 3.5).

While the Kidson and Heyworth (1976) curve presents a similar sea-level history to

Hawkins (1971a) for the latter 8,500 years of the Holocene, there are two main differences between Figures 3.4 and 3.5. First, the Kidson and Heyworth (1976) curve estimates that MSL is generally higher throughout than estimated by Hawkins (1971a). A difference of roughly 2m is apparent consistently between ~8,000 and ~4,000 years BP. Second, the Kidson and Heyworth (1976) curve levels off to a lower rate of change earlier than the Hawkins (1971a) curve, such that the Hawkins (1971a) curve is the steeper during years 4,000 BP to present.
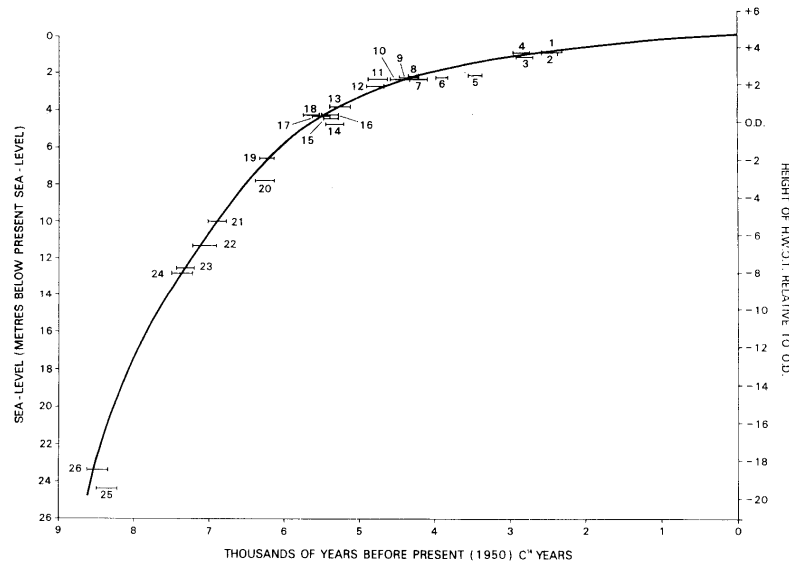
Figure 3.5: Holocene sea-level rise in the Bristol Channel, from Kidson and Heyworth (1976). Dates are in ^{14}C years. Reproduced with permission from The Geological Society of London.

Haslett *et al.* (1998) evaluate the Kidson and Heyworth (1976) curve and put forward three main criticisms. They argue that the effect of sediment compaction is underestimated, that sea-level tendency is not established and that undue emphasis is placed on age-altitude data derived from peats with uncertain relationships with sea-level. Because Kidson and Heyworth (1976) do not establish the sea-level tendency, indicative meaning or indicative range of their peat layers, true SLIPs are not derived. Haslett *et al.* (1997) stress the importance of determining these parameters, along with age and altitude.

Many of the peat horizons used by Kidson and Heyworth (1976) were taken from within peat layers that were considered by Coles and Orme (1982) to be of raised bog origin, and to have tenuous relationships with sea-level. The Kidson and Heyworth (1976) sea-level curve for the Bristol Channel region therefore represents peat accumulation, which may not have a direct relationship with sea-level (Haslett *et al.*, 1998).

In a later paper on Holocene sea-level change in the southwest of England and in Wales, that includes eleven SLIPs from the Severn Estuary region, Heyworth and Kidson (1982) discuss the issue of the relationship between water-table and sea-level as a potential source

of error. They conclude that radiocarbon dates should be taken from horizons that represent the lowest limit of freshwater conditions. However, the authors do not make it clear whether this condition applies to the SLIPs presented in the study, nor whether they underwent any microfossil or pollen analysis to establish the peats' relationships with former MSL.

Allen (2000c) proposes that the Kidson and Heyworth (1976) curve is a misleading representation of Holocene sea-level change in the Severn Estuary region because it is smooth, masking the possible existence of several fluctuations in the sea-level record, and with local factors superimposed onto the regional trend. He argues that across the region the presence of several peat layers in the coastal stratigraphy, intercalated with clays and silts, may reflect oscillations in MSL of a few decimetres to one or two metres, over a centennial timescale.

Shennan and Horton (2002) present a comprehensive sea-level curve for the Bristol Channel (see Figure 3.6) composed of 70 SLIPs from Haslett *et al.* (1998, 2001a), Heyworth and Kidson (1982), Jennings *et al.* (1998) and Smith and Morgan (1989). The majority of the data points are from intercalated peats and the most recent of the nine basal SLIPs is dated to ~7,000 years BP. Figure 3.6 shows that the basal SLIPs fit close to the RSL model curve, whereas the majority of the intercalated points sit beneath the RSL model for the UK (Peltier *et al.*, 2002), suggesting that there is a tendency for intercalated index points to overestimate the rate of change in the long term. None of the SLIPs for the Bristol Channel curve have been designated by Shennan and Horton (2002) as limiting dates (as discussed in Section 2.4 of the previous chapter), despite the aforementioned uncertain relationship between some of the original sampled horizons and sea-level in Kidson and Heyworth (1976).

The apparent long term rate of sea-level rise, since 4,000 years BP, based on the data presented in Shennan and Horton (2002), is 1.06 ± 0.08mm/yr. With an attempt at allowing for sediment autocompaction they give the best estimate of relative sea-level rise in the Bristol Channel as 0.8mm/yr for the last 4,000 years. This figure is comparable to the relative sea-level rise in the South East and East Anglia, and slightly lower than the best estimate for Devon and Cornwall, over the same time period, according to the summary land-/sea-level changes map of Shennan and Horton (2002) (Figure 3.7). Numerical estimates of late Holocene vertical land-/sea-level change in the south west are supported by data from only a small number of sites. While these values of -0.8mm of relative vertical land movement per year for the Bristol Channel, -0.5mm per year for west Wales and -1.0mm per year for Devon and Cornwall are based on the rigorous assessment of many SLIPs, the spatial resolution of data points for the east and west coasts of northern England and Scotland is higher. Relative Holocene sea-level change across the Severn Estuary/Bristol Channel region may be more

variable, in reality, than the implied rate of 0.8mm/yr given by Shennan and Horton (2002) for that whole region.

The second aim of this thesis, which is to reconstruct Holocene sea-level at the Steart Peninsula, will contribute an additional late-Holocene relative land-/sea-level rate to the records for the region.

Table 3.2 summarises the SLIPs established in previous research for the Severn Estuary region, highlighting those that include biostratigraphic analysis to estimate indicative meaning, basal versus non-basal SLIPs and those which establish an associated sea-level tendency.
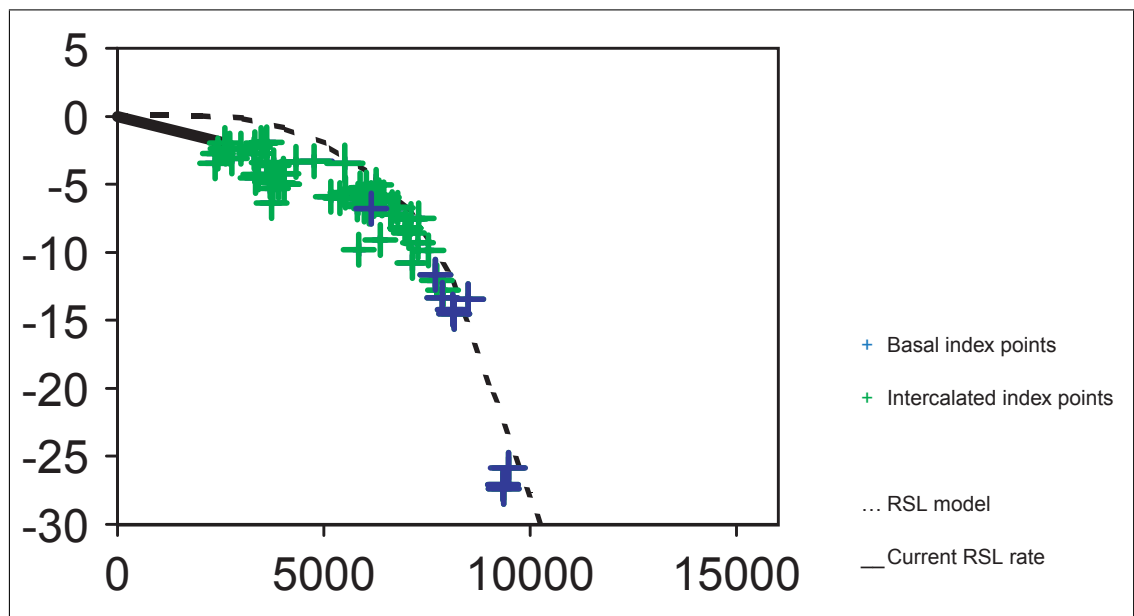
Figure 3.6: 70 SLIPs for the Bristol Channel region plotted as calibrated age (years BP) on the horizontal axis, against change in sea-level relative to present (m) on the vertical axis. The dashed line shows the predicted relative sea-level from Peltier *et al.* (2002). Adapted from Shennan and Horton (2002) with permission from John Wiley and Sons.

Basal peats are rare in the Somerset Levels and Moors, but Kidson and Heyworth (1976) used the frequent occurrence of peat beds lapping onto bedrock in the area around Stolford near the Steart Peninsula in their study of sea-level in the Somerset Levels (see Section 3.7.1), and Haslett *et al.* (1998) was able to exploit the solid geology at Nyland Hill to take a transect of cores, all with basal peat layers (see Figure 3.8). Across the transect of 11 cores Haslett *et al.* (1998) used radiocarbon dating of the basal peat and the variation in diatoms, pollen and foraminifera to give three SLIPs, showing that between 3,330 and 3,725 years BP, MHWST was 4.64m OD. Given that MHWST at Hinkley Point is 5.93m OD, the results from the Haslett *et al.* (1998) study suggest that MSL at this time was -1.29 OD. This estimate agrees more closely with Kidson and Heyworth (1976) than with Hawkins (1971a). However, the authors do note that it may be erroneous to assign MHWST an altitude due to the distance
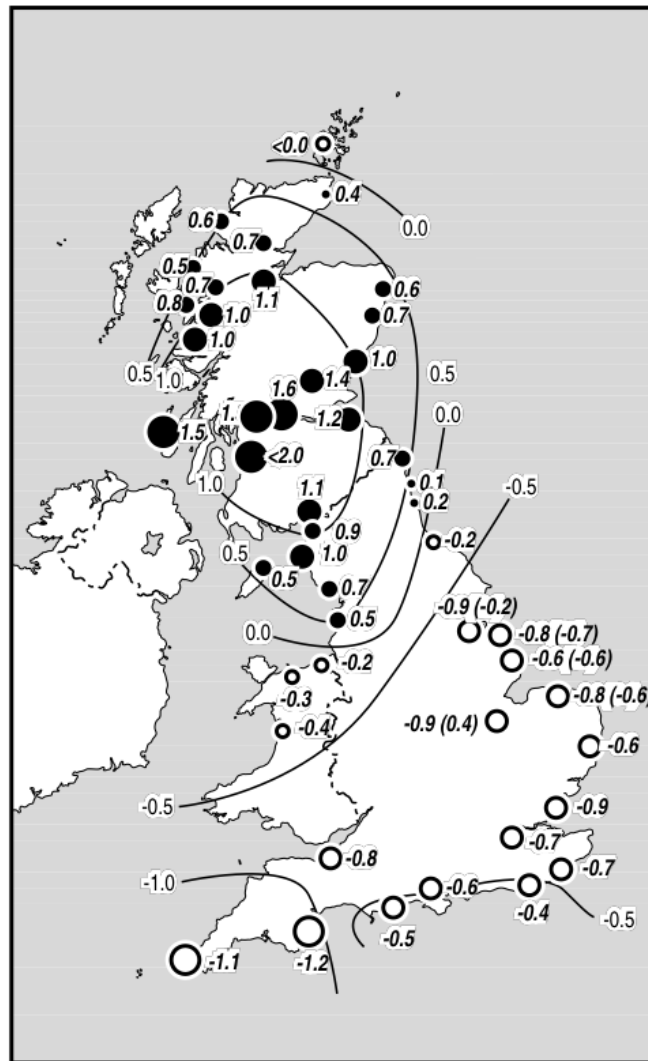
Figure 3.7: Late Holocene relative land-/sea-level changes in Great Britain (mm/yr). Values are for relative vertical land movement, so negative values indicate relative sea-level rise. Black circles represent sites experiencing relative sea-level fall and white circles are those experiencing relative sea-level rise. The size of each circle is in proportion to the magnitude of the rate of sea-level change at each site. Figures in parentheses take into account changes in tidal range in the Holocene. Reproduced from Shennan and Horton (2002) with permission from John Wiley and Sons.

of the site from the current coastline and the absence of modern faunal analogues for the foraminifera and diatom assemblages found.

Sea-level indicators are precise when vertical zones are narrow (Gehrels, 2002). The Severn Estuary, however, has a very large tidal range; the second largest in the world, at up to 14.85m between LAT and HAT at Avonmouth (Proudman Oceanographic Laboratory, 2012a), and therefore the zonation of foraminifera, or any other group of tidal indicators, is likely to be broader than that which would be found in micro- or mesotidal estuaries.

Haslett *et al.* (1997) investigated the modern distribution of intertidal foraminifera at Oldbury-on-Severn and Northwick Oaze so that more informed conculsions might be drawn
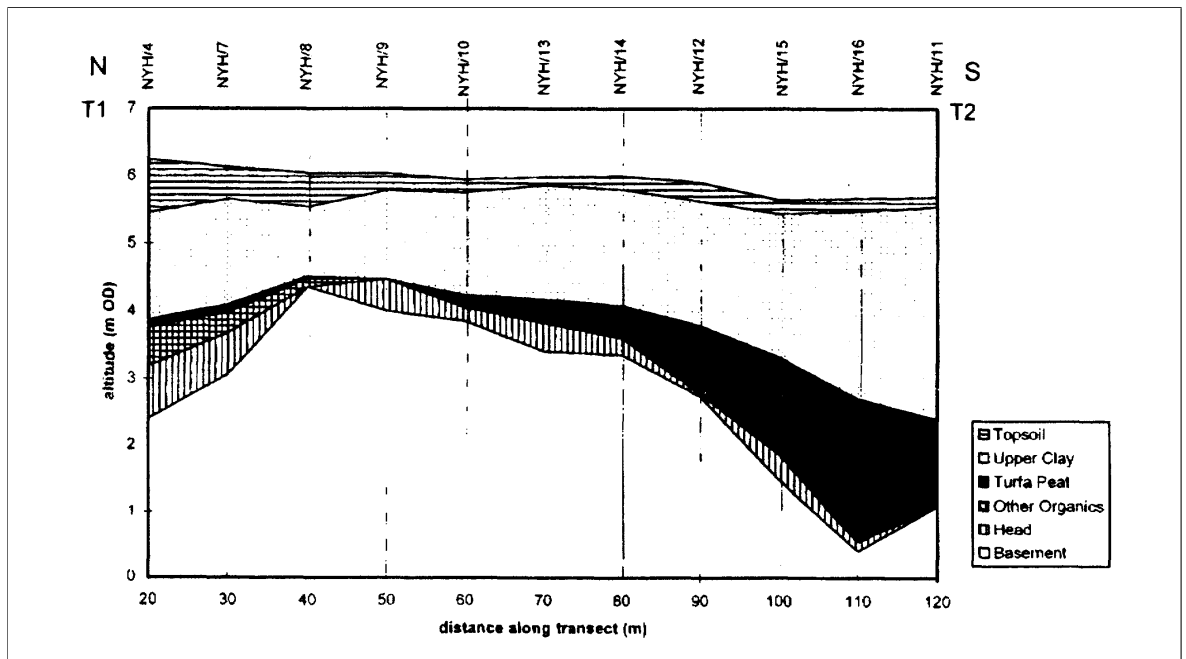
Figure 3.8: Stratigraphy of the Rookery Farm transect at Nyland Hill, Somerset. Reproduced from Haslett *et al.* (1998) with permission from SAGE Publications.

in further research as to the indicative meanings of SLIPs. They found that species diversity was low. 13 species were identified in total and the five most common were *Ammonia beccarii, Elphidium williamsoni, Haplophragmoides wilberti, Jadammina macrescens* and *Trochammina inflata,* all showing strong zonation in the intertidal zone. The study showed that foraminifera do not appear to inhabit the upper saltmarsh (MHWST to HAT) at either of these two sites. This is an unusual but not unique finding, and Haslett *et al.* (1997) discuss the large tidal range throughout the Severn Estuary as an explanation for this, suggesting that as the highest tide in any one year may not reach the level of HAT, the region between the elevation of MHWST and HAT might not be sufficiently marine influenced for foraminifera to inhabit them.

Leorri *et al.* (2010) have reported finding a similar barren zone in marshes in northern Portugal, between MHHW and HAT. However, the Minho and Lima estuaries sampled are mico- to meso-tidal rather than macro-tidal as in the case of the Severn Estuary. In eastern North America studies have shown the high marsh to be characterised by a monospecific assemblage of *Jadammina macrescens* (Zone 1A; Scott and Medioli (1978)).

Table 3.2: Sea-level index points from research in the Severn Estuary region. P = pollen, PM = plant macrofossils, F = foraminifera, D = diatoms. IM = indicative meaning. V. error = vertical error. HK82 = Heyworth and Kidson (1982), SM89 = Smith and Morgan (1989), H et al 98 = Haslett *et al.* (1998), H et al 07 = Hill *et al.* (2007), D98 = Druce (1998).

Site	Dating method	Lab Code	Age (cal. BP)	cal +	cal -	Alt. (m OD)	Biostrat.	IM	Tendency	Basal?	RSL (m OD)	V. error (m)	Ref.
Avonmouth	14C	IGS27	3,312	242	309					No	-2.740	0.47	HK82
Goldcliff	14C	CAR644	3,350	193	234		P			No	-4.530	0.21	SM89
Nyland Hill	14C	Beta-101740	3,610	105	150	3.88	F, D, P	MHWST	+ve	No	-1.920	0.21	H et al 98
Nyland Hill	14C	Beta-101741	3,620	105	155	2.42	F, D, P	MHWST	+ve	No	-3.380	0.21	H et al 98
Nyland Hill	14C	Beta-101742	3,640	180	130	3.81	F, D, P	MHWST	+ve	No	-1.990	0.21	H et al 98
Goldcliff	14C	CAR645	3,704	164	225		P			No	-4.820	0.80	SM89
Stolford	14C	NPL146	3,730	229	253	0.60				No	-6.370	0.07	HK82
Gordano Valley	AMS	Beta-189681	3,740	100	100	2.78	P, D		+ve	No	-4.784	0.88	H et al 07
Kenn Pier	14C	IGS36	3,790	291	305					No	-3.610	0.50	HK82
Weston super Mare	14C	IGS40	4,014	328	298					No	-4.200	0.32	HK82
Kingston Seymour	14C	I4846	4,036	364	317	1.30				No	-5.000	0.47	HK82
Avonmouth	14C	IGS28	4,330	454	342					No	-3.350	0.25	HK82
Portbury	14C	I4842	4,759	452	318	3.40				No	-3.300	0.41	HK82
Weston super Mare	14C	IGS41	5,173	290	304					No	-5.930	0.32	HK82
Gordano Valley	AMS	Beta-189682	5,385	85	85	2.04	P, D		-ve	No	-4.814	0.88	H et al 07
Stolford	14C	I3395	5,514	369	436	2.30				No	-3.470	0.42	HK82
Burnham on Sea	14C	Wk 5,300	5,525	205	205	-0.01	PM, F	MHWST	+ve	No	-5.590	0.21	D98
Gordano Valley	AMS	Beta-189683	5,650	60	60	1.92	P, D		+ve	No	-4.904	0.88	H et al 07
Goldcliff	14C	CAR654	5,825	165	174		P			No	-6.080	0.21	SM89
Stolford	14C	I3396	6,031	267	317	0.80				No	-5.270	0.42	HK82
Gordano Valley	AMS	Beta-189684	6,055	125	125	1.77	P, D		-ve	No	-5.740	0.88	H et al 07
Stolford	14C	I3397	6,107	287	341	-0.50				No	-6.770	0.43	HK82
Burnham on Sea	14C	Wk 5,299	6130	180	180	-0.17	PM, F	MHWST-HAT	-ve	No	-6.010	0.21	D98

Site	Dating method	Lab Code	Age (cal. BP)	cal +	cal -	Alt. (m OD)	Biostrat.	IM	Tendency	Basal?	RSL (m OD)	V. error (m)	Ref.
Clevedon	14C	IGS35	6,132	266	224					No	-6.070	0.85	HK82
Goldcliff	14C	CAR656	6,132	159	189		P			No	-6.280	0.21	SM89
Stolford	14C	NPL147	6,149	162	217	0.60				Yes	-6.770	0.12	HK82
Tealham Moor	14C	Q120	6,186	258	271	0.00				No	-6.160	0.25	HK82
Goldcliff	14C	CAR655	6,225	172	228		P			No	-6.220	0.21	SM89
Goldcliff	14C	CAR776	6,270	158	269		P			No	-5.030	0.70	SM89
Shapwick Heath	14C	Q423	6,300	250	309	0.30				No	-5.870	0.32	HK82
Goldcliff	14C	CAR657	6,329	174	326		P			No	-5.810	0.21	SM89
Kingston Seymour	14C	I4844	6,398	260	215	0.15				No	-6.150	0.47	HK82
Tealham Moor	14C	Q126	6,420	299	239	0.00				No	-6.160	0.25	HK82
Goldcliff	14C	CAR778	6,452	180	152		P			No	-5.960	0.21	SM89
Burnham on Sea	14C	Wk 5,297	6,455	165	165	-2.89	PM, F	MHWST-HAT	-ve	No	-9.070	0.21	D98
Clevedon	14C	IGS34	6,618	268	298					No	-7.200	0.85	HK82
Goldcliff	14C	CAR658	6,658	195	203		P			No	-6.660	0.21	SM89
Gordano Valley	AMS	Beta-189685	6,770	100	100	0.48	P, D		+ve	No	-6.246	0.88	H et al 07
Goldcliff	14C	CAR659	6,792	209	224		P			No	-6.720	0.21	SM89
Kenn Pier	14C	IGS39	6,974	277	295					No	-8.240	0.32	HK82
Bridgwater	14C	NPL148	7,121	288	313	-2.00				No	-7.570	0.22	HK82
Burnham on Sea	14C	Q134	7,152	272	347	-4.60				No	-10.770	0.54	HK82
Burnham on Sea	14C	Wk 5298	7,290	130	130	-3.10	PM, F	MHWST-HAT	-ve	No	-9.280	0.21	D98
Bridgwater	14C	I2689	7,734	211	223	-5.95				No	-12.090	0.23	HK82
Bridgwater	14C	I2688	7,879	294	284	-7.30				Yes	-13.335	0.83	HK82
Bridgwater	14C	I3713	8,130	235	251	-8.45				Yes	-14.220	0.82	HK82
Bridgwater	14C	I2690	8,168	235	291	-8.95				Yes	-14.520	0.22	HK82
Highbridge	14C	I4403	9,337	219	331	-21.30				Yes	-27.070	0.82	HK82
Highbridge	14C	IGS53	9,359	174	268					Yes	-27.370	0.81	HK82
Highbridge	14C	I4402	9,474	415	439	-19.50				Yes	-25.870	0.80	HK82

In a study of the modern saltmarsh foraminifera at Stert Flats in Bridgwater Bay, King and Haslett (1998) report a high abundance of foraminifera in most samples collected over the course of one year, and that their distribution demonstrates that certain species are restricted by altitude in this locality. The authors do not mention a barren zone, but it is not clear based on the details given in the study, at what elevation each sample was taken. Given that there is no saltmarsh environment above 4.5m OD at Stert Flats (see Section 4.1.1 of Chapter 4), sampling may not have reached the elevation of MHWST or above. King and Haslett (1998) go on to propose that the modern zonation of intertidal foraminifera at Stert Flats has the potential to accurately inform the indicative meaning of Holocene sediments in future sea-level studies of the Somerset Levels.

Pollen analysis can also be used to assist in the interpretation of stratigraphic boundaries in relation to sea-level change, in examining their integrity. For example, Haslett *et al.* (1998) used pollen analysis to establish whether or not erosion of the ancient peat surface had occurred in the Nyland Hill stratigraphic sequence, since saltmarsh species should be present in the peat adjacent to the peat-clay contact if the peat surface is intact. If erosion is gone unnoticed, the age assigned to any SLIP established will inevitably be increased (Haslett *et al.*, 1997).

Druce (1998) used pollen analysis of peat layers in conjunction with plant macrofossil and foraminifera studies to identify past trends in relative sea-level at Burnham-on-Sea, from an exposed stratigraphic sequence. Variations in herbaceous taxa were found to dominate the pollen profiles. For example, a shift from Chenopodiaceae to Poaceae in the upper part of the profile suggests a rise to a higher marsh level relative to the tidal frame. Coinciding with this shift in the dominant vegetation is what appears to be a transitory stage in the foraminifera record, between low and high saltmarsh species, where high marsh species (*Jadammina macrescens* and *Trochammina inflata*) are present with low to middle marsh indicators (*Ammonia beccarii* and *Hayenesia germanica*). The study corroborates the proposal of Allen (1995, p. 22) of " the possibility of a lag between a change of level and its lithological registration", and highlights one of the difficulties involved in producing sea-level curves from intercalated silt-peat boundary SLIPs. This effect was noted by Druce (1998) during a regressive phase at Burnham-on-Sea, where the onset of peat formation may represent a period of time well after the onset of the fall in MSL. Haslett *et al.* (1997, p 37) attribute this effect to " the resistance of the established depositional environment to sea-level change". The study stresses how important it is to investigate sea-level tendencies of SLIPs from intercalated peats.

Based on the sedimentary and biostratigraphic evidence from the Burnham-on-Sea area, Druce (1998) estimated that a rapid marine inundation began between 6,670 and 6,340 years BP, lasting between 20 and 700 years. The stratigraphy shows that almost three metres of silt deposition occurred in this short space of time. Following that rapid period of relative sea-level rise, marine conditions decreased from $5,370 \pm 70$ years BP, and then returned again from $4,790 \pm 70$ years BP.

Hawkins (1971b) outlines some of the difficulties of studying Holocene sea-level in the Bristol Channel region. The main problems are the great vertical range over which peat can develop, due to the macrotidal nature of the Severn Estuary, the significance of isostatic tipping of the southwest of England, and sediment consolidation or compaction, which was mentioned previously in Section 2.4 of Chapter 2.

3.6 Bridgwater Bay

The Bridgwater Bay coastline is located to the very western extent of the Somerset Levels and Moors, between Hinckley Point and Brean Down (Figure 3.9). The mouth of the River Parrett is a dominant feature of the coastline, and several other waterways such as the River Brue and the manmade Huntspill channel also meet the Bristol Channel in Bridgwater Bay.

When the tide is at its lowest extent, over 50km^2 of tidal flats are exposed at Stert Flats, Gore Sand and Berrow Flats (McDonnell, 1993). The important bird population inhabiting Stert Flats prompted Natural England to designate 27km^2 of the tidal flats around the mouth of the Parrett an National Nature Reserve (NNR) (Natural England, 2012a). In addition to its NNR status, 62km^2 of Bridgwater Bay was also designated an SSSI in 1989, based on the intertidal habitats, such as saltmarsh, shingle, mudflats and grazing marshes, supporting nationally and internationally important species of wading birds (Natural England, 1989).

The site of particular interest in the context of this thesis is the Steart Peninsula.

3.7 The Steart Peninsula

In proper geomorphological terms the Steart Peninsula is a spit, but is refered to by the Environment Agency, the Wildfowl and Wetlands Trust and other organisations as a peninsula. The spit protrudes from the coast at Stolford and extends in a north easterly direction for about 6km to Stert Point at the mouth of the River Parrett (Figure 3.9). The spit tapers to the north east end due to the north easterly flow of along-shore currents and the course of the River Parrett to the landward side (Haslett, 2010).

To the west of Stolford and the Steart Peninsula, Hinkley Point nuclear power station is built upon the Jurassic Blue Lias Limestone headland. At Stolford another outcrop of Blue Lias forms a smaller headland and an intertidal shore platform, overlain by sandstone head and gravel deposits. To the east of Stolford a series of gravel beach ridges occur, with gaps between them that allow sea water to enter at high tide, depositing fine sediments and facilitating the build-up of mud flat and saltmarsh in the back-barrier area (Case, 2013).

East of Wall Common the fringing mixed gravel and sand beach has developed against a former gravel coastline that forms a ridge behind the modern intertidal environment (Haslett, 2010). The upper tidal mud flats and sand to mixed gravel and sand beach sediments are increasingly vegetated with distance towards Stert Point by *Spartina anglica* (common cord-grass). The *Spartina* was planted in 1928 in response to erosion of the vulnerable coastline (Kidson, 1960), and has successfully trapped fine sediment, building up the elevation of the intertidal zone and reducing wave energy (Case, 2013).

Landward of the fringing *Spartina* saltmarsh environment small embryo dunes occur, colonised by *Elymus farctus* (sand couch-grass). Behind the dunes tidal lagoons provide an ideal environment for reed beds, and *Phragmites australis* (common reed) dominates the area between the lower tidal lagoon and the relict gravel ridge behind.

Through a series of experiments Kidson and Carr (1961) showed that the net movement of beach material from west to east is slow and erratic, and that longshore drift tends to cease at Wall Common and recommences at Stert Point.

Historical maps show that the tip of the spit was breached in the nineteenth century, separating Stert Island and Fenning Island from the mainland (Figure 3.10). By the twentieth century Fenning Island was incorporated back into Stert Point due to reorganisation of shingle ridges at the end of the spit (Case, 2013).

The spit has been described as a unique coastal site (Kidson, 1960), given the numerous features (shore platforms, cliffs, tidal mudflats, saltmarsh, shingle ridges and beaches, sand flats and sand dunes) occuring within a small geographical area, in the context of the large tidal range of the Severn Estuary. The tidal range between LAT and HAT is 13.21m at Hinkley Point (Proudman Oceanographic Laboratory, 2012b).

3.7.1 Holocene coastal change at the Steart Peninsula

Kidson and Heyworth (1976) cored the Steart Peninsula coast extensively; the locations of the cores are shown in Figure 3.11. Figure 3.12 shows the stratigraphy of the region from south to north at Stolford. Landwards, three to four peat layers are intercalated within the
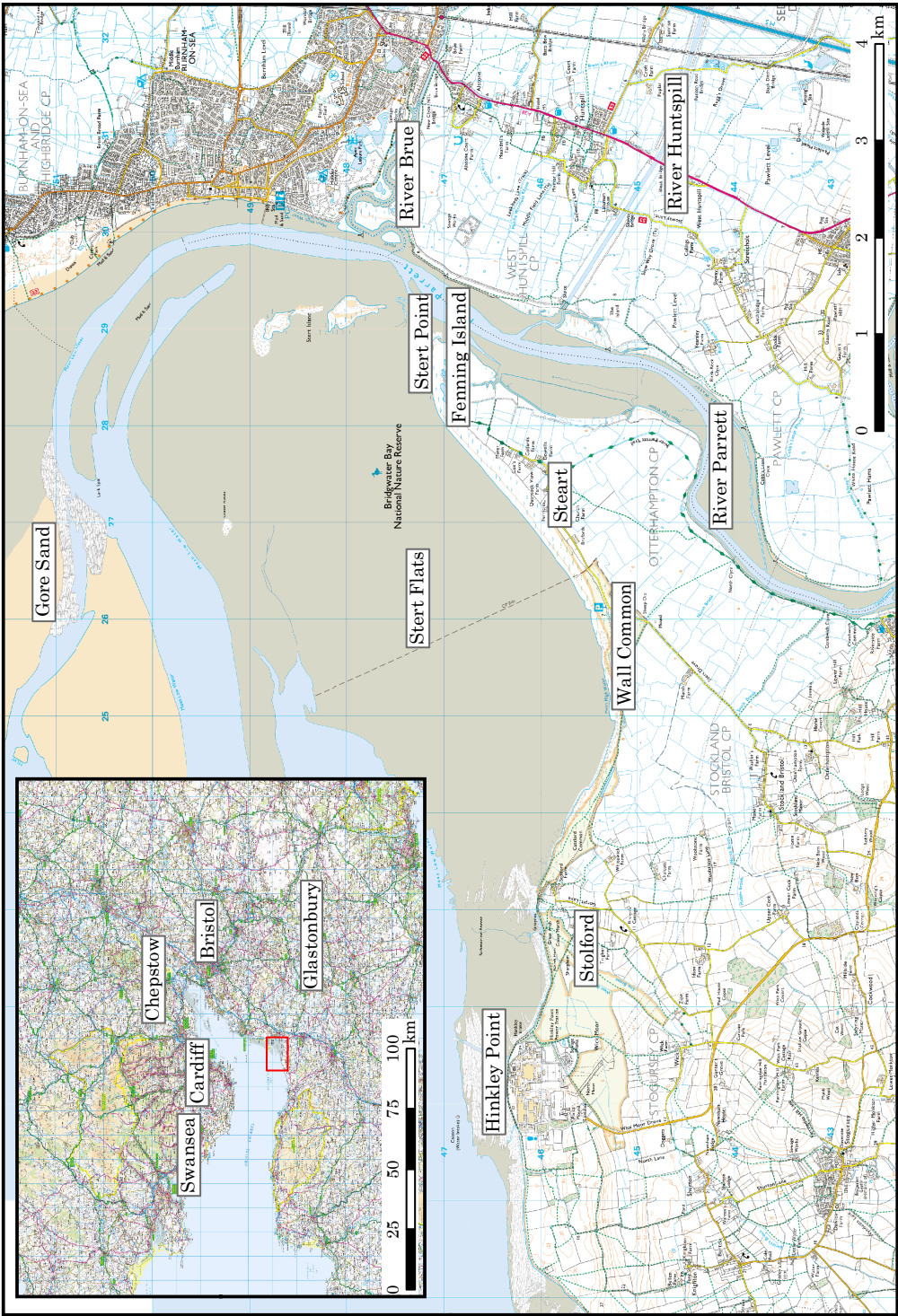
Figure 3.9: Map of Bridgwater Bay and the locations mentioned in the text. Sources: Ordnance Survey (GB) (2012b) and Ordnance Survey (GB) (2012d).
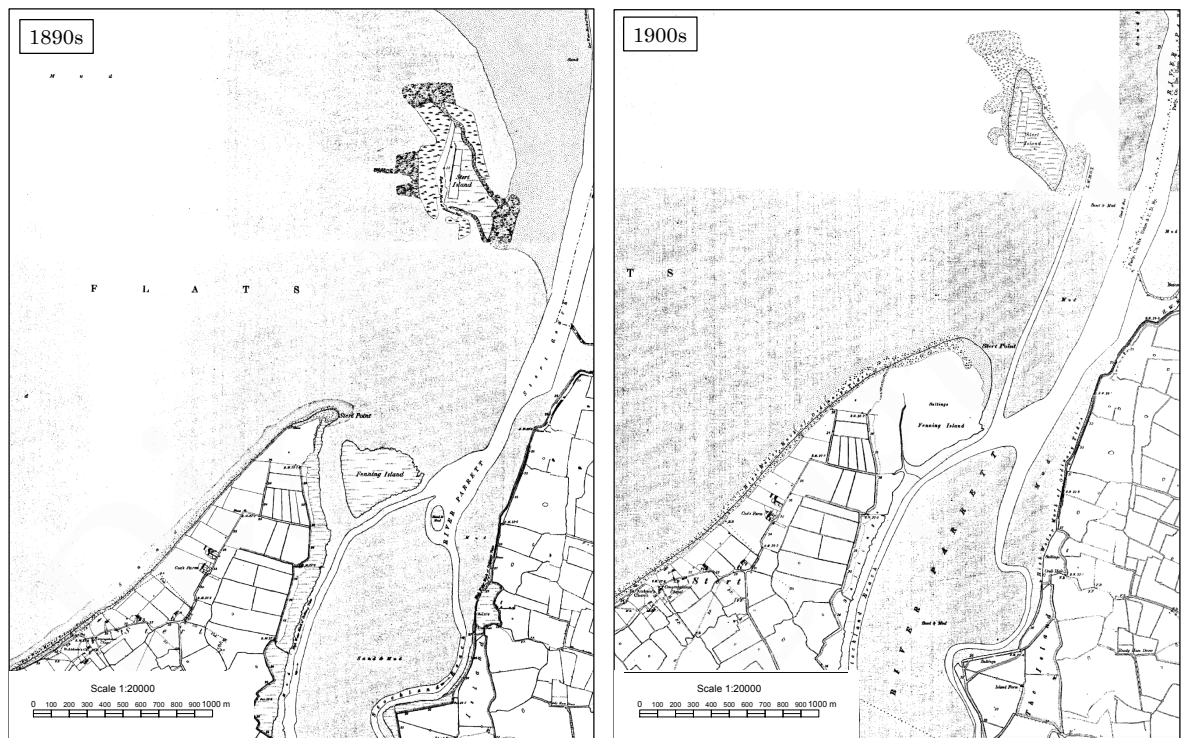
Figure 3.10: Historic OS maps illustrating the changes at Stert Point that occurred between the 1890s and 1900s. Left: 1891 OS map, originally 1:10560, sheet number ST24. Right: 1904 OS map, originally 1:10560, sheet number ST24.

estuarine clay between OD and 4m OD, and beneath this peat-clay sequence 1-4m of shingle sits directly above the solid base. Kidson and Heyworth (1976) propose that the fossil shingle ridges in the present intertidal zone are now immobile and have remained stable for a period of around 6,000 years. They infer that the basal peat was formed as the water table rose in response to Holocene sea-level rise and that the intercalated peats reflect variations in the rate of sea-level rise as it slowed later in the Holocene. Further into the estuary itself the present day mudflats cover a layer of estuarine clay that is interleaved at various points between -1m and -9m OD by thin peat units.

An extension of this sequence inland from south to north is interpreted from the boreholes presented in Figure 3.13 (Kidson and Heyworth, 1976). Between cores 6F and 6V the shingle ridges atop the solid base give way to soliflucted gravel and the thicker peats are seen to merge with the basal peat with distance inland. A 1m thick layer of estuarine clay occurs between the 2-3m thick peats and the topsoil and clay at the surface. Radiocarbon dating estimates that the ~0.8m thick peat layer around 2m OD was deposited from $4,970\pm120$ ^{14}C years BP onwards. The Intcal13 curve (Reimer *et al.*, 2013) calibrates this date to 5,469-5,990 years BP.

The stratigraphy between Wall Common and Burnham-on-Sea, across the mouth of the River Parrett, is presented in Figure 3.14 (Kidson and Heyworth, 1976). This stratigraphic

diagram is composed both of cores collected by Kidson and Heyworth (1976) (6P to 8B) and of boreholes put down by Soil Mechanics Ltd. in preparation for building the M5 motorway (212/11 to 211/23). At the southwestern end of the transect the deepest peat layer is at -9m OD and sits above about 1m of clay that itself rests on the solid base. The top of this peat is dated to 7,360±140 ^{14}C years BP (8,421-7,936 cal. years BP (Reimer *et al.*, 2013)), while the peat unit at -6m OD was deposited from 6,890±120 ^{14}C years BP (7,522-7,960 cal. years BP, IntCal13) onwards.

To the eastern side of the Parrett a basal organic mud layer sits above the pre-Holocene head deposit of soliflucted gravel, which gaves way to sand near Burnham-on-Sea. Here the deepest peats are basal, at depths of -16 to -20m OD. The organic mud unit seen in boreholes 8B and 212/11 has been dated to 7,320±120 ^{14}C years BP (8,377-7,947 cal. years BP, IntCal 13).

Since the Holocene stratigraphic work of (Kidson *et al.*, 1978) coastal change research at the Steart Peninsula has been limited to studies of the contemporary coastal zone. In a study of mudflat elevation changes Kirby and Kirby (2008) demonstrated that the average rate of intertidal erosion at Stert Flas was 16mm yr^{-1} between 1990 and 2006. This is at least four times the average rate of sea-level rise in the region and has implications for the challenges of coastal management at Steart. Since the publication of that research, and following a consulatation by the Environment Agency (Environment Agency, no date), Sedgemoor District Council granted planning permission for 400 hectares of wildlife-rich saltmarsh and freshwater marsh to be created on the Steart Peninsula, along with improved protection of Steart village and Steart Drove, the road linking Steart Village with the surrounding villages and roads (Environment Agency, 2012a,b). To compensate for the impending loss of wetland habitats to sea-level rise the UK Government aims to create 300 to 600 hectares of new wetland habitat in the Severn Estuary region by 2030 and the habitat creation scheme on Steart Peninsula will contribute significantly to the Government's target (Environment Agency, 2012b). Subsequently, research at Steart has focussed mainly on engineering challenges (Wright *et al.*, 2011a; Burgess *et al.*, 2013) and ecosystem services (da Silva, 2012; da Silva *et al.*, 2014) in recent years. This thesis provides a palaeoenvironmental focus that has not been present in research at this important site for several decades.

3.7.2 The Steart Peninsula as the geographical focus

The motives for focussing the palaeoenvironmental aspects of the research presented in this thesis on the Steart Peninsula are three-fold. The first is the potential to build upon and
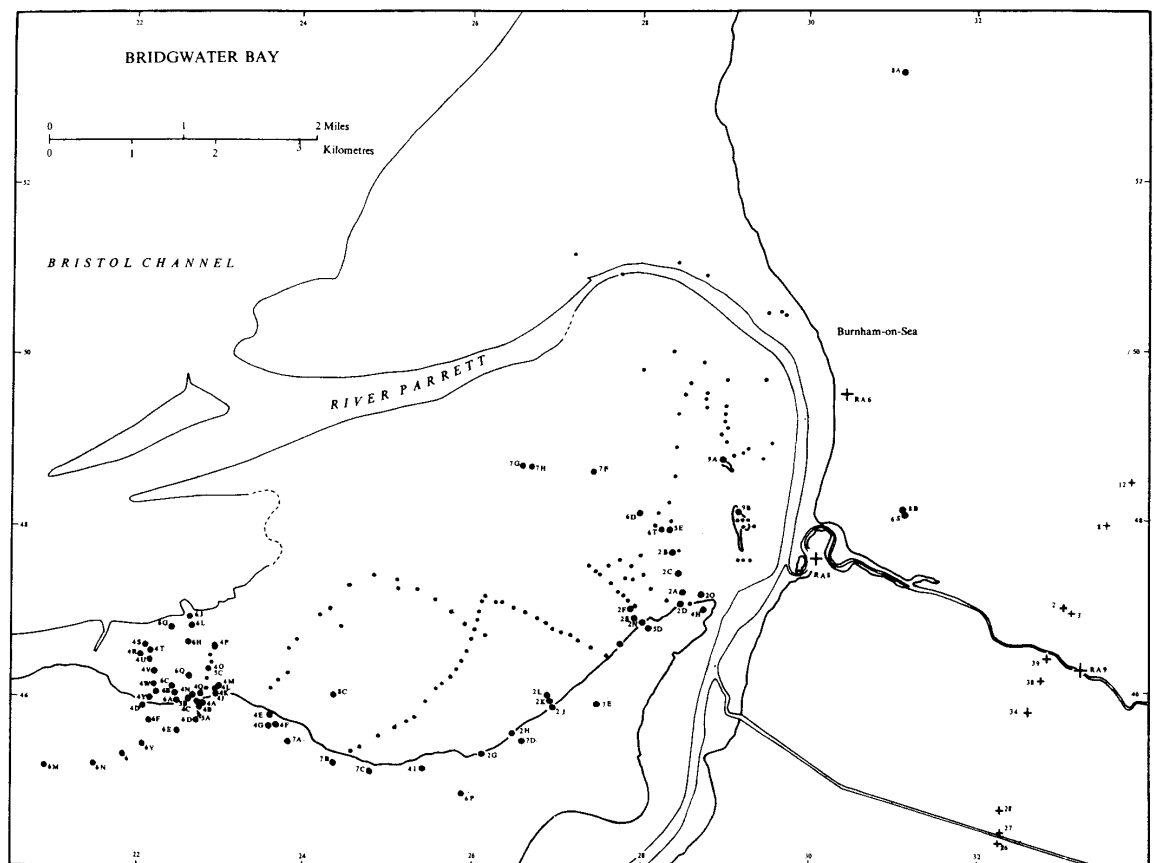
Figure 3.11: Locations of boreholes in Bridgwater Bay and the Somerset Levels. Dots are cores collected by Kidson and Heyworth, and those that are labelled relate to the cores presented in Figures 3.12 to 3.14. Large crosses are cores collected by the River Authority and small crosses are those collected by Soil Mechanics Ltd. From Kidson and Heyworth (1976). Reproduced with permission from The Geological Society of London.

link to the stratigraphic work by Kidson and Heyworth (1976) who, using their own data and that of two other organisations (Soil Mechanics Ltd and the Somerset River Authority) produced a comprehensive account of the Holocene stratigraphy of the area (see Section 3.7.1 and Figures 3.11 to 3.14). The second aim of this thesis, "To reconstruct Holocene sea-level at the Steart Peninsula, Somerset", adds further sedimentary, chronological, biostratigraphic and palaeoenvironmental context to the work of Kidson and Heyworth (1976), enabling a more robust impression of sea-level and environmental change at the Steart Peninsula to be derived.

Second is the apparent historical focus on the Somerset Moors and inner areas of the Levels in preference to the coastal areas in terms of palaeoenvironmental and archaeological research (Caseldine, 1980, 1988; Godwin, 1941; Haslett *et al.*, 1998; Housley, 1988; Housley *et al.*, 1999; Wilkinson, 1998). There are very few recent studies of environmental and sea-level change in the coastal part of the region (Druce, 1998; Kidson and Heyworth, 1976) and this study of environmental and sea-level change at Steart allows for comparisons to be
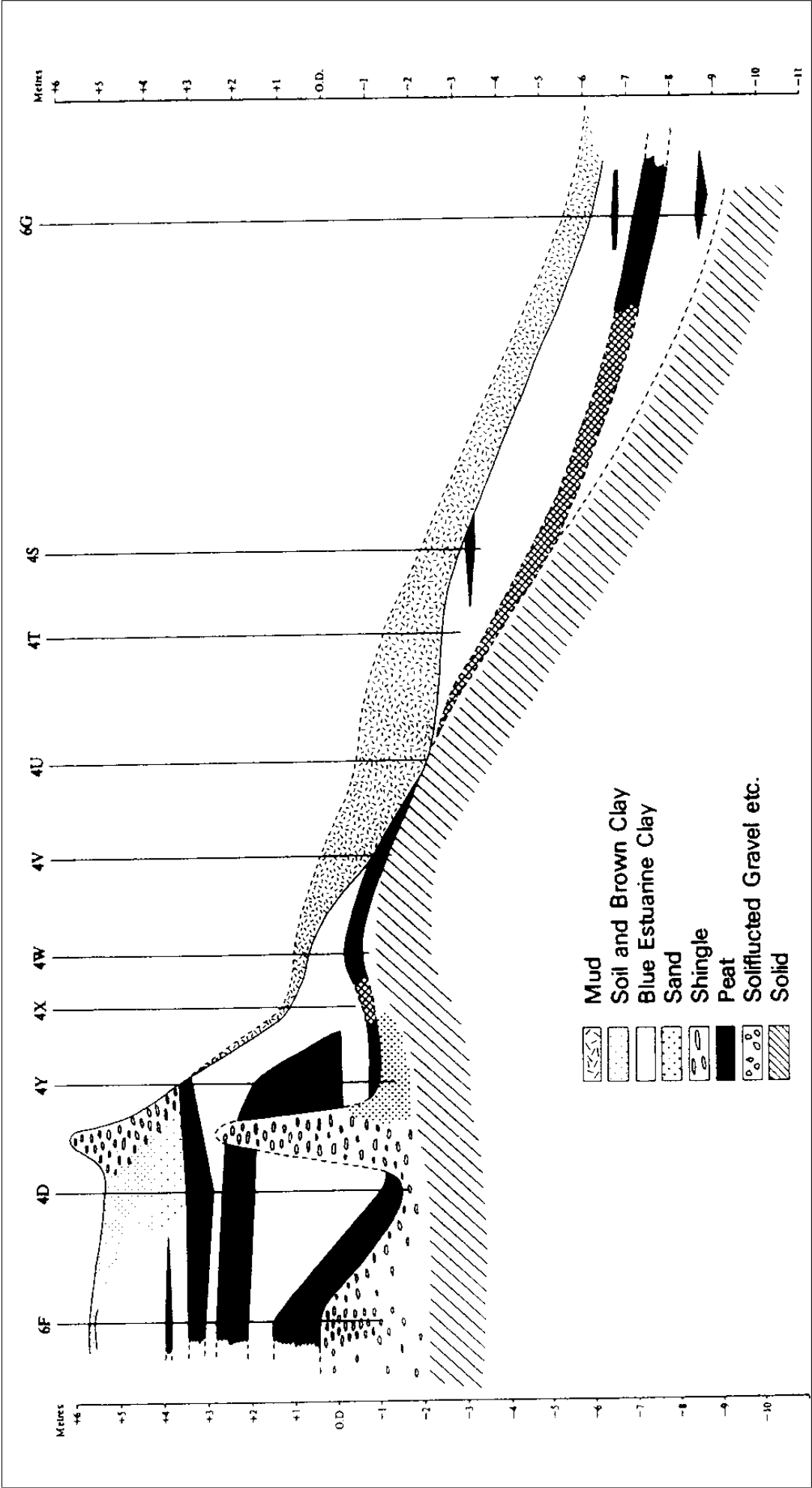
Figure 3.12: Section through the beach at Stolford, from Kidson and Heyworth (1976). Reproduced with permission from The Geological Society of London.
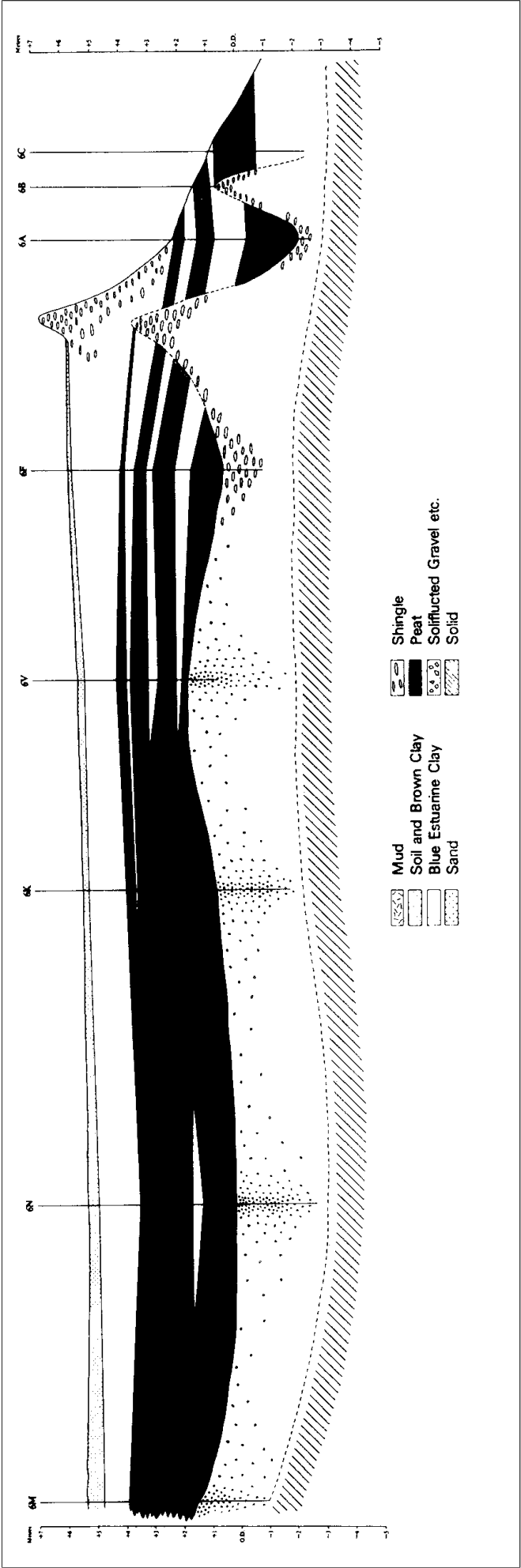
Figure 3.13: Inland extension of the sequence shown in Figure 3.12, from Kidson and Heyworth (1976). Reproduced with permission from The Geological Society of London.
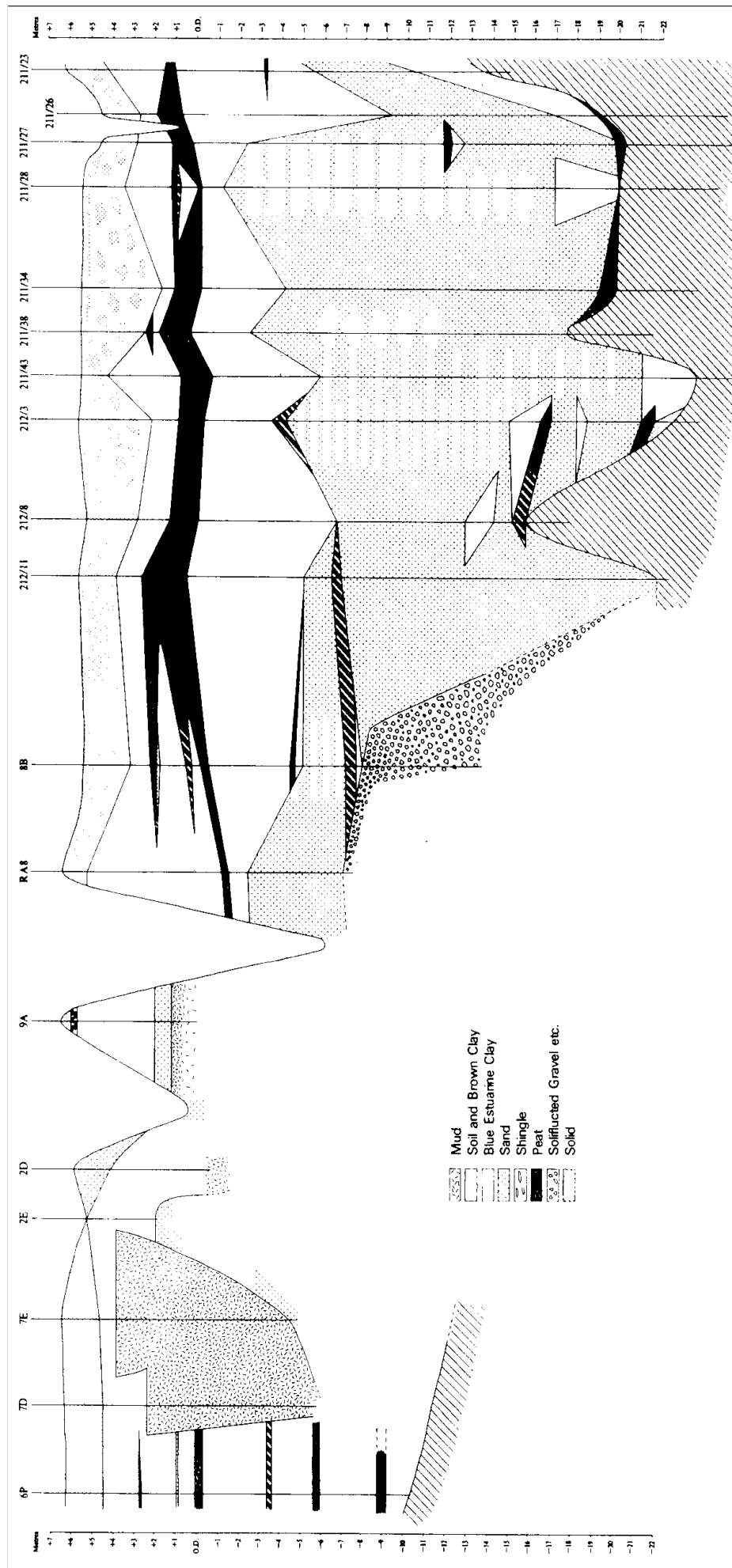
Figure 3.14: Section across the mouth of the River Parrett, from Kidson and Heyworth (1976). Reproduced with permission from The Geological Society of London.

made with recent work on the other Severn Estuary Levels at Gordano (Hill *et al.*, 2007) and Redwick (Allen and Haslett, 2007) in the context of regional versus local influences and change.

Finally, the *Spartina* foremarsh at the Steart Peninsula allows the regional sea-level transfer function developed as part of this research to be underpinned by modern data that is local to the site of palaeoenvironmental interest, as advised by Scott and Medioli (1986) and Kemp *et al.* (2012). King and Haslett (1998) have confirmed the abundance of species of foraminifera in the intertidal zone at Stert Flats. Saltmarsh conditions occur up to around 4.5m OD, meaning that a significant proportion of the data involved in the transfer function development is local to the reconstruction site. This issue is discussed further in Section 4.1 of Chapter 4 (Methodology).

3.8   Chapter summary

The Somerset Levels and Moors form a system of buried valleys that were incised during Quaternary sea-level lowstands and filled with Holocene and earlier Quaternary sediments. The marine and estuarine clay Levels lie to the west of the low-lying fen and raised peat Moors alongside the coast of the Severn Estuary and Bristol Channel. The sediment stratigraphy of the Levels provides an archive of environmental and sea-level changes for the Holocene. Broadly, the Holocene sequence consists of basal peats resting on pre-Holocene bedrock or Pleistocene head, overlain by intercalated estuarine silty clays and peats. The basal peats are not always present (Haslett *et al.*, 2006).

Research into Holocene sea-level change in the Severn Estuary region has broadly mirrored the methodological developments discussed in Chapter 2. Research includes stratigraphic work and basic dating of fossil peats in the 1970s and 1980s (Heyworth and Kidson, 1982; Kidson and Heyworth, 1976; Smith and Morgan, 1989), more robust SLIPs established in the 1990s (Druce, 1998; Haslett *et al.*, 1998) and finally a quantitative diatom-based transfer function used to reconstruct MTL at Gordano in the early 21st century (Hill *et al.*, 2007).

A collection of SLIPs from five key publications, synthesised in Table 3.2 and Figure 3.15, depicts rapidly rising MTL from -27m OD 9,360 cal. years BP for around 2,700 years, followed by a more moderate rate of rise from around -6.6m OD to -2.7m OD between 6,660 and 3,310 cal. years BP. Vertical error bars range from ±0.21 to 0.88m, reflecting the large tidal range, and one indication of the relative benefit of the methodological approach take in this thesis will be if a lower mean average vertical error than these previous studies is attained.
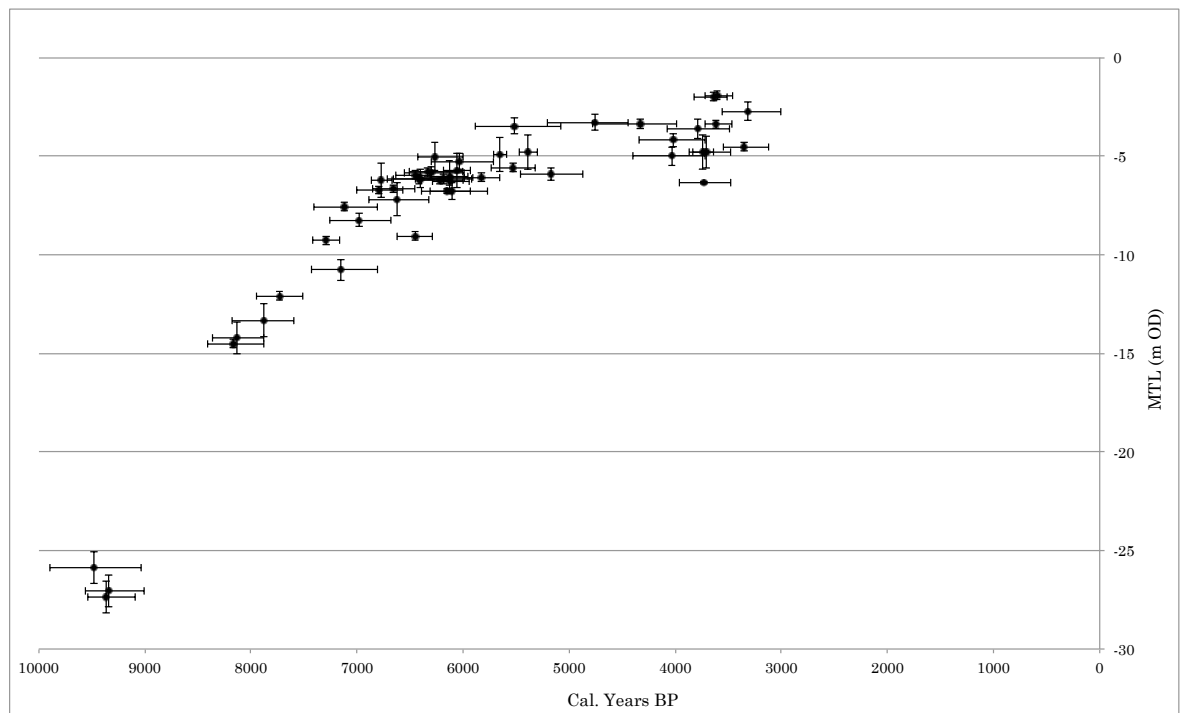
Figure 3.15: Sea-level index points (SLIPs) from five publications on Holocene sea-level in the Severn Estuary region, as listed in Table 3.2. Data from Druce (1998), Haslett *et al.* (1998), Heyworth and Kidson (1982), Hill *et al.* (2007) and Smith and Morgan (1989).

Holocene sea-level research is accompanied by a number of issues and sources of uncertainty which were discussed in Chapter 2, and include autocompaction of sediments, the level of interpretation required in environmental change resesrch, sampling and dating errors, statistical error and many others. However, the two main challenges specific to working in the Severn Estuary are the extreme tidal range and the scarcity of suitable intertidal sites available for modern sampling.

As discussed in Chapter 2, researchers have higlighted the need for more detailed studies of macrotidal environments to establish their potential for high quality, high resolution Holocene sea-level reconstruction, and the methodological approach of this study is intended to optimise sampling and analytical techniques, while being transparent about the potential margins of error involved.

Through this literature review the Steart Peninsula was identified as a key location where the Holocene stratigraphy is well documented and where more sophisticated quantitative techniques for sea-level reconstruction might further the understanding of local and regional patterns in Holocene sea-level change om the Severn Estuary. The site has the additional advantage of a suitable intertidal location for modern sampling and transfer function development.

Chapter 4

Methodology

The methodological approach of this thesis is based on a move towards quantitative techniques becoming more widely used in palaeoenvironmental research (Hammer *et al.*, 2001) and seeks to extend the established research, both in the Severn Estuary region and in the field of sea-level research, where a multi-proxy sea-level transfer function was developed from contemporary intertidal microfaunal and environmental data from sites in the Severn Estuary region. That multi-proxy transfer function was applied to microfaunal data from a sediment core collected from the Steart Peninsula in Bridgwater Bay, bringing together developments in quantitative modelling of sea-level indicators and micropalaeontology to further the existing knowledge of sea-level change in the region. The work of Haslett *et al.* (1998), Hill *et al.* (2007) and Kidson and Heyworth (1976) indicates that this approach may lead to a more accurate and detailed sea-level history of the Bridgwater Bay area.

The development and application of a multi-proxy sea-level transfer function has not been tested in a macrotidal setting, where microfaunal zones relative to MTL are likely to have broader ranges (Gehrels, 2002), and this work reflects on the relative merits and disadvantages of spending time basing a sea-level transfer function on two, rather than one, microorganism groups. Attempts have been made to develop multi-proxy sea-level transfer functions (Gehrels *et al.*, 2001; Kemp *et al.*, 2009a), but as yet, there are no published examples of one being applied to fossil data and used to reconstruct former sea-levels.

4.1 Contemporary intertidal microorganisms and environmental factors

A multi-proxy sea-level transfer function for Bridgwater Bay or the wider Somerset Levels region has not previously been developed, and therefore a training set of sea-level indicator species in the contemporary intertidal zone is required. This section describes and discusses the methods used to address research objective 1a; to establish the key environmental fac-

tors affecting the presence and species abundance of surface-dwelling intertidal diatoms and foraminifera in the contemporary Severn Estuary intertidal zone. Foraminifera and diatoms have been chosen as the biological sea-level indicators to base the transfer function development on, because of their prior success as accurate and precise sea-level indicators on various Holocene time scales.

Previous research has shown foraminifera to respond significantly to tidal level in contemporary intertidal environments (Callard *et al.*, 2011; Edwards and Horton, 2000; Gehrels, 2000; Gehrels and Newman, 2004; Horton *et al.*, 1999a,b; Kemp *et al.*, 2012, 2013; Leorri *et al.*, 2010). In terms of the reconstruction from fossil assemblages, the species of foraminifera that inhabit the intertidal zone are well known (Gehrels, 2002) and they are very unlikely to be found in supratidal bogs or other freshwater environments that might resemble buried marsh sediments (Scott and Medioli, 1980). Therefore, foraminifera provide reliable information about fossil organic units and their former relationship with sea-level. Foraminifera are well preserved in intertidal sediments, and while diversity is often low, abundance of tests in modern and fossil environments is usually high (Gehrels, 2007). King and Haslett (1998) have confirmed the abundance of intertidal foraminifera in the intertidal zone at the Steart Peninsula.

Diatoms also have been shown to display strong zonation in the intertidal zone and previous authors have found an abundance of diatoms in small volumes of modern and fossil sediments (Hill *et al.*, 2007; Kemp *et al.*, 2009a; Ng and Sin, 2003; Szkornik *et al.*, 2006; Woodroffe and Long, 2010; Zong and Horton, 1999). A diatom-based sea-level transfer function for the Gordano Valley in the Severn Estuary has been successfully developed and used to reconstruct Holocene sea-level by Hill *et al.* (2007).

Testate amoebae have not been used as sea-level indicators in this study because, while they display strong correlation with tidal level in the upper intertidal zone (Charman *et al.*, 2010), a testate amoebae-based transfer function has not, as of yet, been used to reconstruct sea-level beyond ~100 years BP, in part because methods have not been established to concentrate together significant numbers of tests from core sediments (Charman, 2001).

Some studies have presented pollen-based sea-level transfer functions (Engelhart *et al.*, 2007; Gregory, 2007). However, Roe and van de Plassche (2005) highlight the poor understanding of the dispersal of regional and local wetland pollen in modern saltmarshes.

Diatoms and foraminifera meet the first requirement of quantitative environment reconstruction outlined by Birks (1995) and Birks *et al.* (2010), which is that a biological system is used, that produces abundant identifiable fossils and is responsive to the environmental

variable of interest today. In addition to previous research that indicates that these two microorganism groups respond in predictable patterns to sea-level (Callard *et al.*, 2011; Edwards and Horton, 2000; Gehrels and Newman, 2004; Horton and Edwards, 2000; Kemp *et al.*, 2009a,b; Scott and Medioli, 1978, 1986; Szkornik *et al.*, 2006; Woodroffe and Long, 2010; Zong and Horton, 1999), ordination methods and software are used in this study to estimate the extent to which species respond to the variable elevation above MSL. These methods are discussed fully in Section 4.2 of this chapter.

4.1.1 Site selection and field sampling

Birks (1998) proposes that the modern training set should represent the maximum range of modern environmental variation for the system of interest. In sea-level studies the contemporary intertidal zone is ideally sampled between HAT and MTL (Gehrels *et al.*, 2001), but it is not always possible to achieve this by sampling at only one site (Hill *et al.*, 2007). Views differ among the sea-level community as to how a transfer function training set is best sampled. The terminology of Wilson and Lamb (2012) is used here to distinguish between different approaches. A local training set is likely to consist of samples taken from one modern intertidal transect in close geographical proximity to the site where sea-level is being reconstructed. Examples of local training sets include a foraminifera training set from one transect in Skallingen, Denmark (Gehrels and Newman, 2004) and another from one transect near Pounawea on the south island of New Zealand (Southall *et al.*, 2006). An extra-local training set would be constructed from several modern transects in the broader region of the reconstruction site, taking in a limited range of coastal ecosystems. Examples include a Tasmanian foraminifera training set collected from two sites at Little Swanport Estuary by Callard *et al.* (2011), and foraminifera and diatom training sets from three back barrier marshes in Outer Banks, North Carolina, USA (Kemp *et al.*, 2009a). Wilson and Lamb (2012) do not define what spatial extent would constitute the broader region of the reconstruction, presumably because coastal systems vary in scale across the world. Examples of regional training sets might include the UK diatom training set by Zong and Horton (1999) composed of data from six sites, and the UK foraminifera training set compiled by Horton and Edwards (2006) from 15 intertidal transects.

   The argument that Horton and Edwards (2000) put forward in support of the use of a regional transfer function is that much of the UK coastline has undergone significant change in historic times, such as the introduction of exotic species of vegetation. The condition of an estuary today may not be the best analogue for the condition of that same estuary some

thousands of years ago, and therefore in combining training sets from many different UK environments, the likelihood of producing a successful environmental reconstruction for a site increases. Horton and Edwards (2005) directly compare the performance of local and regional foraminifera-based transfer functions to reconstruct sea levels from the Holocene sediment sequence at Holkham. They conclude that reconstructions derived from the regional transfer function are more reliable, as the local transfer function achieves a slight increase in precision at the expense of a significant amount of predictive power. While it is useful to maximise precision, if the modern environment from which the local training set is derived is not a good analogue for past conditions at that site, reconstructed heights will not be accurate. Horton and Edwards (2005) suggest that where a local site does not yield suitable modern analogues for fossil assemblages, based on some robust statistical process, an extra -local or regional set should be used.

When Wilson and Lamb (2012) applied the UK regional diatom-based transfer function of Zong and Horton (1999) to fossil assemblages from sites in the Mersey estuary, UK, they found, through the application of the MAT, that 69% and 28% of the fossil assemblages from their two sites respectively, were without modern analogues. They suggest the reason for this lack of modern analogues is the limited scope of the Zong and Horton (1999) UK diatom training set which only includes six different sites. They also noted that the transfer function was more successful for assemblages that were deposited lower in the tidal frame, suggesting that non-analogue situations are more likely to be encountered for fossil assemblages from upper intertidal deposits, where local factors such as changes in climatic variables, vegetation and anthropogenic activity might be expected to influence the microfaunal ecology to a greater extent, and where environmental changes in the Holocene are likely to have been more influential.

Gehrels *et al.* (2001) conclude from a study of three sites from the UK that while the pattern of intertidal zonation of micro-organisms may be variable between sites, regional training sets increase the likelihood that environmental information from modern training sets, such as intertidal variation in sediment salinity and pH, can more accurately reflect palaeoenvironmental conditions at any given site within that region.

Conversely, Allen and Haslett (2002) argue that for a study of sea-level change in the Gwent Levels a local model of foraminiferal zonation was preferable because the UK regional foraminiferal training set (Horton *et al.*, 1999b; Horton and Edwards, 2005) at the time of the study did not include any sites from the coasts of South Wales and south west England. Allen and Haslett (2002) also highlight the fact that various researchers have their own preferences

about sample sizes and the use of dead, live or total species assemblages in their foraminifera training sets, and propose that a nationally applicable scheme, compiled of many researchers' training set data, should not be sought. Rather, research should focus on the extra local level, where oceanographic conditions should be similar throughout sites.

Kemp *et al.* (2012) argue for using modern sites close to the reconstruction site because they found that foraminifera in particular, while displaying low species diversity at any given site (compared to diatoms, for example), often have quite site specific assemblages and high inter-site variability. However, Kemp *et al.* (2012) also point out that the elevational tolerance ranges of individual species are likely to increase when more sites are introduced into the training set, potentially reducing the precision of any transfer function model subsequently developed.

Woodroffe and Long (2010) conclude in a study of relative sea-level changes in west Greenland that local diatom-based transfer functions are superior to regional models. They found that certain species existed at different elevations at the two sites studied, despite standardising samples to SWLI.

In terms of the Severn Estuary region, King and Haslett (1998) present preliminary findings from a transect across Stert Flats in Bridgwater Bay. Rather than using the existing foraminiferal training set of Haslett *et al.* (1997) from Oldbury-on-Severn and Northwick Oaze in the inner Severn Estuary, King and Haslett (1998) argue that the Somerset Levels is sufficiently different from the inner Severn Estuary and that a local training set is desirable. Like many UK estuaries, the range of coastal environments encountered near to any one study site is quite limited in the Severn Estuary due to extensive reclamation (Wilson and Lamb, 2012). It would appear that there may be no 'correct' method, because each situation is different, but that there is merit in starting with local sites where possible, and then looking to sites further afield if modern analogues cannot be found locally for the assemblages encountered in fossil sediments, or if the entire intertidal range cannot be sampled locally, such that an extra-local or regional training set may still be underpinned by some local data. In the Severn Estuary region saltmarsh environments are scarce at altitudes above 4 to 5m OD, and an extra-local approach has been taken here, whereby a site close to the Steart Peninsula was sampled initially, then a site further afield, but still within the Severn Estuary region in South Wales, was used to supplement the local data and provide samples from the upper part of the intertidal zone.

Stert Flats form one part of the tidal flats of Bridgwater Bay, occuring from Hinkley Point at the western extent to the River Parrett and Burnham-on-Sea to the northeast (Figure 4.1),
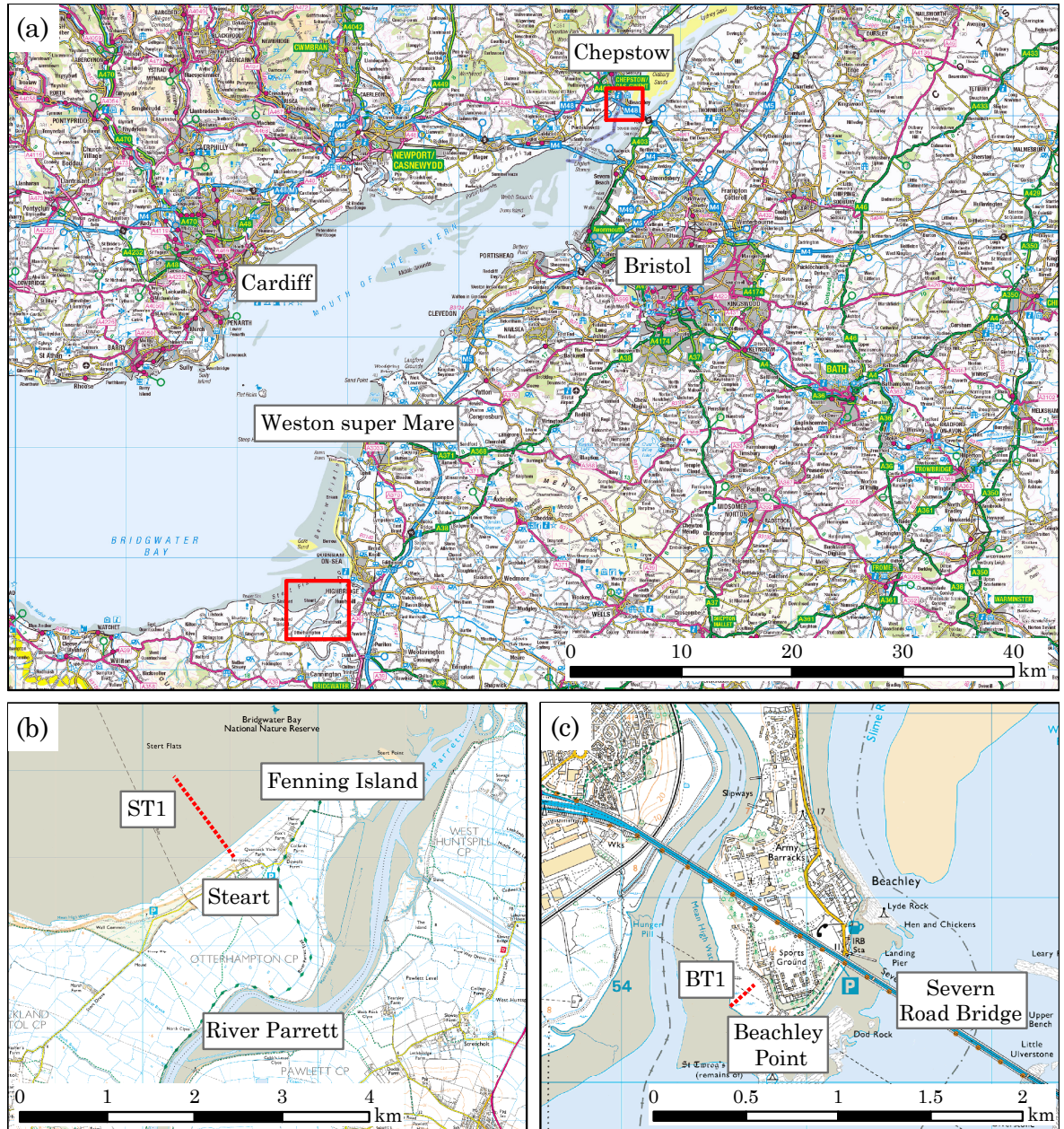
Figure 4.1: Maps of (a) the Severn Estuary/Bristol Channel region and the sites of the two modern transects, (b) the site of transect ST1 at Stert Flats and (c) the site of transect BT1 at Beachley Point. The length of each transect is approximate. Sources: Ordnance Survey (GB) (2012b), Ordnance Survey (GB) (2012d) and Ordnance Survey (GB) (2012c).

extending around 3km into the channel at low tide (Haslett, 2010). Between Hinkley Point and Wall Common the intertidal zone consists of Blue Lias cliffs and shore platforms, head deposits and cobble and gravel beach sediments, giving way to a mixed sand and gravel beach at Wall Common. Eastwards of Wall Common the intertidal zone is composed, from MTL upwards, of tidal mudflats and silts, to sand, to mixed gravel and sand. From around 3.8m OD upwards the surface is vegetated with *Spartina anglica* (common cordgrass), planted in 1928 to encourage the trapping of fine sediment and the dissipation of wave energy to reduce the incidence of erosion (Case, 2013).

The *Spartina* marsh is replaced by small embryo dunes colonised by *Elymus farctus* (sand couch-grass) around 4.5m OD, behind which occurs a tidal lagoon environment dominated by *Phragmites communis*. Landward of the lagoon environment a raised ridge occurs, with pebbles originating from the shale and limestone cliffs at Lilstock to the west and sandstone carried down from the Quantock Hills by river processes (Haslett, 2010).

The *Spartina* marsh was surveyed for foraminifera by King and Haslett (1998), who found an abundance of intertidal species. The ramped marsh shown in Figures 4.1 and 4.2 was chosen for the modern microorganism analysis based on the findings of King and Haslett (1998) and its location close to the site of palaeoenvironmental interest.

Sampling at Stert Flats alone does not provide the full range of intertidal environments required for the training sets. While HAT in Bridgwater Bay is 7.12m OD[1], the saltmarsh environment ceases to exist above 4.5m OD, resulting in the requirement for an additional modern site.

Hill *et al.* (2006) successfully sampled from two sites in the Severn Estuary region that overlapped in altitude, thus encompassing the requisite range of intertidal environments required (HAT to MTL) to develop a diatom-based sea-level transfer function for the inner Severn Estuary. He showed statistically that the diatom assemblages from the overlapping sections of the two transects sampled were not significantly different. A similar approach has been adopted here, and a second site sampled to complete the upper part of the training set (see Figure 4.1 (c) for the transect location). A ramped marsh (Allen, 1993) at Beachley Point, 3.7km south-southwest of Chepstow in South Wales, was selected based on the saltmarsh habitat occurring up to the level of the highest tides (Figure 4.3), and the known presence of diatoms in the surface sediments (Hill *et al.*, 2007). According to the classification of Wilson and Lamb (2012) this approach results in the development of an extra-local

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[1]Proudman Oceanographic Laboratory gives values for tidal levels relative to Admiralty Chart Datum (ACD). Personal communication with Ferguson (2012) details how to convert ACD values to levels in metres above OD. All tidal levels mentioned in this thesis are given as levels above OD (m).
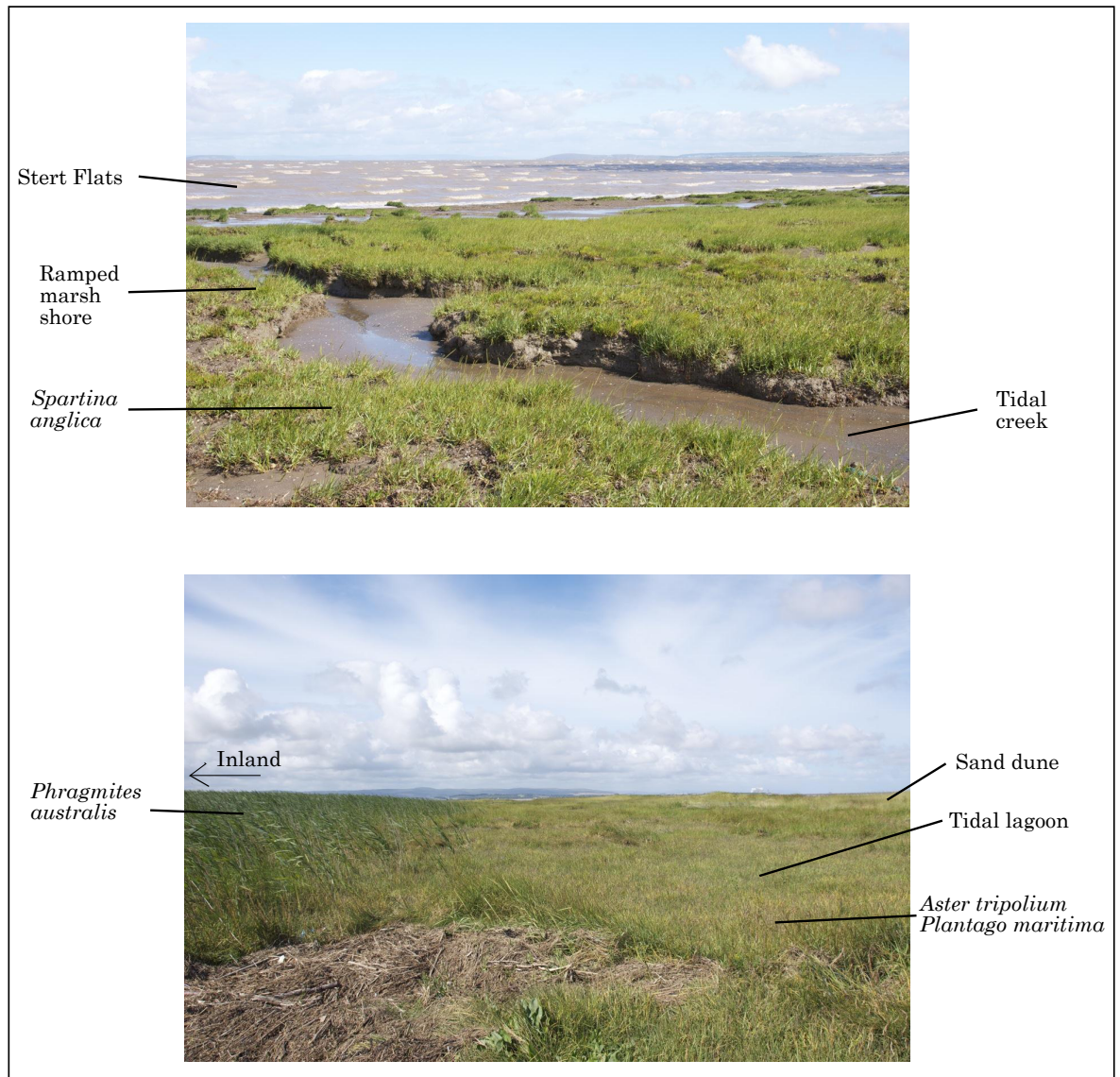
Figure 4.2: Annotated photographs of Stert Flats. Top: looking north west across Stert Flats. Bottom: looking west-south west towards Hinkley Point and beyond. Author's own.

training set.

In seeking to use the transfer function approach to reconstruct tidal level in relation to OD from sediment cores it is necessary, in sampling from the contemporary intertidal zone, to make all measurements and analyses with respect to elevation above MSL. Elevation is one of the key variables to which microorganisms such as foraminifera and diatoms have been shown to respond (Scott and Medioli, 1978; Zong and Horton, 1999). When two sites with different tidal ranges are combined together to form a training set, the elevation of each sample taken requires standardisation for this vertical difference to be taken into account. The most common approach used in such cases is to convert the elevation of each sample to a standardised water level index (SWLI) (Horton and Edwards, 2006; Leorri *et al.*, 2008; Wright *et al.*, 2011b).

The formula used for SWLI is given by Horton and Edwards (2006) as follows:

Tidal flats

Ramped marsh
shore

Limonium vulgare
Plantago maritima
Glaux maritima
Festuca sp.

Tidal
creek

MHWST
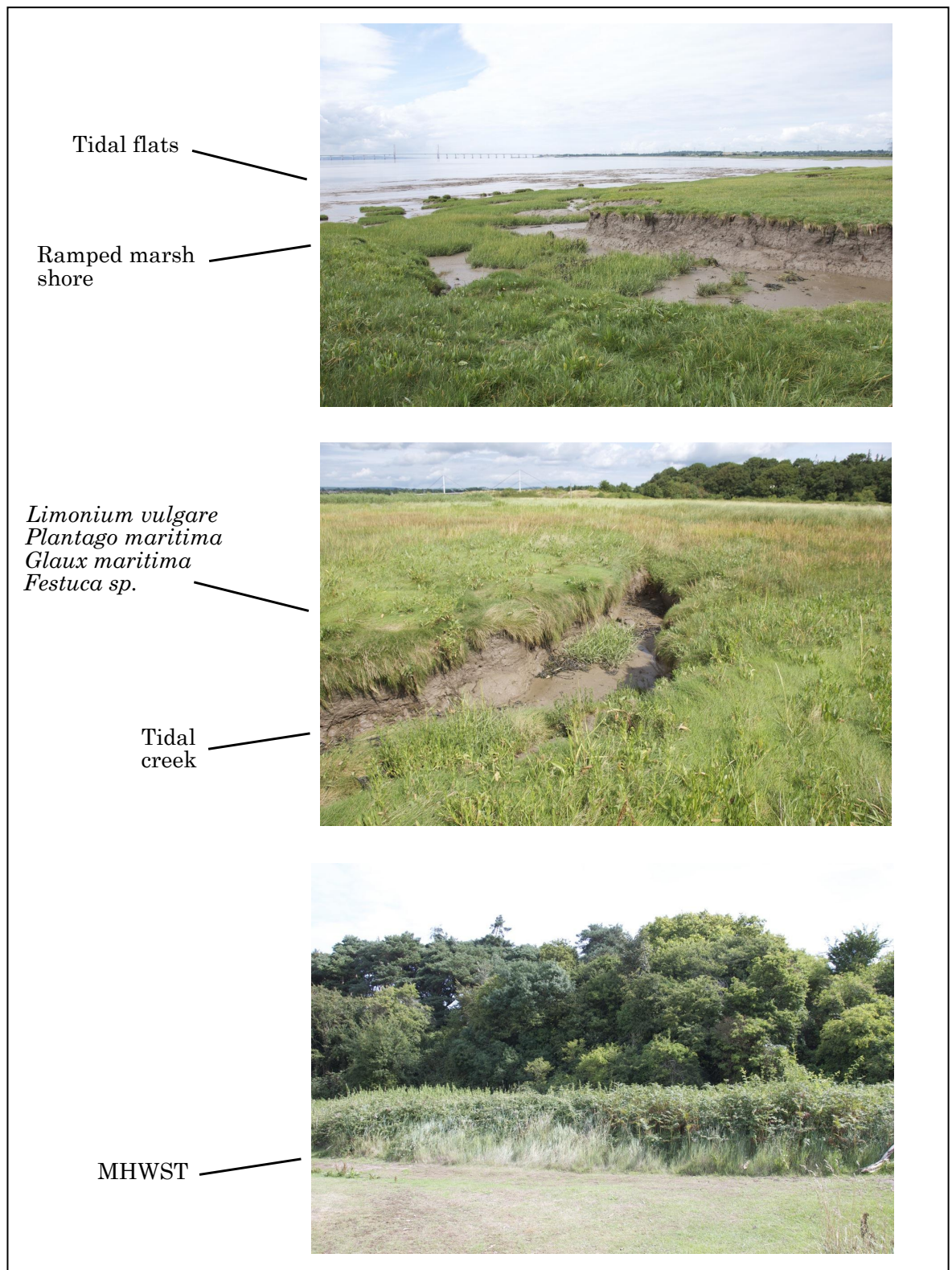
Figure 4.3: Annotated photographs of Beachley Point. Top: looking south west across the tidal flats towards the Second Severn Crossing. Middle: looking north-north west towards the estuary of the River Wye. Bottom: looking north east at the hedge and trees at MHWST and above. Author's own.

$$SWLI = \frac{Alt_{ab} - MLWST_b}{MHWST_b - MLWST_b} \tag{4.1}$$

Alt_{ab} is the altitude of sample a at site b, $MLWST_b$ is mean low water spring tide at site b and $MHWST_b$ is mean high water spring tide at site b (all in metres above OD). This standardisation means that each sampling site is defined by its height in the tidal frame as a proportion of the tidal range, rather than its absolute elevation above OD, such that samples from various sites can be compared directly and meaningfully. The sea-level transfer function will therefore ultimately give estimated past SWLI values that can be transformed back into tidal levels at the Steart site by rearranging Forumla 4.1 for altitude.

There are three approaches to surface sampling that have been used in sea-level research; sampling at regular horizontal intervals (Ng and Sin, 2003), sampling at regular vertical intervals (Charman *et al.*, 2002; Edwards *et al.*, 2004; Szkornik *et al.*, 2006) and sampling irregularly, encompassing marked changes in topography and vegetation (Zong, 1997; Horton *et al.*, 1999b; Leorri *et al.*, 2008; Kemp *et al.*, 2009a, 2012). As elevation relative to the tidal frame is the main variable in question, sampling at regular vertical intervals was the approach chosen. It does not seem efficient to sample at regular horizontal intervals when several samples in a row could be taken from the same, or very similar elevation. The third approach is not systematic, and may involve walking the length of the transect before sampling to select the sites, in order to ensure that a sufficient number of samples are taken from each of the relevant intertidal habitats, while also spanning the full vertical range of the intertidal zone adequately. This is not an option when working in the Severn Estuary as the large tidal range means that the tide has to be followed out as the water level drops while sampling takes place, and samples collected quickly and efficiently to minimise any safety risks.

Telford and Birks (2011) found that observations sampled unevenly across the environmental gradient can have an adverse effect on transfer function performance. Ter Braak and Prentice (1988) also reveal that weighted averaging regression methods (those used for species data sets with unimodal responses to the environmental gradient) work more efficiently when the distribution of the environmental variable being modelled and reconstructed is strictly equally spaced over the whole range of occurrences, lending further affirmation for the even vertical sampling approach.

Vertical intervals of 10cm between sampling sites were ensured by placing a tripod and levelling instrument at a temporary benchmark of known elevation with respect to OD at a fixed point on the shore and using a metered staff to measure out the 10cm intervals in

a straight line, normal to the tide. Previous authors have used 10cm vertical intervals in studies carried out at sites with smaller tidal ranges than the Severn Estuary (Leorri *et al.*, 2010; Woodroffe and Long, 2010). Given that the Severn Estuary is extremely macrotidal, a sampling interval of 10cm will ensure that the sampling resolution is finer relative to previous studies.

The Steart transect (ST1) ranged from 0.646m OD to 4.546m OD and the Beachley transect (BT1) ranged from 4.01m OD and 7.00m OD. The closest tide gauge to Beachley Point is at Newport in South Wales where the tidal range is 13.95m between LAT and HAT (Proudman Oceanographic Laboratory, 2012c). At Hinkley Point, close to Stert Flats, the tidal range is slightly smaller, with 13.21m between LAT and HAT (Proudman Oceanographic Laboratory, 2012b). The corresponding SWLI values for LAT and HAT at the two sites are given in Table 4.1. This sampling strategy ensured that the two transects overlapped by 0.07 SWLI units, which is equivalent to about 0.5m vertical distance at each site.

Table 4.1: Tidal statistics for the two contemporary sites and the vertical ranges of transects ST1 and BT1, in m (OD) and converted to SWLI.

	ST1		BT1	
	m (OD)	SWLI	m (OD)	SWLI
LAT	-6.090	-0.102	-6.400	-0.095
MLWST	-4.980	0	-5.300	0
MHWST	5.930	1	6.330	1
HAT	7.120	1.109	7.550	1.105
Transect lower end	0.646	0.516	4.010	0.801
Transect upper end	4.546	0.873	7.000	1.058

HAT at the Beachley site is at 7.55m OD. However, it was not practical to sample above 7.00m OD due to the presence of a thick hedge composed of *Rubus fruticosus* (blackberry), *Pteridium* (bracken) and *Crataegus* (hawthorn) (see Figure 4.3). At 7.00m OD the vegetation is predominantly terrestrial (*e.g. R. fruticosus*, *Hedera helix* (ivy), *Lolium perenne* (ryegrass) and *Bellis perennis* (English daisy)) and not of the type which is normally associated with the intertidal zone. Proudman Oceanographic Laboratory (2012c) predicts that HAT (7.55m OD) will only be reached by the tide once between now and 2026 and that 7.00m OD will only be flooded by the tide once or twice per year, so it is reasonable to assume that the ground surface above 7.00m OD at Beachley does not experience much marine influence. MHWST is 6.33m OD (Proudman Oceanographic Laboratory, 2012c), and that altitude has been exceeded sufficiently by the range of the transect. A total of 40 samples was collected from ST1 and 31 from BT1. Figure 4.1 shows the location of each transect within the Severn Estuary/Bristol Channel region.

Approximately 50cm^3 of sediment was collected per sample, from the top 1cm of the sediment. The top centimetre is considered by other researchers to be the surface (Scott and Medioli, 1980; Gehrels *et al.*, 2001). Although living specimens of foraminifera have been found up to 60cm deep (Duchemin *et al.*, 2005), most live in the top 10cm and Culver and Horton (2005) conclude that assemblages of tidal indicators found in the 0–1cm interval are directly comparable with fossil assemblages found preserved in deeper sediments. Zong and Horton (1999) use this 1cm rule to account for seasonal changes in diatom assemblages when sampling is a "one-off" exercise in a given year, with no specific intentions to study seasonality in assemblages. A ruler was used to measure the 1cm deep surface layer and a small trowel used to slice off or scoop up a sediment sample.

Samples were sealed in plastic bags and labelled. A photograph of each sampling site was taken, in order for the vegetation zonation across the transect to be recorded later as a desk-based exercise.

Each sample was sub-divided following this approach:

- 4cm^3 for foraminifera analysis

- 1cm^3 for diatom analysis

- 2cm^3 for loss on ignition

- 10 grams for pH and conductivity measurement

- The remainder kept in cold store at $< 4°C$ for any replication or additional analysis needed

4.1.2 Foraminifera preparation and analysis

Foraminifera preparation and analysis largely followed that of Gehrels (2002). The 4cm^3 sub-samples set aside for foraminifera analysis were each divided into two 2cm^3 portions. Gehrels (2002) states that 2cm^3 of material is normally enough to achieve a sufficient number of foraminifera for sea-level studies, so in preparing two subsamples from each surface sampling site, a duplicate was available if the first did not yield a high enough count.

Each subsample was placed in a solution of 4% formaldehyde, baking soda and rose Bengal stain (one teaspoon of each per litre of formaldehyde) within 24 hours of field sampling, and sealed in vials in cold storage (Scott and Medioli, 1986). Rose Bengal is a stain that dyes the protoplasm of the living individuals bright red, allowing them to be counted separately from the dead assemblage (Murray and Alve, 2000). There is an ongoing debate surrounding

the use of live, dead and total assemblages in ecological studies of foraminifera (Murray, 2000). The live assemblage will fluctuate throughout the year, whereas dead assemblages are time-averaged accumulations of tests and so are removed from most seasonal fluctuations in the life assemblage (Horton, 1999; Leorri *et al.*, 2008). Murray (2000) argues that the dead assemblage will have undergone taphonomic change and that the live assemblage should be used in ecological studies. However, for palaeoecological studies Wright *et al.* (2011b) counters this argument by suggesting that, as modern training set data should serve as an analogue for the fossil individuals that are preserved, the dead assemblage more reliably represents that which will eventually be preserved in fossil form, and so should be used in favour of the live assemblage. Gehrels *et al.* (2001) did happen to note that for three UK saltmarshes the modern distributions of live foraminifera and dead foraminifera were both similar to that of the total assemblage, but that finding may have been dependent on the time of year that the samples were taken. Horton and Edwards (2006) found that the size of the live assemblage at Cowpen Tees, UK, peaked in August and was at its lowest in February, but that the dead assemblage stayed relatively stable, when sampling the same 32 sites every two weeks for one year. Because the two contemporary sites used in this study were sampled at different times of year (Stert Flats in October, Beachley Point in May), it is possible that the live assemblages in the two datasets could make different contributions to the total assemblages, suggesting that if included in the subsequent foraminifera training set for the transfer function analysis, the live assemblages would make it erroneous. It would seem that the evidence for distinguishing between the live and dead assemblages and using the dead assemblage for any analysis that will later have any bearing on the fossil reconstruction, is the most compelling (Horton, 1999). Thus, rose Bengal was used to facilitate this distinction.

There are some caveats to using rose Bengal as a protoplasm stain. The main disadvantage is that adherent bacteria, algae and even metabolically inactive protoplasm can sometimes be vividly stained in the same way as the protoplasm of living foraminifera, leading to mis-categorisation of living and dead individuals (Walker *et al.*, 1974; Bernhard, 2000; Lutze and Altenbach, 1991). However, the risk of this is lowered if the wet picking method is chosen over the drying method (Schönfeld, 2012; Duffield and Alve, 2014). Murray and Bowser (2000) reviewed rose Bengal, Sudan Black B and CellTracker Green CMFDA, concluding that none is any more or less reliable than any of the others, but that rose Bengal is the most practical to use in terms of specialist equipment required and the time frame within which samples must be immersed in the stain following their collection in the field.

After being soaked in the rose Bengal solution for 48 hours the subsamples were sieved

and rinsed between 63μm and 500μm sieves (Gehrels, 2002). The sediment remaining in the 63μm sieve was collected and decanted into a grooved counting tray. Various researchers have noted that analysing foraminifera in suspension (the "wet-counting" method) is superior to any method which allows the sediment to dry (Patterson *et al.*, 1999; Edwards and Horton, 2000; Gehrels, 2002; Culver and Horton, 2005). The rose Bengal stain can be detected more readily when tests are wet (Horton and Edwards, 2006), and the drying out of organic residue can cause the delicate organic linings of agglutinated foraminifera to be destroyed (Gehrels, 2002; Schönfeld, 2012) and make identification more difficult due to sediment consolidation (Scott and Medioli, 1980).

The foraminifera were identified and counted under a binocular microscope. Taxonomy was based on Murray (1979), Loeblich and Tappan (1987), De Rijk (1995) and Gehrels (2002). A fine paintbrush was used to pick out those which could not be identified immediately and those individuals were placed onto a pre-glued microfaunal slide for subsequent identification.

Each subsample was analysed for foraminifera in its entirety. Prior to the 1980s some researchers would terminate the count when the required minimum number of individuals was reached. There are two advantages to analysing the entire subsample. Population density, normally referred to as the number of living individuals per 10cm^3, can be expressed (Schönfeld, 2012). More importantly, tests may be sorted to some extent by size or weight when decanted into the grooved counting tray (Gehrels, 2002), thus having the potential to bias the results if only part of a sample is analysed.

Many researchers suggest that counting between 200 and 300 individuals is sufficient to be representative of the total population (Gehrels, 2002; Edwards *et al.*, 2004; Murray, 2006). Kemp *et al.* (2009a), based on work by Fatela and Taborda (2002) chose to use 200 individuals as a minimum, based on the low species diversity found in the intertidal zone. So if the first subsample did not yield at least this number of tests, the second subsample was also analysed, and the total volume of sediment (*i.e.* 2cm^3 or 4cm^3) recorded.

A record of cumulative species diversity was recorded simultaneously to ensure that, for each sample, the total count of at least 200 individuals was sufficient in representing the species diversity of the total population (Woodland, 1996). For every ten individuals counted the total number of species encountered in the sample up to that point was noted.

4.1.3 Diatom preparation and analysis

Diatom preparation followed Palmer and Abbott (1986). 1cm^3 of material from each surface sediment sample was measured out and digested in a 20% solution of 100 volume hydrogen

peroxide (H_2O_2) and left overnight (Plater *et al.*, 2000). H_2O_2 is an alkali which selectively destroys most non-siliceous organic matter (Palmer and Abbott, 1986). After around 18 hours of digestion at room temperature the samples were heated gently on a hot plate. Droplets of less dilute H_2O_2 were added to particularly organic samples to speed up digestion.

Following digestion and dilution with distilled water a small amount of the solution was transferred to a microscope cover slip and heated until dry, and this then mounted onto a microscope slide using the mounting medium Naphrax (Hill, 2006).

Slides were examined under a binolcular microscope at x400 and x600 magnification and a minimum of 300 diatom valves counted per sample (Zong and Horton, 1999). The reference keys of van der Werff and Huls (1958-1974) and Hendey (1964) were used for identification, and cumulative species diversity was recorded every ten individuals.

4.1.4 Organic content of intertidal sediments

LOI and pH were measured because previous studies have shown these variables to contribute to up to 20% of the explained variation in intertidal biological data sets (Horton and Edwards, 2005). Techniques used to calcuate the relative importance of these variables compared with elevation above MSL are discussed in Section 4.2.

Some researchers also measure conductivity which is related to the salinity of the environment, but Szkornik *et al.* (2006) found salinity to contribute to only 1.5% of the variation in their diatom data that was explained by the variables measured. Gehrels and Newman (2004) also found salinity to be insignificant in the distribution of intertidal foraminifera at Ho Bugt in Denmark, whereas tidal elevation and pH were the most important factors. On this basis, and due to the known problems with measuring the salinity of intertidal sediments (Woodland, 1996), salinity is not one of the variables measured.

To measure the variation in organic matter throughout the transect the LOI method was used. This is the most common method used to estimate the organic content of unconsolidated sediments, where sediments are heated in a furnace to 500–550°C to oxidise any organic matter to carbon dioxide and ash (Heiri *et al.*, 2001).

The method used was based on the preferred method of Heiri *et al.* (2001) who analysed the results produced by ten different laboratories where LOI combustion was carried out using both the laboratories' own normal procedures and a standard procedure set by the authors. They concluded that the following procedure gives the most consistent results. Sediment samples were dried at 105°C overnight in pre-weighed crucibles to remove any moisture, then cooled to room temperature in desiccators. After weighing, samples were heated at 550°C

for four hours. After combustion the samples were left to cool to around 100°C and placed back in desiccators to cool to room temperature. Finally, the samples were weighed again. This approach ensures that carbonates such as $CaCO_3$ are not oxidised (Heiri *et al.*, 2001).

The percentage of organic matter in each sample was then calculated using formula 4.2, where LOI_{550} is loss on ignition at 550°C, DW_{105} is the dry weight of the sample before combustion (g) and DW_{550} is the dry weight of the sample after combustion (g).

$$LOI_{550}(\%) = ((DW_{105} - DW_{550})/DW_{105}) \times 100 \tag{4.2}$$

4.1.5 pH of intertidal sediments

Each 10g subsample set aside for the measurement of pH was immersed in 25ml of distilled water, as recommended by the Soil Reaction Committee of the International Society of Soil Science (Bascomb, 1982), and stirred into suspension. The solution was left to settle and then pH was measured with a calibrated VWR pH100 pH probe, calibrated with pH 4 and 7 buffers. This measure was acquired within 24 hours of field sampling.

4.1.6 Intertidal species zonation

Software package 'Tilia' (Grimm, 2011) was used to plot the intertidal zonation of foraminifera and diatom assemblages at the two modern sites with respect to SWLI.

All of the samples from both sites yielded significant numbers of diatoms and at least 300 were identified per sample. A sample size of 300 diatoms is defined here as being acceptable (Zong and Horton, 1999). All of the 71 samples were combined to form the diatom training set.

Gehrels (2002) advises that a minimum sample size of 200 tests should be sought in foraminifera analysis. However, 63 of the 71 samples did not yield counts of 200 or more foraminifera, even when 4cm^3 of sediments were analysed. Due to the low species diversity in the samples from both transects, the dead assemblages of those samples that contained at least 100 foraminifera tests were used to form the foraminifera training set (Horton and Edwards, 2006). Any further analysis done using the foraminifera training set is with the caveat that low numbers were used.

In order to minimise the effects of potentially insignificant foraminifera and diatom species, those species that did not reach 3% abundance in at least one modern sample were excluded from the training sets (Shi, 1993; Szkornik *et al.*, 2006). CONISS (Constrained Incremental Sum of Squares) cluster analysis (Grimm, 1987) was carried out on the two training sets in Tilia to reveal groups of statistically similar samples and delineate assemblage zones. The

cluster analysis was constrained with respect to SWLI and the square root transformation method (Cavalli-Sforza and Edwards, 1967) was used as the distance measure (Grimm, 2011), because it enhances the representation of species with low percentage abundance (Birks, 2012).

4.2 Quantifying the role of environmental factors in explaining intertidal microfaunal variation

This section discusses the methods used to estimate the extent to which the measured variables influence the variation in diatoms and foraminifera in the data sets. Some authors do not use statistical techniques to make estimations about causal relationships between species and their environment at their particular study sites or regions, instead relying on previous research to justify the assumption of those relationships (Callard *et al.*, 2011; Edwards and Horton, 2000; Horton *et al.*, 1999b; Leorri *et al.*, 2010). Juggins (2013) warns that due caution should be taken when attempting to reconstruct variables that account for only a small independent proportion of species variation in a training set. For multi-proxy studies this is a particularly important step because the extra time and expertise involved in adding an extra proxy needs to be justified, and as Huntley (2012) summarises, multi-proxy studies that do not ensure that the appropriate variables are being reconstructed from the proxies do little to reduce the uncertainty in the reconstructions.

4.2.1 Multi-proxy training sets

The nature of the two sea-level indicators means that the way in which they ought to be combined together into one single statistical training set is not immediately obvious. In this case this is because many of the samples in the training set did not contain a sufficient abundance of foraminifera. In fact, while all 71 samples yielded acceptable diatom counts, only 23 samples contained at least 100 foraminifera.

There are three systematic ways in which the two training sets could have been merged together given this issue:

A. Only those 23 samples with acceptable foraminifera counts (at least 100 tests) are included. This means that only those samples based on significant numbers of both proxies are used in the analysis, but that in adding some new information to those 23 samples by using two proxies, 48 acceptable diatom samples are rejected, potentially leaving large gaps where environments are not modelled by the microfaunal data, with repurcussions for the reconstruction.

B. All 71 samples are used, but those without acceptable foraminifera counts are given values of zero for all foraminifera species. This results in the diatom data being fully utilised while excluding foraminifera samples with insufficient numbers.

C. All 71 samples are used and those with low foraminifera counts are nevertheless included. This may be justified by viewing the approach as simply adding some more variables (species) to the already significant diatom data. While samples low in foraminifera could not be used alone, adding them to the diatom data contributes further information to aid the transfer function and reconstruction.

As it was not clear at this stage of the process which of these approaches was the most suitable, combined training sets A, B and C were compiled using all three of these methods, and compared with the two single proxy training sets in terms of the results of the multivariate analysis and the transfer function development (see Sections 4.2.2 and 4.3 respectively for these methods).

4.2.2 Multivariate analysis

Several techniques for exploring and analysing ecological and palaeoecological data have been developed since the 1950s (Goodall, 1954). Ecological datasets very often consist of a number of samples or sites, many species and their relative abundances per sample, and sometimes several other variables, such as environmental measures like water pH or temperature. In the case of this research, the contemporary data collected at Beachley Point and Stert Flats is in this multivariate format, with 71 sampling sites, relative abundances of many species of foraminifera and diatoms, and three environmental variables: SWLI (linked to elevation above OD), pH and LOI.

Multivariate datasets are by their nature very complex, and it is not possible to visualise or present raw, multidimensional data in any useful or meaningful way, hence the development of a suite of multivariate techniques, designed to reduce the number of variables or dimensions in a dataset to a number that is comprehendable and presentable on paper. Two main groups of techniques are available (Shi, 1993); those that classify samples or sites into groups (cluster analysis) and those that arrange samples or variables in an ecological space according to their overall similarity to each other or in relation to their environment (gradient analysis or ordination).

Cluster analysis has already been described in Section 4.1, and the results of the cluster anlaysis of the modern species data from the two sites is presented in Section 5.1 of Chapter 5. The remainder of this section will explore ordination, the second branch of multivariate

analysis available to ecologists and palaeoeologists, and describe and discuss the techniques that have been used in this thesis to attempt to quantify the role that tidal level plays in explaining intertidal microfaunal composition.

Principal components analysis (PCA) was the first ordination method to be used in ecology (Digby and Kempton, 1987). The procedure converts a set of variables that may display some degree of correlation into a smaller number of new variables in such a way that the first component or new variable contains or explains as much of the variation in the data as possible (Hammer *et al.*, 2001). The goal of PCA in ecology and palaeoecology, therefore, is to reduce species abundance data down to the smallest number of components that can account for the majority of the variation in the dataset, and to plot the original samples onto a two or three dimensional diagram, so that groups or clusters of similar samples, and differences between those groups, might be noted (Ter Braak and Prentice, 1988).

PCA is a relatively simple technique, and since computational power has increased beyond that which was available when PCA was first developed as a mathematical technique in 1901 (Pearson, 1901), several more sophisticated techniques have replaced PCA as the standard ordination methods for ecologists and palaeoecologists. One of the main underlying assumptions of PCA is that species respond linearly to factors that influence their abundance. Most ecologists agree that this assumption is questionable and that to assume unimodal responses is more realistic, with most species displaying the greatest abundance at their optimum value of a given variable, with decreasing tolerence away from that optimum to either side (Kent and Coker, 1992).

Figure 4.4 shows the difference between these two models of species response behaviour. One of the great difficulties in ecology is being certain whether or not the entire environmental gradient affecting the abundnace of a particular species has been measured. If a linear relationship between a species and a measured environmental variable is observed, it may not be immediately possible to know whether a true linear relationship is being observed, or whether sampling has taken place on one of the two sides of a unimodal curve, as indicated by points 1 and 2 in Figure 4.4 (B). Without knowing that a bell-shaped response to the environmental variable exists beyond the sampling range, one might logically assume that a simple linear relationship exists between the species and the variable.

Several techniques based on the assumption of unimodal response models have been developed (see Table 4.2). The first of these, correspondence anlaysis (CA), will result in plots that can show both species and samples as points on the same diagram, so that an indication of the species composition of the samples can be gained from observing which species are
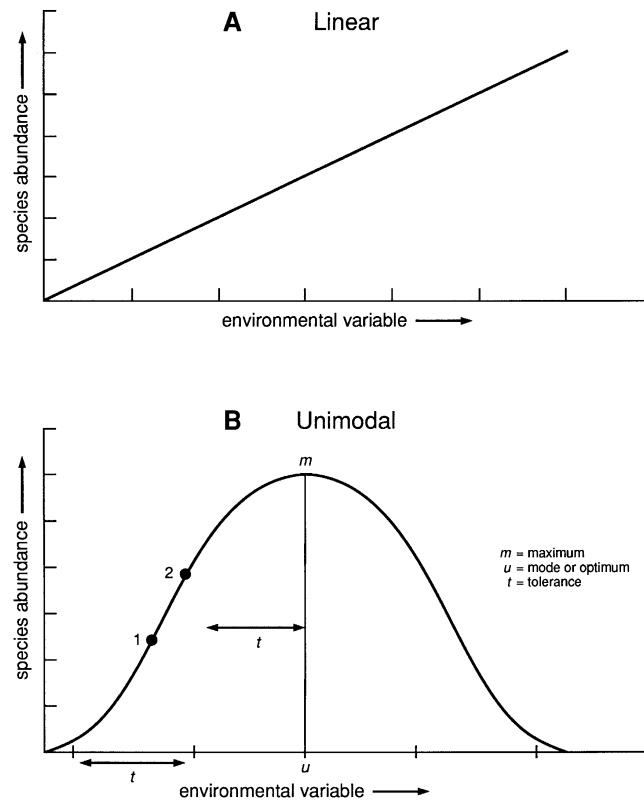
Figure 4.4: A: a linear response model; B: a unimodal response model. u is the optimum (the value of x that gives the maximum abundance), m is the maximum species abundance, t is the tolerance (a measure of ecological amplitude). Reproduced from Dale *et al.* (2002) with permission from Elsevier.

plotted close to which samples, as well as the similarity of samples, reflected by their distance from one another. CA has been shown to distort some data sets in two undesirable ways (Shi, 1993), producing first an 'arch' effect, causing an artificial horse-shoe shape to appear within the plotted points, and second, a 'bunching' effect where points are compressed together at each end of one axis (see Figure 4.5).

Hill (1979) added a detrending step to CA, thereby developing DCA, by dividing the first axis of a CA ordination into segments and rescaling each segment, squashing the artificial horse-shoe arch flat, and stopping the ends of the axis from being compressed relative to the middle.

Palmer (1993) criticises DCA, which apparently performs poorly on skewed species distributions and will destroy any true arch that may actually occur in the data. Instead Palmer (1993) advocates the use of CCA. CCA is a direct ordination method which constructs the axes of variation explicitly to fit real, measured environmental data, in contrast with the indirect methods described previously which do not constrain the axes with measured data, but display samples along axes of variation in their species composition, such that the axes can subsequently be interpreted as important environmental gradients (Ter Braak and Prentice,
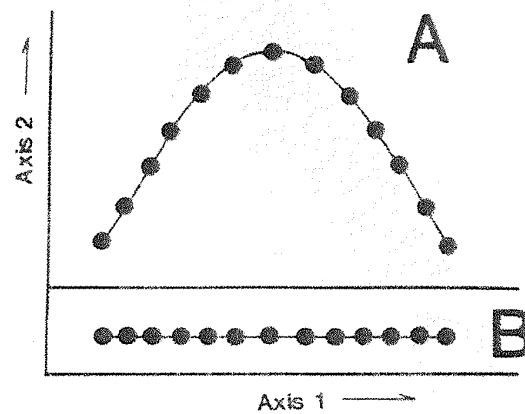
Figure 4.5: The two main types of distortion caused by CA. (A) the arch effect. (B) the compression of the points towards the ends of the first ordinationa axis. Reproduced from Shi (1993) with permission from Elsevier.

Table 4.2: Summary of the main ordination methods used in ecology and palaeoecology.

Technique	Direct or indirect?	Linear or unimodal?	Notes
PCA	Indirect	Linear	Principal components analysis. An early form of ordination, taking a raw data matrix of n samples and m variables (species) and positioning them in subspace of k dimensions which maximise the variation in the m variables.
PCO	Indirect	Linear	Principal coordinates analysis. Similar to PCA, but distances between every possible pair of objects is calculated, and the points plotted so as to preserve these distances as closely as possible.
CA	Indirect	Unimodal	Correspondence analysis. Developed to account for the assumption of non-linear responses of species to environmental gradients.
DCA	Indirect	Unimodal	Detrended correspondence analysis. Developed to overcome the arch and compression effects of CA.
CCA	Direct	Unimodal	Canoncial correspondence analysis. Includes environmental variables and explicitly optimises the axes to fit these measured data.
RDA	Direct	Linear	Redundancy analysis. Calculates PCA on a species data matrix constrained by measured environmental variables.
NMDS	Indirect	No assumption	Non-metric multidimensional scaling. Uses rank orders rather than actual values, so makes no assumptions about species responses patterns.

1988).

Resulting CCA biplots can either show samples or species or both samples and species plotted in the ordination space. The closer two sample points lie the more similar their species composition, and the closer two species points lie, the more similar their distribution. Lines radiating from the centre of the plot represent the measured variables. The lengths of the lines represent how important the variables are and their direction indicates their correlation with one another - a small angle means strong positive correlation, a 90 degree angle means no correlation and a 180 degree angle means perfect negative correlation (Palmer, 1993). In addition, the locations of samples relative to the variable lines indicate the characteristics of those samples and the locations of species points indicate the preferences of each species with regards to the variable represented by each line. The closer a species or sample to a line, the more important that variable. A CCA plot is an elegant method of presenting a large, complex multivariate data set in two (or three) dimensions.

Examples of sample-environment and species-environment CCA biplots are shown in Figure 4.6, from a study by Horton and Edwards (2006) on saltmarsh foraminifera in Cowpen Marsh on the Tees Estuary. The arrows show that there is some positive correlation between elevation, the size of the clay fraction, LOI and salinity, and negative correlation between those variables and pH. It would appear from these plots, from the bunching of some samples and species to the right, that many of the them are influenced strongly by pH, while fewer samples and species are strongly influenced by elevation. The elevation arrow is parallel to the first axis, meaning that elevation is likely to be a strong predictor of species composition.

Palmer (1993) also shows CCA to perform better than DCA under a number of different conditions, such as high data noise, non-optimal sampling design and high collinearity (a large number of highly intercorrelated variables).

The linear equivalent of CCA is redundancy analysis (RDA), which performs PCA on a species data matrix constrained by a matrix of environmental variables (Kent, 2012). Like CCA, RDA leads to plots that can present patterns in species and samples, and trends in environmental variables simultaneously (Ter Braak and Prentice, 1988).

Non-metric multidimensional scaling (NMDS), a further indirect ordination method, makes no assumptions about species response models because the technique uses the rank orders of samples rather than the actual species abundance values (Legendre and Legendre, 1998).

There are no established, rigorous methods available to test ordinations for their accuracy or error because most of the ordination methods do not involve defining a null hypothesis statistically.
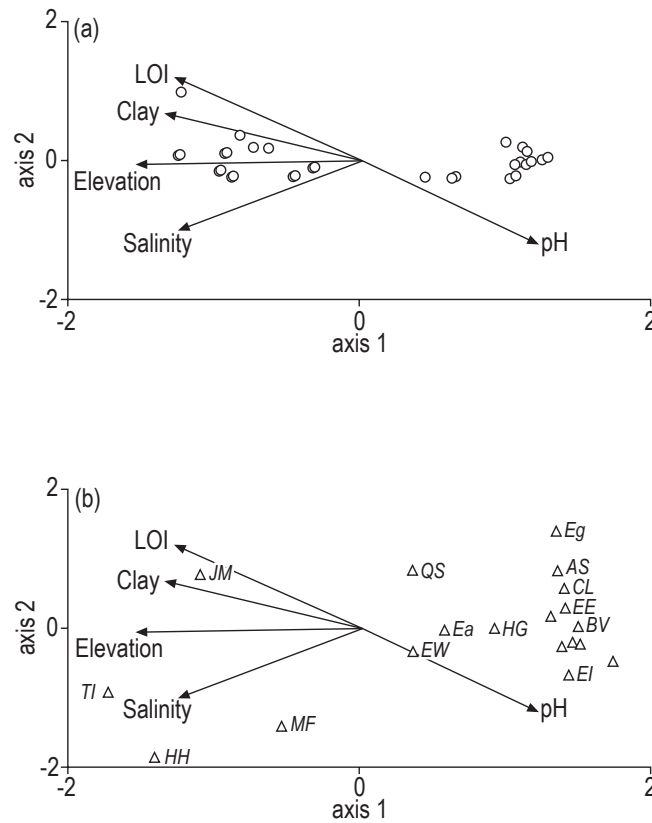
Figure 4.6: Illustration of CCA (a) sample-environment and (b) species environment biplots of foraminifera and environmental data from Cowpen Marsh on the Tees Estuary. From Horton and Edwards (2006). Reproduced with permission from the authors.

Shi (1993) suggests that the best way to evaluate the results of an ordination is to use the value, given by the particular software used for the analysis, of the percentage of variation in the data accounted for by a given number of axes. The higher this value the more successful the ordination is deemed to be.

All ordination methods are vulnerable to three main kinds of distortion (Orlóci, 1978; Whittaker and Gauch, 1978). The first type occurs when the wrong method is used; in particular, when a linear ordination model is used with non-linear data. The risk of this kind of distortion can be reduced by transforming data to make it more linear, dividing the data into clusters that display more linear characteristics and examining each cluster separately, or by using DCA, CCA or NMDS in preference to PCA or principal coordinates analysis (PCO) (Shi, 1993).

The second kind of distortion is linked to the very nature of ordination, which is the projection of a multidimensional configuration onto a plot with fewer axes than the number of dimensions that the data has been reduced down into, much like the way that projections of the surface of the Earth onto two dimensions are always distorted (Shi, 1993). For example, CCA might reduce a data set with 50 species and 5 environmental variables down to four axes,

but only two or three axes can ever be visualised and plotted, so distortion will occur. This type of distortion is the hardest to avoid, so researchers must decicde for themselves whether risking some distortion is or is not made up for by the insight gained from the analysis.

The third type of distortion is caused by choosing an inappropriate method for measuring the distance between two points. PCO was developed out of PCA (see Table 4.2) in order to provide analysts with a choice of distance measures, because PCA only offers one distance measure (Euclidean/Pythagorean) which is not always appropriate.

In seeking to produce a sea-level transfer function based on assemblages of intertidal microorganisms, the effects of certain, measured environmental variables on species distribution are particularly important, therefore direct ordination methods are preferred. As discussed in Section 2.6 of Chapter 2, previous authors have used direct ordination (*e.g.* CCA) methods to estimate the extent to which measured environmental variables explain variation in the species data, in preparation for developing a transfer function (Ng and Sin, 2003; Charman *et al.*, 2002; Horton and Edwards, 2000; Zong and Horton, 1999). For example, if contemporary data shows pH to be the main influence on species distribution of foraminifera and tidal level to be a relatively minor influence, a sea-level transfer function based on that particular data set would be likely to produce questionable results.

First, direct ordination methods CCA and RDA can be used to estimate the percentage of the variation in the species assemblages in a data set that can be attributed to the environmental variables used to constrain the ordination. Then, partial direct ordination can be implemented to partition off one environmental variable at a time from the main variable matrix, in order to estimate the proportion of that explained variation attributable to each of the measured variables (Oksanen, 2011).

Other authors have noted that the sum of the percentages given by partial direct ordination rarely comes to 100% and attribute any remaining explained variation to intercorrelation between the measured variables (Zong and Horton, 1999; Horton and Edwards, 2000).

The two direct ordination options available are linear method RDA and unimodal method CCA. Rather than making an arbitrary assumption about the shape of the species' responses to their environment, DCA was first used to inform which method was most appropriate for each of the training sets.

Ter Braak and Prentice (1988) propose that the length of the first axis of a DCA ordination is a good proxy for the shape of species' response to their environment, despite the limitations of DCA as an ordination method, as outlined above. Several authors have used this approach to determine the most appropriate ordination methods to use to explore multivariate data,

and to determine which regression models to us to develop species-based transfer functions (Horton *et al.*, 1999b; Dale *et al.*, 2002; Horton and Edwards, 2006; Lu *et al.*, 2011; Ooms *et al.*, 2011).

If the gradient length of axis one is less than 2 standard deviation (SD) units, linear models are most appropriate, whereas unimodal models are more suitable when the first axis is more than 2 SD units long (Birks, 1995).

The 'vegan' package (Oksanen, 2011; Oksanen *et al.*, 2013) was implemented in R, a software environment for statistical computing and graphics (R Core Team, 2011), to run DCA ordination on the foraminifera and diatom training sets separately and on the three versions of the combined training set.

The full results of the DCA ordination tests are given in Chapter 5, but for the purposes of determining the next step in the methodology, the results are outlined briefly here. The diatom training set was found to show non-linear species responses to the environmental gradient, with an axis one length of 5.29 SD units, therefore CCA was used for the diatom training set. The DCA ordination of the foraminifera training set indicated that linear models might be more appropriate. The gradient length of the first axis in this case is 1.68 SD units. With the gradient length being so close to 2, both RDA and CCA were used (Callard *et al.*, 2011) and the results compared.

The gradient length of the first axis of combined training set A was 1.98, so both RDA and CCA were used. The gradient length of combined training sets B and C were both greater than 2 SD units, so CCA was used.

To summarise, the following full and partial direct ordination analyses were performed on the four training sets:

- Diatom training set: full CCA, partial CCA

- Foraminifera training set: CCA, partial CCA, RDA, partial RDA

- Combined training set A: CCA, partial CCA, RDA, partial RDA

- Combined training set B: CCA, partial CCA

- Combined training set C: CCA, partial CCA

4.3 Developing a multi-proxy sea-level transfer function

The development and implementation of a transfer function involves a regression step and a calibration step (Ter Braak and Prentice, 1988). The modern relationships between the

biological species and the environmental variable are modelled using a regression method (Birks *et al.*, 2010), then this function is reversed to perform the calibration step, such that the model and the species data are used to estimate the environmental variable at a given site (Bere and Tundisi, 2009). Most authors use some form of cross-validation test, such as the jackknifing and bootstrapping methods mentioned previously in Section 2.5 of Chapter 2 (Birks, 1995; Racca *et al.*, 2001; Gehrels *et al.*, 2006a). The predictive ability of a resulting transfer function is given by the results of this cross validation exercise (Szkornik *et al.*, 2006).

Two categories of regression and calibration methods are available to construct transfer functions: linear and unimodal. These were described briefly in Table 2.1 of Chapter 2.

The PLS method is the main multivariate linear method available in the software C2 (Juggins, 2007) and combines features from PCA and multiple linear regression to form components that capture most of the information in the species data, reducing the number of dimensions down to a small numbers of components, then performs multiple linear regression on those components and the environmental variable (Abdi, 2004; Yeniay and Göktaş, 2002). PLS regression was introduced into ecology because it is particularly effective when the number of predictor variables is similar to or higher than the number of observations (*e.g.* more species than samples) and when there is strong collinearity among the predictors (Carrascal *et al.*, 2009). Principle components regression (PCR) has also been used in the past, but is considered to be a weaker method than PLS because, while PCR maximises the variance within the species data, PLS maximises the covariance of the environmental variable with the species data, thus giving a better fit (Ter Braak and Juggins, 1993; Birks, 1995, 1998).

Three unimodal regression and calibration methods are available: WA, WA-Tol and WA-PLS. WA regression is based on the assumption that a species with a particular optimum for a given environmental variable will be most abundant when the variable is close to that optimum (Ter Braak and van Dam, 1989), and takes the average of the environmental variable over sites where the species are present, weighted by the species abundance to calculate this optimum (Bere and Tundisi, 2009).

WA-Tol is a modified form of WA that gives more weight to species with narrower ranges of tolerance to variation in the environmental variable being modelled (Korsman and Birks, 1996; Gehrels, 2000; Ng and Sin, 2003).

By combining features of WA and PLS regression (Juggins and Birks, 2012), namely the ability to model unimodal species responses and the efficient extraction of components from a complex, multivariate data set,WA-PLS (Ter Braak and Juggins, 1993) often, but not always, shows improved performance compared with WA transfer functions (Salonen

et al., 2012). WA can overestimate optima at the lower end of an environmental gradient and underestimate at the upper end, causing what is known as the "edge effect" (Birks, 1995). WA-PLS was designed to reduce this problem, and also uses the interactions between predictive variables to improve predictions (Sawai *et al.*, 2004).

Based on the aforementioned gradient lengths, given by the DCA ordination for each training set, the software package C2 (Juggins, 2007) was used to produce the following transfer functions:

- Diatom training set - WA, WA-Tol and WA-PLS models

- Foraminifera training set - WA, WA-Tol, WA-PLS and PLS models

- Combined training set A - WA, WA-Tol, WA-PLS and PLS models

- Combined training set B - WA, WA-Tol and WA-PLS models

- Combined training set C - WA, WA-Tol and WA-PLS models

Two methods of cross validation are available in software C2, and both of them have been used successfully in many sea-level studies; jackknifing (Massey *et al.*, 2006a; Ooms *et al.*, 2011) and bootstrapping (Zong and Horton, 1999; Gehrels *et al.*, 2005; Woodroffe and Long, 2010; Rossi *et al.*, 2011). Bootstrapping is considered to be the superior method because it offers greather precision (Lanyon, 1987) than jackknifing.

Bootstrapping with 1,000 cycles (Kemp *et al.*, 2009a; Leorri *et al.*, 2008, 2011) was used for cross validation of all of the regression models because of its increased precision and its superior function of producing an individual error estimate for each fossil sample (Birks, 1998; Hill, 2006; Kemp *et al.*, 2009a).

Bootstrapping cross-validation gives a mean average coefficient of determination (r^2_{boot}) and prediction error (RMSEP) for each transfer function, as well as an estimated SWLI value and associated residual for each training set sample. A residual is defined as the difference between results obtained by observation and by the transfer function (Horton and Edwards, 2006). Sample specific estimates and residuals give some indication of which parts of the intertidal zone the transfer function is strongest and weakest in, and whether it is likely to over- or underestimate the former elevation of certain environments.

4.3.1   Model evaluation

When creating WA and WA-Tol regression models software package C2 will return two sets of results per model, one based on classical regression and one on inverse regression (Juggins,

2007). Using the example of a diatom-based sea-level transfer function, where modern training set Y_m relates to modern elevation X_m, the assumption is made that elevation has some causal relationship with the modern diatom data, such that X_m influences Y_m in a way that can be modelled statistically. The ultimate goal of a diatom-based sea-level transfer function is to use fossil diatom data Y_f to predict past elevation data X_f, but there are two ways in which to model the relationship between Y_m and X_m.

The first, the classical approach, is to produce a regression model that predicts the species data (Y_m) from the elevation data (X_m), based on the assumption about their causal relationship as in equation 4.3, then invert this to predict X_f from Y_f (Juggins and Birks, 2012).

$$Y_m = f(X_m) + error \qquad (4.3)$$

The second way is to use the species data (Y_m) to predict modern elevation (X_m), since this will be the eventual direction of prediction from the fossil data, as in equation 4.4, even though we do not actually think that the species data influence elevation. This is the inverse method where the regression model itself is not inverted but elevation is treated as a dependent variable and the species abundances as predictor variables (Ter Braak and Prentice, 1988).

$$X_m = f(Y_m) + error \qquad (4.4)$$

These two methods will produce slightly different results, because in the regression step the classical method models many species on the variation in one environmental variable, whereas the opposite is true in the inverse approach.

Statisticians and palaeoecologists have noted that inverse models tend to perform best if fossil assemblages are similar to the modern assemblages found towards the middle of the environmental gradient(Ter Braak, 1995; Birks *et al.*, 2010). Classical methods appear to perform better at the extemities of the modern training set and with slight extrapolation beyond it (Birks *et al.*, 1990; Birks, 1995).

Both classical and inverse WA and WA-Tol transfer functions were produced and their application to the fossil data was dependent on the nature of the fossil assemblages with respect to their relationship with the modern gradient and any significant differences between the r^2 and RMSEP values.

While PLS and WA-PLS models do not have classical and inverse forms because the species are always taken to be the independent variables, the nature of these methods of multivariate regression means that models based on increasing numbers of components are

returned by the analysis. The more components used, the more successful a model will appear to be but adding components also adds statistical complexity and the relationships between species and the environmental variable are modelled less directly (Barlow *et al.*, 2013). The principle of parsimony in relation to multivariate PLS and WA-PLS recommends that the lowest number of components that gives an acceptable model should be chosen to perform the palaeoenvironmental reconstruction (Wright *et al.*, 2011b; Hawkes *et al.*, 2010; Cearreta *et al.*, 2008; Horton *et al.*, 2003).

Birks (1998) highlights the issue that introducing more components may improve the prediction statistics (r^2 and RMSEP), but that these statistics will continue towards 1 and 0 respectively until the number of components equals the number of species in the training set and the regression model will no longer be of any use to reconstruct the environmental variable from a fossil data set. The choice of how many components to use was therefore a compromise between good prediction statistics and a low number of components. Brooks and Birks (2000) suggest that an additional component should give a reduction in RMSEP of 5% or more in order to constitute as "useful". Barlow *et al.* (2013) also advise that no more than three components should be used. Therefore, successive components were only added if model improvement, defined by a 5% reduction in RMSEP, was achieved by adding the next component, up to a maximum of three. This approach was taken in those cases where WA-PLS or PLS transfer functions proved to be superior to the corresponding WA and WA-Tol versions.

4.4 Reconstructing Holocene sea-level change in at the Steart Peninsula

4.4.1 Collection and sampling of sediment cores

Following an intial scoping investigation of the sediment stratigraphy of the Steart Peninsula, contact with land owners was made and on two occasions, sediment cores totalling just over 11m in length were retrieved using a percussion gouge corer, from the site shown in Figure 4.7.

The scoping investigation revealed the Holocene stratigraphy published by Kidson and Heyworth (1976); silty clays interbedded with several organic units, and the coring site was selected for its stability behind the beach ridge and away from the River Parrett. Stolford and the Steart Peninsula were important sites for Kidson and Heyworth (1976) and Heyworth and Kidson (1982) due to the presence of basal peats lapping onto bedrock (Case, 2013). The Steart core collected for this study benefits from this feature, providing a SLIP that will not have experienced sediment autocompaction and any corresponding inaccuracy in altitude.

The Steart core is 11.22m in length, the top 1m being discarded as it was composed mainly of top soil. The core was extracted from the ground at ST 26110 44906. At 12.22m deep the corer hit an inpenetrable surface and could not be drilled any further. The coring site was levelled to ordnance datum (OD) via a local benchmark.
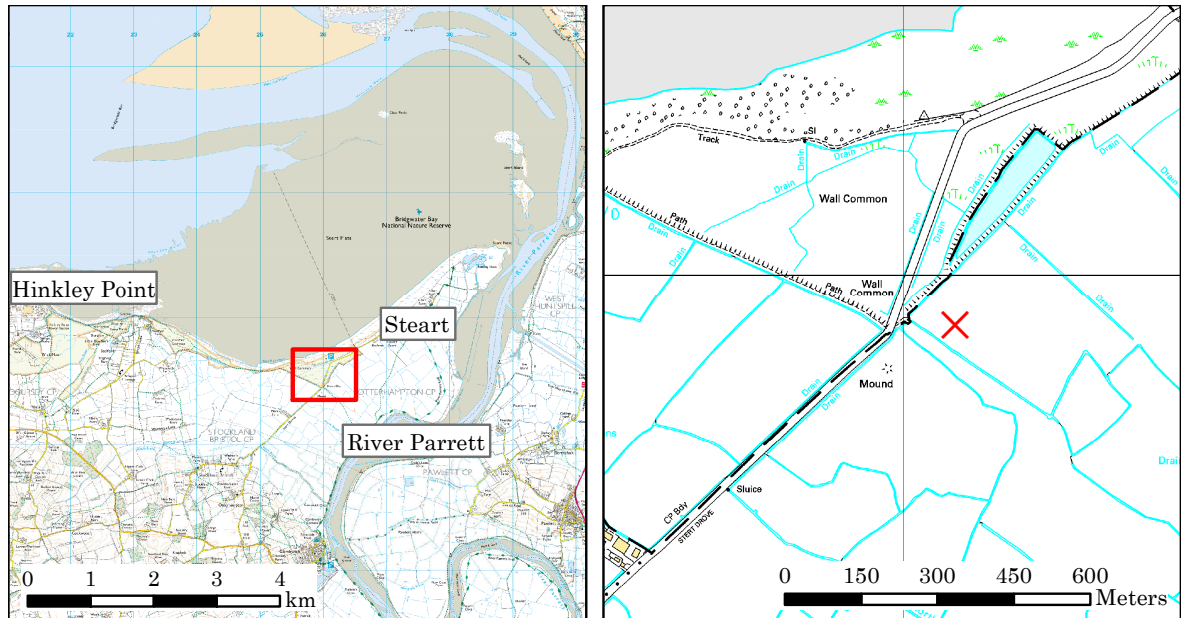
Figure 4.7: Location of the coring site near Wall Common on the Steart Peninsula, denoted by a red cross. Source: Ordnance Survey (GB) (2012a).

The core was described using the Troels-Smith sediment description system (Troels-Smith, 1955). The system is used to describe the various sediments present based on the physical properties, degree of composition of organic substances and the component parts of each sedimentary unit (Aaby and Berglund, 1986), and can be useful in recording the physical properties of sediment cores and informing decisions about where to sample for the various analyses. LOI was also measured every 2cm throughout, using the method described previously for the modern sediments in Section 4.1.

4.4.2   LOI and micropalaeontology

The diatom and foraminifera content of the upper 6m was analysed at 8cm intervals in the silty-clay units, following the examples of Charman *et al.* (2010) and Wilson and Lamb (2012). At transitions between sedimentary units the sampling resolution was increased to 4cm intervals (Massey *et al.*, 2008). In the organic units samples were also taken at 4cm intervals (Horton and Edwards, 2000). The lower 5m indicate little change in environment, with consistent grey silty-clays throughout, with a thin organic unit at the very base, so here sampling resolution was reduced to 24cm intervals. The basal organic unit was sampled every 2cm. The samples were prepared and analysed using the procedures described previously for

the modern sediments in Section 4.1, with the only differences being that the foraminifera samples were not soaked in a rose Bengal solution prior to sieving, because the fossil assemblages are not expected to contain any live specimens, and in the interest of conserving enough material for all of the analyses, only 2cm^3 of material was used per sample for the foraminifera analysis. Any sediment that was particularly cohesive was soaked in a Calgon (sodium hexametaphosphate) solution for 24 hours to disperse before foraminifera analysis (Houston *et al.*, 1999). Cluster analysis was implemented in 'Tilia' (Grimm, 2011) to identify distinct fossil microfaunal zones within the core.

Five samples were selected for AMS radiocarbon dating (see Section 4.4.4).

4.4.3 Analogue matching

One of the limitations in quantitative palaeoenvironmental reconstruction is the possibility of situations where some of the fossil samples do not have good analogues in the modern training set. Woodroffe (2009) warns that a seemingly precise transfer function model may prove to be unusable if there are many samples in the core without modern analogues in the training set. A lack of modern analogues can be due to limited modern elevational range, mitigated in this study and others by modern sampling of the intertidal zone from MTL to above MHWST (Gehrels *et al.*, 2001; Hill *et al.*, 2007; Horton and Edwards, 2006).

Wright *et al.* (2011b) propose that the similarity between fossil and modern assemblages should be be quantified and accompany any RSL reconstruction. Birks (1998) proposes two simple measures of reconstruction reliability related to modern analogues; 1) the percentage of each fossil assemblage that is composed of species that are not represented at all in the modern training set, and 2) the percentage of each fossil assemblage that is composed of species that are poorly represented (*e.g.* maximum occurrence of 10%) in the modern training set. The optima and tolerances of those species in 1) will be unknown and in 2) will be poorly estimated by the transfer functions. These two measures were calculated for each of the fossil samples to give an impression of which fossil samples might lack good analogues in the modern training set.

However, a more sophisticated method has been used by several authors to determine statistically how well represented the fossil assemblages are in the modern environment (Birks *et al.*, 1990; Edwards and Horton, 2000; Edwards *et al.*, 2004; Hamilton and Shennan, 2005; Horton and Edwards, 2005). This method is referred to variously as analogue matching and the modern analogue technique (MAT) by different authors. To avoid confusion with the method of reconstruction known as the MAT as detailed in Section 2.5 of Chapter 2, the

term ' 'analogue matching' will be used in reference to identifying samples in a modern data set that are the closest matches to the species assemblages identified in a set of fossil data (Simpson, 2007, 2012).

The 'analogue' package (Simpson and Oksanen, 2013; Simpson, 2007) was used in R (R Core Team, 2011) to compare every fossil diatom sample to every modern diatom sample, every fossil foraminifera sample to every modern foramininfera sample, and so on for all five of the single-proxy and combined training sets. The diatom and foraminifera core data were combined together to form multi-proxy fossil data sets in the same three ways the modern training sets were compiled. Thus, fossil data set A is composed only of the samples with significant foraminifera *and* diatom counts, fossil data set B takes each sample with significant numbers of at least one of the proxy groups and replaces any low counts in the other proxy with zeros, and fossil data set C takes each sample with significant numbers of at least one of the proxies and retains any low counts in the other proxy.

The Bray-Curtis dissimilarity (equation 4.5) was used to compile the distance matrices and a minimum dissimilarity coefficient estimated for each fossil sample and the modern sample most similar to it (Brodersen and Bennike, 2003). The Bray-Curits dissimilarity was developed by Bray and Curtis (1957) specifically for use by ecologists and biologists and is widely used in multivariate analysis of assemblage data. A coefficient of 0 between two samples indicates that they are identical and coefficient of 1 indicates that two samples do not share any species (Clarke *et al.*, 2006).

$$d_{jk} = \frac{\sum_i |x_{ij} - x_{ik}|}{\sum_i (x_{ij} + x_{ik})} \tag{4.5}$$

d_{jk} is the dissimilarity between samples j and k, i is a species, x_{ij} is the proportion of species i in sample j and x_{ik} is the proportion of species i in sample k.

Simpson (2007) instructs that proportion data, rather than raw counts, ought to be used in analogue matching. For the single proxy data this is not a problem, but becomes more complex when combining together data for two proxies that have been measured in different ways. In both the modern and fossil data sets the diatom samples each have counts of approximately 300 individuals (after accounting for a number of species excluded due to low abundance), whereas the foraminifera samples are counted per unit volume and vary widely in size.

The options for combining these two different types of ecological data are; 1) to ignore the advice of Simpson (2007) and use count data, 2) to add all species of both proxies together per sample and take proportions of the totals, and 3) to take proportions in each proxy

separately, so that the total proportion of each whole sample is two rather than one. The first option is not advised by the author of the analogue package and documentation so is best avoided. The second option is a naïve way of combining two different kinds of data (Simpson, 2012), not least because the diatom samples are generally larger and more species rich, so will carry more weight, but also because the two data sets are mutually exclusive. They were not counted together, but analysed using separate methods, so an increase in one diatom species should not necessarily result in the decrease of any foraminifera species. This leaves the third option which uses proportions while preserving the distinction between the two proxies and gives equal weight to each of them. Mitchell *et al.* (2013) used a similar rationale to combine presence/absence data for bryophytes and vascular plants and abundance data for testate amobae in a study of mire surface wetness and pH, in order to give the same weight to each data set in the analysis. Each version of the combined modern and fossil data sets (A, B and C) was converted to proportions in this way prior to analogue matching analysis.

Horton and Edwards (2006) consider core samples with dissimilarity coefficients below the 10th percentile of the distribution of coefficients to have good analogues. This approach was adopted by Kemp *et al.* (2009a) who also assumed that those with coefficients between the 10th and 20th percentile to have fair or reasonable analogues in the modern data. The rationale behind this approach has not been fully explained by the authors of their of the two papers, and the choice of percentiles seems arbitrary. Wright *et al.* (2011b) calls for a consensus on what exactly constitutes a "good" analogue, but that is beyond the scope of this study. Therefore, the method of Kemp *et al.* (2009a) has been adopted here, using the 10th and 20th percentiles to distinguish between fossil samples with good, fair and poor modern analogues, so that a direct comparison can be made with Horton and Edwards (2006) and Kemp *et al.* (2009a). Those with less than good modern analogues have still been used for the quantitative sea-level reconstruction, because transfer function models that use weighted averaging regression (WA, WA-Tol and WA-PLS) do still have the potential to perform well in non-analogue situations (Birks *et al.*, 2010), but with this caveat being made explicit in the presentation and discussion of the results.

With the same approach as the modern microfaunal data analysis, species accounting for less than 3% abundance of at least one core sample were removed from the data sets prior to any statistical analysis (Shi, 1993; Szkornik *et al.*, 2006).

Poor modern analogues as a limitation to the transfer function approach to palaeoenvironmental reconstruction is discussed further in Section 4.6.

4.4.4 AMS radiocarbon dating

Five AMS radiocarbon dates were derived from organic sediments at points in the Steart core where environmental changes were indicated by transitions to and from organic and minerogenic deposition. Samples were sent to Beta Analytic in Florida, USA for pre-treatment and analysis (Beta Analytic, 2013).

Radiocarbon dating has a history of use in sea-level studies of several decades (Kidson and Heyworth, 1976; Zong, 1997; Gehrels, 1999; Horton and Edwards, 2005; Engelhart and Horton, 2012) and since the introduction of AMS the dating of very small samples (*i.e.* 1mg of organic carbon or less) has been possible, on a much faster timescale than was possible with conventional radiocarbon dating (Lowe and Walker, 1997). Based on the principle that radioactive decay of ^{14}C to ^{14}N occurs at a known rate, radiocarbon dating is a technique that measures the proportion of the residual ^{14}C to ^{12}C in a sample of organic material to give an estimate of the amount of time that has passed since radioactive decay began, when the previously living matter stopped absorbing CO_2.

Radiocarbon dating is limited to material that is less than 50,000 years old, which means that the Holocene sediments of the Somerset Levels are suitable for dating using this method (Haslett *et al.*, 1997, 1998; Housley *et al.*, 1999).

Care was taken to avoid contamination of samples by sediment from other parts of the core and by preserved, vertically placed roots that might bring young carbon down into lower depths. Ages in radiocarbon years were converted to calibrated (cal.) years BP using the INTCAL09 database (Heaton *et al.*, 2009; Reimer *et al.*, 2009; Stuiver and Braziunas, 1993; Oeschger *et al.*, 1975).

The employment of AMS radiocarbon dating satisfies the requirement outlined by Birks (1995) and Birks *et al.* (2010) that chronological control of the fossil data sets in a quantitative environmental reconstruction should be independent of those fossil data sets.

4.4.5 Establishing sea-level index points

Five sea-level index points (SLIPs) were established based on the five radiocarbon dated samples. As outlined in Section 2.4 of Chapter 2 a SLIP must include an age, an altitude, an indicative meaning, an indicative range and a sea-level tendency (Shennan *et al.*, 1994). Relative sea-level can then be estimated for the particular age using formula 4.6 (Engelhart and Horton, 2012).

$$RSL_i = A_i - RWL_i \qquad (4.6)$$

A_i is the altitude and RWL_i is the reference water level of core sample i.

A_i for each SLIP was recorded by subtracting the depth of the sample in the core from the altitude of the surface of the coring site (m OD). The indicative meanings of the SLIPs were established based on the diatom and foraminifera assemblages present. Some authors use previously established microfaunal or vegetation zones to estimate the reference water level (*e.g.* MHWST) of SLIPs (Gehrels *et al.*, 2006c; Selby and Smith, 2007; Roberts *et al.*, 2011). For example, Engelhart and Horton (2012) use a compilation of plant macrofossil, foraminifera diatom evidence developed by previous authors for various intertidal environments such as high marsh or marine limiting zones, and their associated reference water levels and indicative ranges for the Atlantic coast of the US.

However, because sea-level transfer functions based on foraminifera and diatom training sets have been produced for this study, the optimal transfer function was used to calcuate statistical estimates of past reference water levels and indicative ranges for the five SLIPs.

Using the transfer function to estimate the former SWLI of each SLIP is more accurate than arbitrarily assigning intertidal zones to the SLIPs (Edwards and Horton, 2000; Gehrels, 2000). Sea-level tendency was established by comparing the indicative meaning of the SLIP to that of the sediment directly beneath it. An upwards decrease in indicative meaning signifies positive sea-level tendency and vice versa (Haslett *et al.*, 2000).

Because the training sets have been compiled from data from two sites in the Severn Estuary with different tidal ranges, the transfer function will be developed based on SWLI rather than absolute tidal level, which means that the RWL for each SLIP is also given in SWLI units. The reverse of the m OD to SWLI formula gives the simple calculation to transform SWLI back to metres above OD at the Steart site.

Suplementing Alt_{ab} with RWL_i and rearranging formula 4.1 for RWL_i gives:

$$RWL_i = SWLI_i(MHWST_b - MLWST_b) + MLWST_b \qquad (4.7)$$

It is imperative here to note the definitions of MSL and MTL and the key difference between them. MSL is defined by the PSMSL (2013) as "the mean value of sea level extracted from a suitable long series of data (*e.g.* a month)". MSL in the United Kingdom is recorded with respect to Ordnance Datum Newlyn (ODN), based on continuous tide-gauge records at Newlyn, Cornwall, measured between 1915 and 1921 (Pirazzoli, 1996). MTL is defined by the PSMSL (2013) as "the arithmetic mean of mean high water and mean low water over a suitably long period (*e.g.* a month)".

Former sea-level is calculated by subtracting the indicative meaning of a SLIP, which is the estimated elevation of a sediment horizon above MTL based on the preserved microfauna, from the sediment's present day altitude with respect to OD. SLIPs are therefore established to estimate former MTLs with respect to OD.

4.4.6 Age-depth modelling

In addition to the five SLIPs, further information about the behaviour of sea-level change in Bridgwater Bay is available from the other core samples analysed for foraminifera and diatoms but not dated. A method of interpolating between the known radiocarbon dated ages is required.

The 'Clam' package (Blaauw, 2010) was used in R to interpolate between the five radiocarbon dated points, using the smoothing spline method (Nikitina *et al.*, 2000). Estimated dates and associated error margins for each point in the core with biostratigraphical data were extracted from the resulting age-depth model.

4.4.7 Implementing the sea-level transfer function

The software package C2 (Juggins, 2007) was used to estimate palaeo-sea-level throughout the Steart core, using the transfer function models with the most encouraging prediction statistics from each group of models (diatoms only, combined B and so on). The indicative meaning for each core sample reconstructed by each model was converted from SWLI units to metres above MSL at the Steart site, and palaeo-sea-levels calculated by subtracting the indicative meaning of each point from its present day elevation (Gehrels, 2002). Estimates of indicative meaning and palaeo-sea-level given by each model were then compared. As well as presenting a mean prediction error for each transfer function (RMSEP), each prediction of palaeo-sea-level is accompanied by a sample-specific error estimate (Birks, 1995; Birks *et al.*, 2010).

Only the results of applying the preferred transfer function are presented in this thesis. The others are available on request.

4.5 Key assumptions

There are a number of assumptions made in the processes of using regression and calibration to model multivariate relationships and later using those relationships to make estimates about past change. These are outlined in Birks (1995), summarised from Imbrie and Kipp (1971), Imbrie and Webb (1981) and Birks *et al.* (1990), with a sixth later added by Birks

et al. (2010) based on work by Telford and Birks (2005, 2009), as specified below. These assumptions should be recognised, along with certain limitations of the techniques used (see Section 4.6), as caveats that accompany the quantification and modelling of complex, multi-variate ecological relationships and making claims about past environmental parameters that can never truly be known.

1. The species in the training set are systematically related to the environment they live in.

It would certainly be unusual to attempt to reconstruct past occurrences of an environmental variable from an ecological system that shows little or no response to that variable in the present day. As outlined above, previous work by several authors has shown foraminifera and diatoms to respond significantly to elevation above MSL, and statistical techniques (described in Section 4.2) exist with which this assumption can be tested before attempts are made to reconstruct SWLI from species assemblages. Furthermore, uncorrelated ecological systems and environmental variables can be detected from the test statistics (r^2 and RMSEP) produced by transfer function models, though of course, if an apparently significant modern relationship has changed over the time scale being studied, errors that cannot be detected may be introduced (Sachs *et al.*, 1977).

2. The environmental variable to be reconstructed is, or is linearly related to an important determinant in the system of interest that is, on a quantitative continuous scale.

Elevation above MSL, or in this case the standardised version SWLI, is a numeric, measureable and continuous variable, *i.e.* it is not either present or absent, but can take any value.

3. The species in the training set are the same biological entities as in the fossil data and their ecological responses to the variable to be reconstructed have not changed over the time represented by the fossil assemblages.

This reliance on the uniformitarianism principle has been noted by some authors (Horton and Edwards, 2006; Lawrence, 2010) but the overall consensus appears is that for the timescales involved in Holocene research, modern taxa are likely to be the same biological entities as those identified in fossil form (Roberts, 1998). Sachs *et al.* (1977) estimates that the assumption of constancy of ecosystem response limits palaeoecological transfer functions to most of the Pleistocene for foraminifera and diatoms.

4. The statistical techniques used adequately model the species responses to the modern environmental variable and produce functions with sufficient predictive power to give accurate and unbiased estimations of the past variable.

Test statistics r^2 and RMSEP are good indicators of whether the relationship between the species assemblages and the environmental variable have been modelled successfully and how large the errors are, and are presented alongside the results of sea-level reconstruction in this thesis.

5. Other environmental variables have had negligible influence on the species assemblages in the past and those influences have not changed significantly over the time period covered by the reconstruction exercise.

Multivariate ordination techniques used in ecology and palaeoecology can test this assumption for the modern training set and are presented in this thesis. Whether those relationships have changed over time cannot readily be tested.

6. In using cross-validation to estimate the predictive power and prediction errors the test data should be statistically independent of the training set.

The two most widely used cross-validation methods, jackknifing and bootstrapping, are available in C2 and both iteratively leave whole samples out of the training set and attempt to predict the dependent variable from the species data. Thus, the excluded samples remain independent of the set of samples used in the regression. Bootstrapping is considered to be the superior method and is used here.

4.6 Limitations of the transfer function approach

The quality of quantitative environmental reconstructions depends on many factors, including the extent to which the relationship between the proxies and the environment in the modern world and in the past can be modelled realistically. So even if the most robust, transparent and rigorous methods are used to collect and analyse the data, there are some limitations to the transfer function approach as a method of reconstructing Holocene sea-level that must be considered, in spite of the level of rigour achieveable in the field and laboratory aspects of the research.

4.6.1 Unacknowledged assumptions

Jackson (2012) warns that while empirical calibration and the associated statistical estimation of error are important and desirable steps in palaeoecology, there are several major risks of oversight that relate specifically to the notion of 'knowns' and 'unknowns'. Jackson (2012) proposes that there are two ways in which researchers can know or not know something, through cognition and ignorance, such that knowledge, or a lack thereof, can be categorised into four main types: known and unknown knowns and unknowns (see Figure 4.8). Known

knowns and unknown unknowns are self-explanatory, referring respectively to more or less definite facts and uncertainties that the researchers only become aware of once they become known entities, respectively. Known unknowns are "explicitly acknowledged sources of error and uncertainty" (Jackson, 2012, p. 2) and through quantification of relationships between species and their environment researchers seek to convert the known unknowns into known knowns.

	Cognition	Ignorance
Knowledge	Known knowns	Unknown knowns
Uncertainty	Known unknowns	Unknown unknowns

Figure 4.8: Classification scheme for cognition and ignorance, knowledge and uncertainty. Adapted from Jackson (2012) with permission from Elsevier.

The fourth category, of unknown knowns, is often overlooked. While recognising that other definitions might exist, Jackson (2012) refers to unknown knowns as those assumptions that are so well understood that they are no longer explicitly expressed or mentioned, because they seem so obvious in underpinning a particular approach or discipline.

In relation to this classification of knowledge and ignorance Jackson (2012) outlines three potential problems in quantitative palaeoecology:

1. Quantifying relationships by regression and calibration to form transfer functions can detract attention from the real mechanisms involved in the relationships being studied. This implies that unknown unknowns or even known unknowns may be neglected when the focus is on the strength of the correlation between two variables. Species and their behaviours become known as numerical values and important factors might be forgotten.

2. While is is imporant to quantify the statistical error associated with transfer functions (RMSE and RMSEP), often this is the only kind of error that is considered and published. Jackson (2012) suggests that researchers should regard the statistical error associated with the regression model itself to be the minimum estimate of total uncertainty, acknowledging that other known and unknown sources of error may be relevant.

3. As the quanitification of relationships between species and environmental gradients becomes more commonplace, there is a risk of those relationships being taken for granted, with proxies being equated exactly with the related variables. Jackson (2012) argues that

known knowns can subtly change into unknown knowns when assumptions become buried in a trail of references to references of original studies and critical knowledge of real underlying mechanisms become lost to retirement, career change or death of key researchers.

Jackson (2012) concludes by urging palaeoecologists not to become complacent but to robustly question all assumptions, however obvious they might seem.

4.6.2 Modern analogues

Several authors address the concern that some fossil assemblages might lack modern analgoues in the training set by using a number of statistical methods to compare the fossil and modern assemblages (Hill, 2006; Kemp *et al.*, 2009a; Wilson and Lamb, 2012; Wright *et al.*, 2011b), some mention this as a potential limitation (Patterson *et al.*, 1999; Szkornik *et al.*, 2006), while others do not address the issue at all (Gehrels *et al.*, 2012; Leorri *et al.*, 2011; Zong and Horton, 1999). This potential limitation of the transfer function approach was touched on previously in the discussion of the analogue approach to quantitative reconstruction of palaeoenvironments in Section 2.5 of Chapter 2.

The combined foraminifera and diatom study in North Carolina by Kemp *et al.* (2009a), mentioned previously in Section 2.6.4 of Chapter 2, suffered from a lack of modern analogues for the fossil diatom assemblages. 12 of the 18 fossil diatom samples had poor modern analogues while only one fossil foraminifera sample lacked an acceptable modern analogue (see Figure 4.9). Combining the data only averaged out the problem, with nine fossil samples having good or fair modern analogues and the other nine having poor modern analogues. The authors also noted that within the assemblages that lacked good modern analogues some of the diatom taxa encountered in the core were completely absent in the modern training set, while others did occur in the modern data, but were in relatively low proportions.

Rossi *et al.* (2011) developed a foraminifera-based transfer function to reconstruct twentieth century sea-level rise in Brittany, France, and found that when comparing the modern and fossil assemblages from the training set and cores, only two out of 33 fossil samples did not have good modern analogues. These two studies highlight the importance of considering the similarity between modern and fossil assemblages before using the modern data to estimate past sea-level changes, and especially diatom assemblages which presented more non-analogue situations in Kemp *et al.* (2009a).

Wright *et al.* (2011b) respond to the non-analogue findings in their study of sea-level change on the Atlantic coast of northeastern North America by suggesting that local training sets should be expanded to take in samples from sites further away from the study site if this
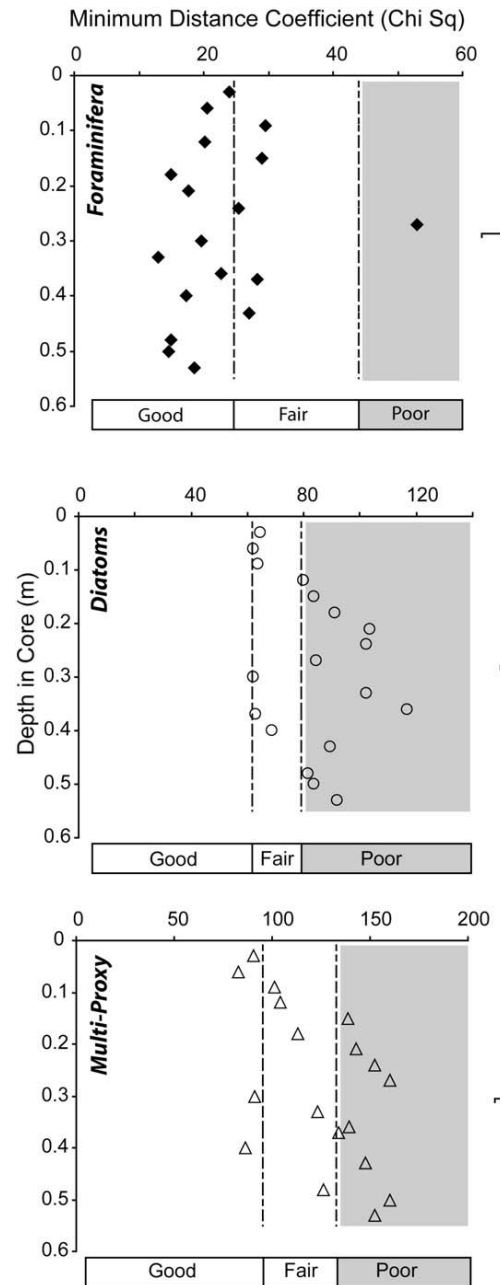
Figure 4.9: Estimates of the strength of analogy for samples from a core from Salvo, North Carolina, with modern training set assemblages. Reproduced from Kemp *et al.* (2009a) with permission from Elsevier.

means finding more modern analogues for the fossil assemblages.

4.6.3 Spatial auto-correlation

Spatial autocorrelation is the tendency of sites close to each other to resemble each other more than randomly selected sites (Telford and Birks, 2005), and is a potential problem for statistical techniques that assume independence of residuals (Telford and Birks, 2009). Residuals are the differences between observed values and the corresponding values predicted by a model, and are used to calculate prediction statistics. In practical terms this means that transfer functions developed from species-environment relationships may display inflated prediction powers and inappropriate models may be chosen based on over-optimistic r^2 and RMSEP values (Telford and Birks, 2005), because if samples are not statistically independent, cross-validation techniques will over-estimate the accuracy and precision of regression models.

Training sets for sea-level studies are often sampled along line transects; a particular concern expressed by Szkornik *et al.* (2006). However, Telford and Birks (2005) do demonstrate that regression models based on weighted averaging (WA and WA-PLS) are far more robust to spatial autocorrelation than linear models and the MAT.

It is not yet known whether sampling along a line transect is likely to result in more spatial autocorrelation than spreading sampling out over a whole site, or how far afield one must go to reduce the risk of spatial autocorrelation, so in the interests of human safety and consistency with other studies, the line transect method was used, given the apparent ability of weighted averaging models to cope well with spatial autocorrelation. Sampling in the intertidal zone of the Severn Estuary is more dangerous than sampling at sites with smaller tidal ranges, and it was felt that deviating from a line transect would have resulted in people spending more time than necessary on the tidal flats between low and high tide.

The spatial autocorrelation effect implies that samples taken in a straight line along the vertical gradient are not statistically independent of each other. This has implications for the sixth assumption of Birks (1995); Birks *et al.* (2010) (Section 4.5) because if data used in cross validation are not independent of the rest of the training set, predictive power may be overestimated.

Chapter 5

Sea-level transfer function

development

In this chapter the results of the contemporary intertidal surveys at Stert Flats and Beachley Point and the associated microfaunal analyses are presented, followed by outcomes of the multivariate ordination analyses and transfer function development work. The concluding part of the chapter presents prediction statistics for the best transfer function model for each single and multi-proxy ecological training set that was consequently applied to the fossil data collected from the Steart Peninsula core.

5.1 Contemporary intertidal microorganisms and environmental measures

5.1.1 Beachley Point and Stert Flats contemporary transects: descriptive statistics

Basic descriptive statistics for the modern transects are presented in Table 5.1; the two contemporary transects are considered separately first, and then together as one dataset. Forty samples were analysed from transect ST1, and 31 samples from BT1. Fifty-six diatom taxa and 13 foraminifera taxa were identified in total.

Figure 5.1 shows the variation in pH and LOI with respect to SWLI, as well as indication of the main floral species noted throughout the two transects.

The proportion of organic matter present in the surface sediments, represented by LOI, followed an upward trend from tidal flat to high marsh, and was highest at SWLI 1.024, which is equivalent to 6.61m OD at Beachley Point; just above the level of MHWST. Below SWLI 0.800 the proportion of organic matter in the surface sediments was around 10% or lower, and then sharpened steeply upwards from SWLI 0.972.

Table 5.1: Basic descriptive statistics of the contemporary environmental and species data collected from transects ST1 at Stert Flats and BT1 at Beachley Point.

	ST1	BT1	All transect samples
Number of samples	40	31	71
Lowest sample elevation (m OD)	0.646	4.010	0.646
Lowest sample elevation (SWLI)	0.516	0.801	0.516
Highest sample elevation (m OD)	4.546	7.000	7.000
Highest sample elevation (SWLI)	0.873	1.058	1.058
Number of diatom species	37	49	56
Number of foraminifera species	11	13	13
Samples with at least 300 diatoms	40	31	71
Samples with at least 100 foraminifera	11	12	23
Lowest sample pH	5.52	7.44	5.52
Highest sample pH	7.52	9.18	9.18
Lowest sample conductivity (µS/cm)	125.6	28.2	28.2
Highest sample conductivity (µS/cm)	1811	1838	1838
Lowest sample LOI (%)	1.79	5.48	1.79
Highest sample LOI (%)	11.75	36.97	36.97

Sediment pH varied between 9.18 and 5.52, and was consistently higher in the samples of BT1 where the two transects overlapped in SWLI. The sediments were least acidic between 1.015 and 1.024 SWLI, around the level of MHWST.

Vegetation across transect ST1 was restricted to *Spartina anglica* (common cordgrass), which occurred upwards from SWLI 0.800 (3.746m OD) and beyond 0.873 (4.546m OD) where the transect ended, and the brief occurence of *Salicornia europea* (glasswort) at the highest point on the transect.

At transect BT1 the vegetation was more diverse. *Limonium vulgare* (common sea-lavendar) and *Glaux maritima* (sea milkwort) were dominant in the lower and middle parts of the transect, disappearing around SWLI 0.946 (5.70m OD). *Aster tripolium* (sea aster) also occurred in the lower part of the transect, but disappeared earlier, at SWLI 0.886 (5.00m OD). *Phragmites australis* (common reed) and *Cochlearia officinalis* (common scurvygrass) were both abundant in the middle section of the transect, giving way to *Plantago maritima* (sea plantatin) and *Festuca* sp. (perennial tufted grass) at around SWLI (5.00m OD). A clear shift in the dominant vegetation was noted at SWLI 0.946 (5.70m OD), where *L. vulgare*, *G. maritima*, *P. maritima* and *Festuca* sp. were all replaced by a monospecific occurrence of *Lolium perenne* (perennial or English ryegrass). The two most elevated sampling stations (SWLI 1.049 at 6.90m OD and SWLI 1.058 at 7.00m OD) also revealed occurrences of terrestrial grass *Dactylis glomerata* (cock's foot grass), as well as *Hedera helix* (common ivy), *Rubus fruticosus* (blackberry) and herbaceous taxa such as *Bellis perennis* (common daisy),

Trifolium sp. (clover) and *Rannunculus repens* (creeping buttercup).
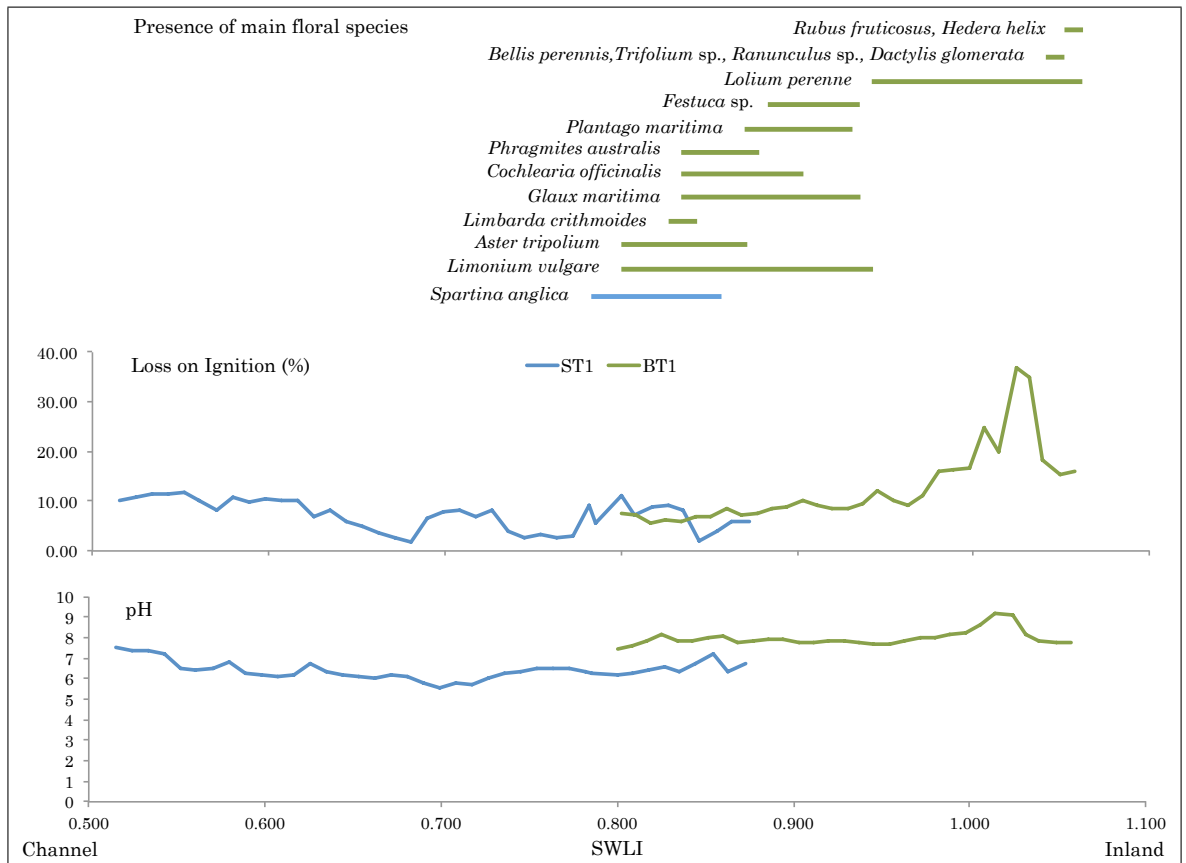
Figure 5.1: Variation in LOI, conductivity and pH across transects BT1 and ST1, and the main floral species present, plotted against SWLI.

5.1.2 Stert Flats: Contemporary microfauna

i   Contemporary distribution of diatoms

Thirty-seven diatom species were noted in the 40 samples collected from Stert Flats, and all 40 samples yielded counts of at least 300 individuals. In total 12,006 diatoms were counted and identified from transect ST1. Figure 5.2 shows the variation across ST1 in the percentage abundance of each diatom species.

Marine planktonic species *Paralia sulcata* clearly dominated the majority of the ST1 samples, with a mean average sample abundance of 30%. *Pseudopodosira westii* and *Podosira stelligera*, also marine species, and marine-brackish *Actinoptychus senarius* had a lower but fairly consistent presence across the transect. Other notable patterns include an increase in brackish-marine, brackish and freshwater-brackish species with increasing SWLI (elevation), such as *Navicula digitoradiata*, *Martyana martyi*, *Diploneis interrupta*, *Caloneis westii* and *Tryblionella compressa*. Species in these salinity groups accounted for 7% of the assemblage at SWLI 0.55 (1.05m OD), 12% of the assemblage at SWLI 0.71 (2.75m OD) and 49% of the assemblage at SWLI 0.87 (4.55m OD). The majority of the species had some presence
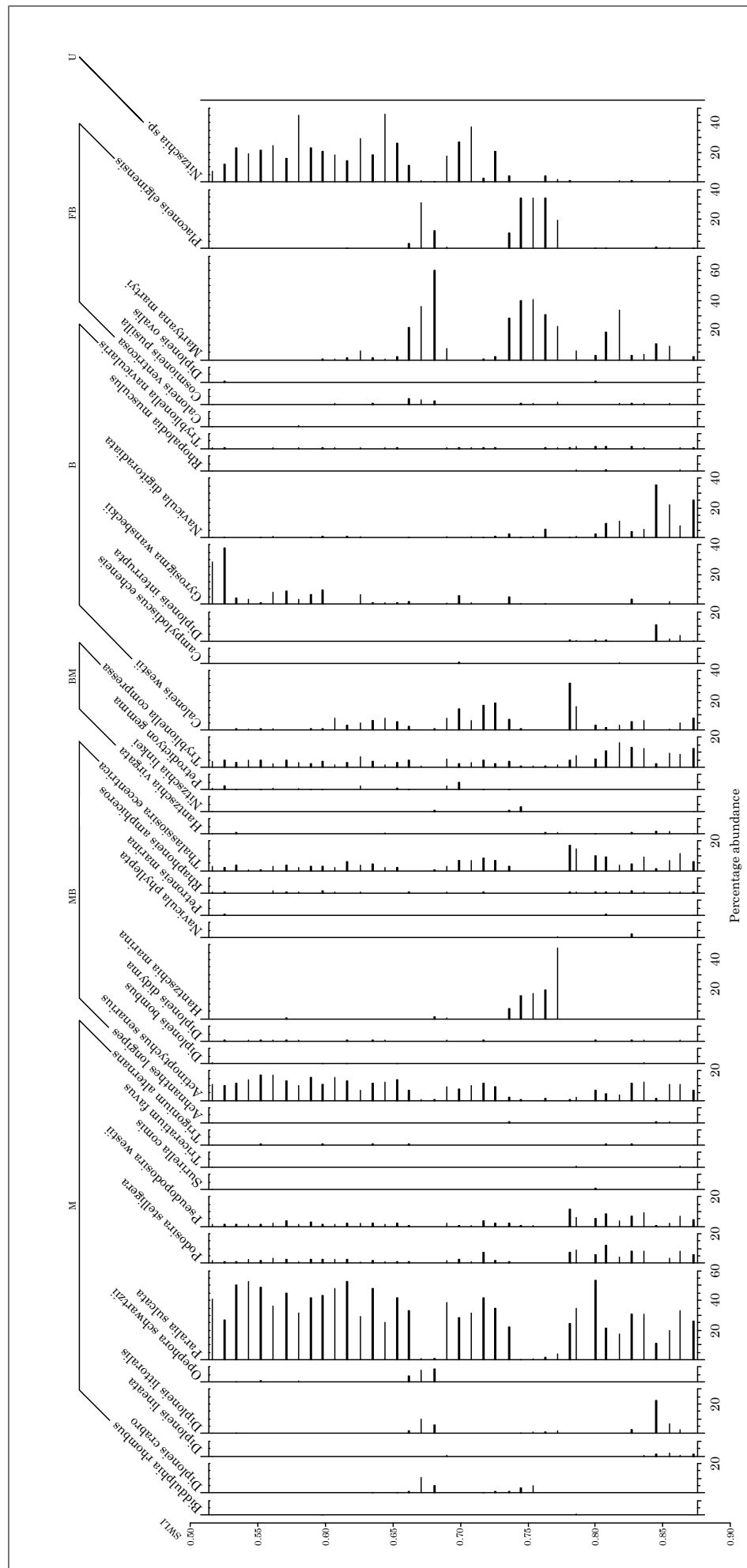
Figure 5.2: Variation in the percentage abundance of diatom species across transect ST1. All of the species encoutered are presented. Species are grouped by their salinity classes. M = marine, MB = marine-brackish, BM = brackish-marine, B = brackish, FB = freshwater-brackish, U = unknown.

throughout the transect, but six species (*Diploneis crabro*, *Diploneis littoralis*, *Hantzschia marina*, *Opephora schwartzii*, *Cosmioneis pusilla* and *Placoneis elginensis*) occurred in peaks with smaller ranges towards the middle of the transect. These less commonly occurring species were not restricted to any particular salinity group.

ii   Contemporary distribution of foraminifera

Eleven species of foraminifera were identified from the sediment surface samples collected at Stert Flats. Dead specimens of all 11 species, and live examples of seven of those species were encountered. Small numbers of juvenile tests were found in some samples, but confident species identification was not possible, so these specimens were not included in any analyses. The number of foraminifera identified per 2cm^3 of sediment varied between just two tests in the least abundant sample and 142 in the most abundant. Figure 5.3 shows the variation in the number of live and dead tests per 2cm^3 across the transect ST1. Thirty-two of the 40 samples contained more dead than living tests. The actual number of foraminifera counted in 13 of the samples was greater than that shown in Figure 5.3 because a greater volume of sediment was examined in order to try and achieve higher, more robust counts. However, for the purpose of direct comparison between samples, the number of tests counted per 2cm^3 is shown, as per convention (Gehrels *et al.*, 2001; Horton and Edwards, 2006). In total 2,917 foraminifera were counted and identified from the samples taken from Stert Flats.
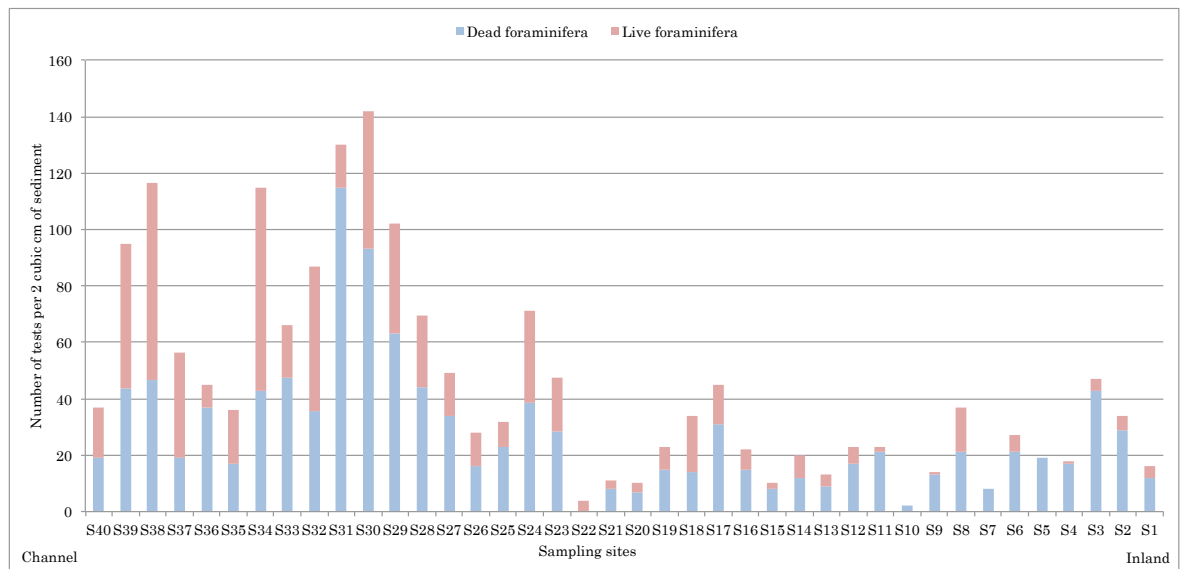
Figure 5.3: Variation in the number of living and dead foraminifera counted per 2cm^3 of sediment across transect ST1. Sampling stations are shown on the *x*-axis, S40 being the lowest in elevation (SWLI 0.516) and S1 being the highest (SWLI 0.873).

Figure 5.4 shows the distribution of the 11 species of foraminifera encountered across the transect. All of the data are presented here, including those samples that have only very low

counts, and the rarer species that only occur at a maximum of one or two percent in any of the samples.

Calcareous species *Ammonia beccarii* dominated the majority of the samples with an average sample abundance of 76%. *Cornuspira involvens*, *Quinqueloculina* sp., *Balticammina pseudomacrescens* and *Haplophragmoides wilberti* appeared in very low proportions in the lower part of the transect, with 5% abundance or lower between the lowest sample and SWLI 0.67 (2.35m OD). *Elphidium williamsoni* and *Haynesina germanica* were present throughout and both increased in percentage in the upper half of the transect. *E. williamsoni* increased from 10% abundance at SWLI 0.73 (2.95m OD) to 21% abundance at SWLI 0.84 (4.14m OD), peaking at 50% abundance at SWLI 0.79 (3.59m OD). *H. germanica* increased from 5% abundance at SWLI 0.66 (2.25m OD) to its peak abundance of 33% at SWLI 0.83 (4.05m OD) before decreasing in sample proportion to 8% abundance at SWLI 0.87 (4.55m OD). *Elphidium macellum* was also present in the upper part of the transect.

Agglutinated species *Jadammina macrescens* and *Trochammina inflata* were present in low proportions in some of the lower samples, and became more dominant in the more elevated samples, from around SWLI 0.80 upwards. The average percentage abundance per sample of *J. macrescens* between SWLI 0.52 (0.65m OD) and 0.61 (1.65m OD) was 1.6%, whereas between SWLI 0.80 (3.75m OD) and 0.87 (4.55m OD) it was 25%.

The number of dead tests present per 2cm^3 fluctuated between a base level of around 25 and peaks of higher counts of 50 to 115 throughout the transect.

5.1.3 Beachley Point: Contemporary microfauna

i Contemporary distribution of diatoms

Forty-nine diatom species were identified in the BT1 transect samples and all 31 samples yielded counts of at least 300 diatoms. In total 9,308 diatoms were indentified. Figure 5.5 shows the relative abundance of each species across transect BT1.

Figure 5.5 shows that, like transect ST1, transect BT1 was dominated by marine planktonic species *Paralia sulcata*, which was present in every sample with an average sample abundance of 43%. Present throughout BT1 in fairly consistent proportions, also similar to ST1, were *Pseudopodosira westii* (range: 0.3% to 4%), *Podosira stelligera* (range: 0.6% to 7%)and *Actinoptychous senarius* (1.3% to 20%). Marine-brackish species *Thalassiosira eccentrica* (average: 2%) and brackish-marine species *Tryblionella compressa* (average: 5.4%) also appeared in low numbers in almost all of the samples, as did the unidentified species of the genus *Nitzschia* (average: 3.9%).
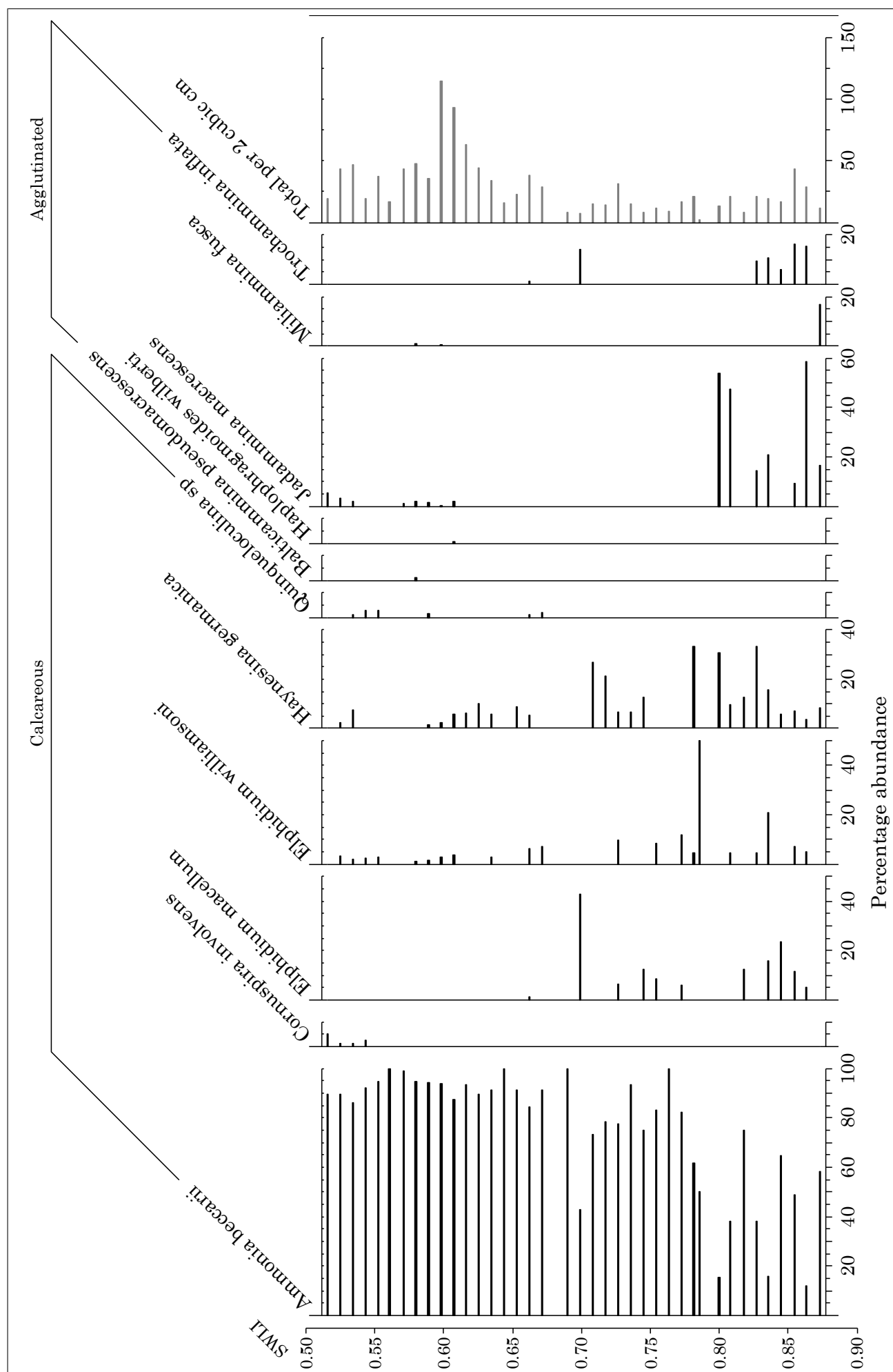
Figure 5.4: Variation in the percentage abundance in the dead assemblage of each species of foraminifera across transect ST1. All samples and species are included here, including those with very low counts.
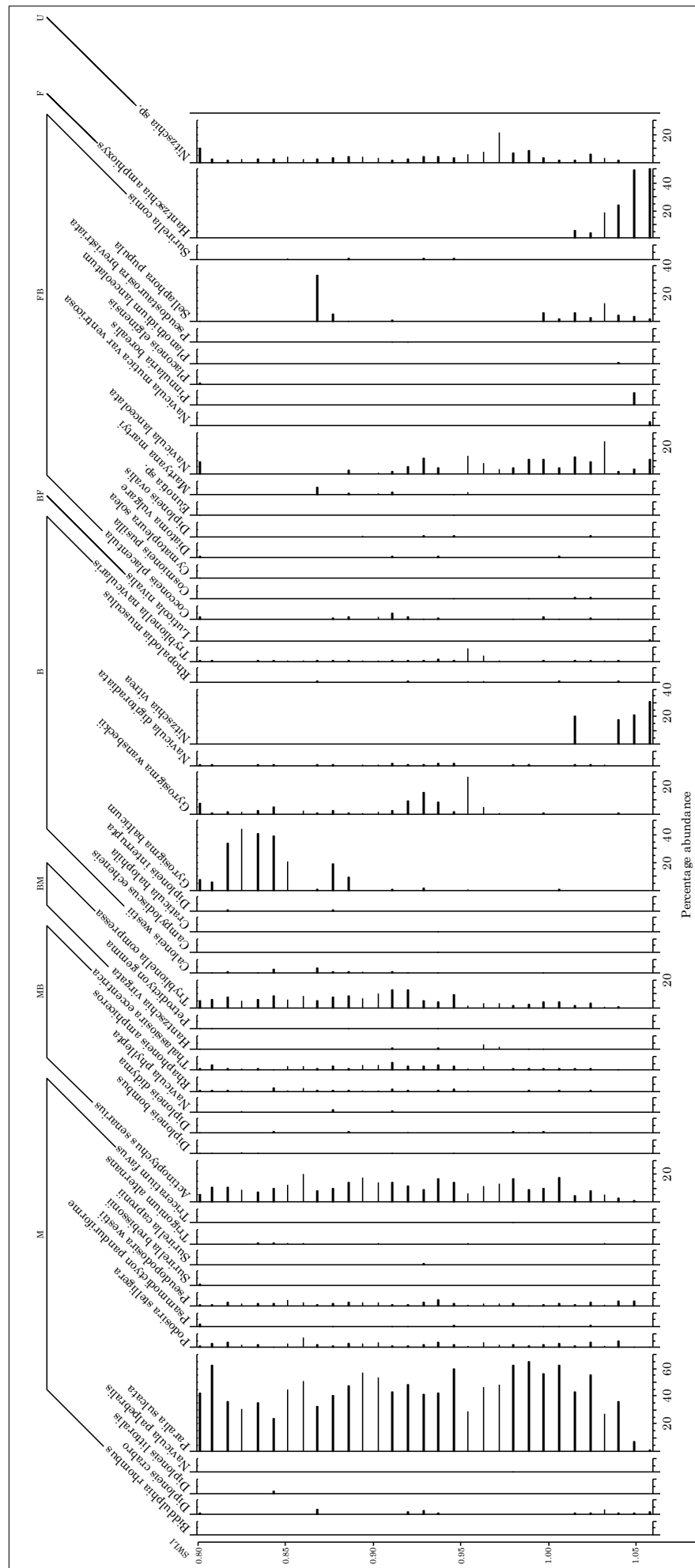
Figure 5.5: Variation in the percentage abundance of diatom species across transect BT1. All of the species encoutered are presented. Species are grouped by their salinity classes. M = marine, MB = marine-brackish, BM = brackish-marine, B = brackish, FB = freshwater-brackish, F = freshwater, U = unknown.

The clearest variation throughout the transect was in the other brackish and the freshwater-brackish and freshwater species. Brackish species were present in substantial proportions in the lower half of the transect and in particular *Gyrosigma balticum* and *Gyrosigma wansbeckii* accounted for a mean average of 17% of the sample abundance between SWLI 0.80 (4.01m OD) and 0.92 (5.4m OD). Freshwater-brackish species increased in proportion around SWLI 0.95, above which the species in this salinity group accounted for 14% of the sample abundance on average.

Freshwater-brackish species *Pinnularia borealis* and freshwater *Hantzschia amphioxys* appeared in the very upper part of the transect and peaked in the highest two samples (8.3% and 50% respectively). Brackish species *Nitzschia vitrea* was also at its highest percentage abundance (31%) in the most elevated sample.

ii Contemporary distribution of foraminifera

As noted in Table 5.1, 13 species of foraminifera were encountered in the samples collected from transect BT1. Dead examples of all 13 species were encountered and live examples of 10 of those species were identified. Again, a small number of juvenile tests were encountered, but were not included in the analyses. The variation in the number of tests counted per $2cm^3$ in BT1 is shown in Figure 5.6 and ranges from zero to 215. For 14 of the samples twice the usual amount of sediment was examined in order to reach higher counts. 2,290 foraminifera were counted and identified in total from the contemporary samples collected at Beachley Point. In this dataset seven of the samples contained no foraminifera at all, and of the 24 samples that did contain at least one test, 15 contained a greater proportion of dead than living specimens. Above SWLI 0.954 (5.8m OD) the number of tests declined very rapidly, and no foraminifera were found in the sediments between SWLI 1.024 (6.61m OD) and SWLI 1.058 (7.00m OD).

Figure 5.7 shows the variation in species of foraminifera across transect BT1. Compared with transect ST1, the proportion of agglutinated species was higher. *Haplophragmoides wilberti*, *Jadammina macrescens* and calcareous *Ammonia beccarii* were the three most dominant species throughout the transect, with average sample proportions of 18%, 31% and 22% respectively.

Brizalina striatula, *Cornuspira involvens*, *Elphidium williamsoni*, *Quinqueloculina* sp. and *Milliammina fusca* all occurred in low proportions from the lower extent of the transect to around SWLI 0.95 (5.7m OD), with average proportions of 1.6%, 5%, 3.6%, 0.8% and 1% respectively between the lower end of the transect and SWLI 0.95. Above SWLI 0.95
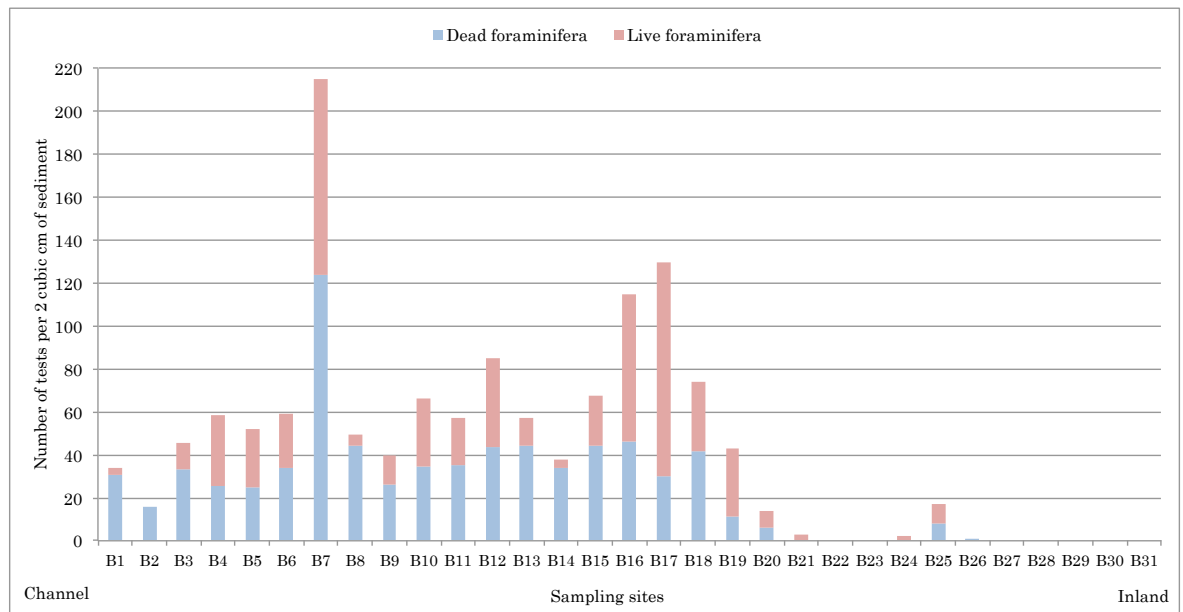
Figure 5.6: Variation in the number of living and dead foraminifera counted per 2cm^3 of sediment across transect BT1. Sampling stations are shown on the x-axis, B1 being the lowest in elevation (SWLI 0.801) and B31 being the highest (SWLI 1.058).

H. wilberti, *J. macrescens* and *Trochammina inflata* dominated the dead assemblage with average sample proportions of 12.5%, 25% and 34% respectively. However, the right hand plot shows the total number of dead tests to fluctuate throughout and eventually drop at around SWLI 0.95, so these examples of apparently dominant agglutinated species are high percentages only of very low counts. Above SWLI 1.024 (6.61m OD) no foraminifera were encountered at all.

5.1.4   The diatom and foraminifera training sets

The ultimate purpose of collecting intertidal microfaunal and environmental data from Stert Flats and Beachley Point is to compile a training set with which to perform the regression and calibration stages of the development of foraminifera-based, diatom-based and multi-proxy transfer functions.

The diatom datasets from the two contemporary transects were therefore combined together to form a diatom training set and likewise, the foraminifera datasets were combined to form a foraminifera training set. The full training sets are presented below, including the results of constrained cluster analyses which divided the intertidal range (MSL to HAT) into a number of zones based on the microfaunal assemblages identified.

i   The diatom training set

The diatom training set was composed of all 71 diatom samples from the two contemporary transects and the 29 species that account for 3% or more of at least one of those samples.
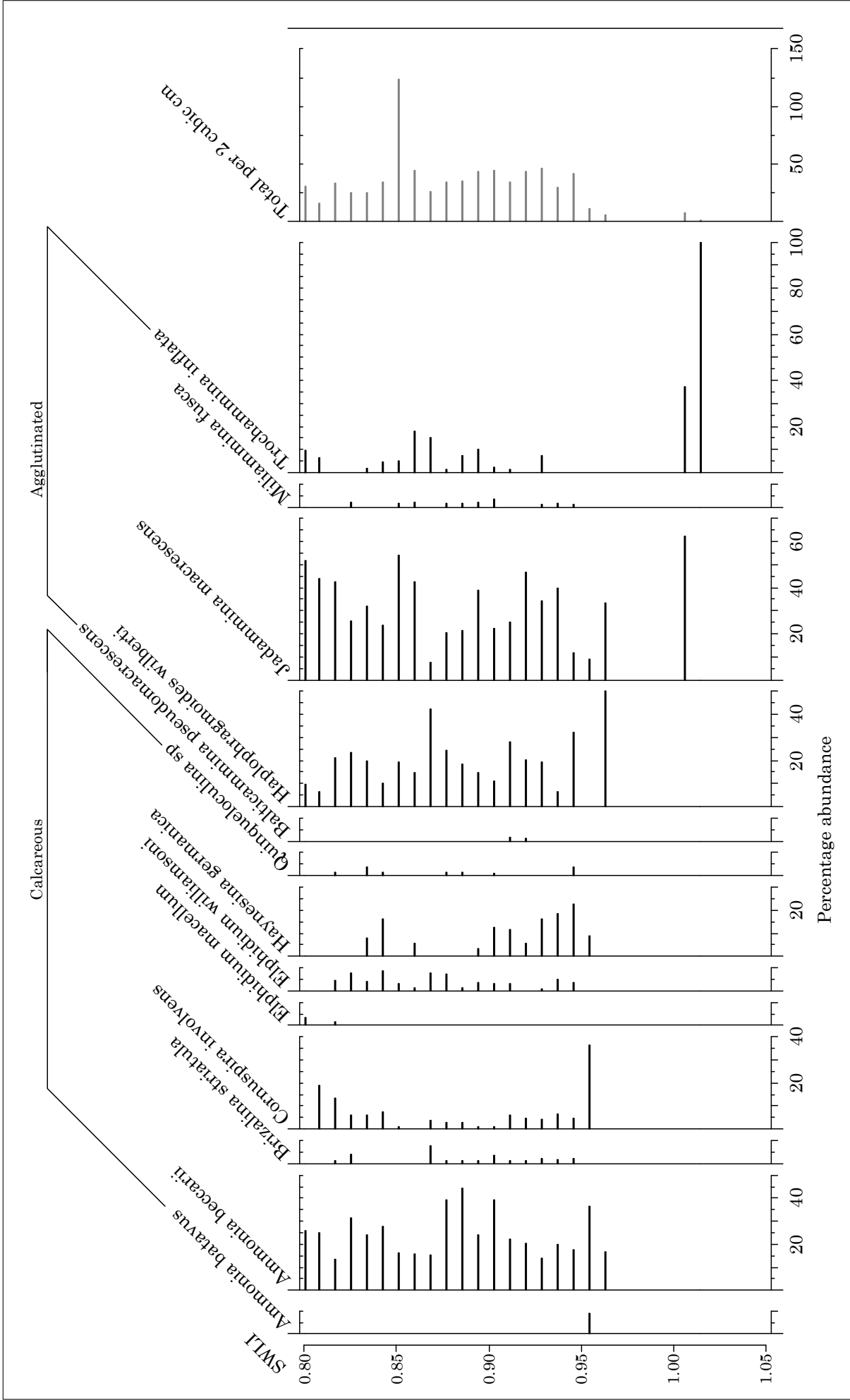
Figure 5.7: Variation in the percentage abundance in the dead assemblage of each species of foraminifera across transect BT1. All samples and species are included here, including those with very low counts.

The diatom training set is presented in Figure 5.8. Those species excluded from the diatom training set due to low abundance can be found listed in Table 5.2, along with the maximum percentage abundance of all of the species encountered in the modern data.

Several species were present throughout the intertidal zone. The most notable was marine species *Paralia sulcata*. Other species that had a consistent presence were *Pseudopodosira westii*, *Podosira stelligera*, *Actinoptychus senarius*, *Tryblionella compressa* and the unidentified *Nitzschia* species. Cluster analysis revealed patterns in the other, more diverse species, such that four zones were identified: the tidal flat, lower saltmarsh, upper saltmarsh and terrestrial zones. The main diatom components of these four zones can be found in Figure 5.10 alongside those zones identified as a result of the foraminifera analysis.

Table 5.2: The maximum percentage abundance in any one sample of each diatom species encountered in the modern training set. Those with less than 3% maximum abundance in any of the 71 contemporary samples have been excluded from any further analysis.

Species	Max. %	Species	Max. %
Paralia sulcata	64.45	*Navicula mutica var ventricosa*	2.66
Martyana martyi	60.67	*Navicula phyllepta*	2.00
Hantzschia amphioxys	49.83	*Psammodictyon panduriforme*	2.00
Hantzschia marina	48.00	*Rhaphoneis amphiceros*	2.00
Nitzschia sp.	45.67	*Diploneis lineata*	1.67
Gyrosigma balticum	43.85	*Diploneis bombus*	1.00
Gyrosigma wansbeckii	37.87	*Achnanthes longipes*	0.67
Navicula digitoradiata	35.67	*Diatoma vulgare*	0.67
Placoneis elginensis	34.33	*Diploneis didyma*	0.67
Sellaphora pupula	33.33	*Pseudostaurosira brevistriata*	0.67
Caloneis westii	31.67	*Rhopalodia musculus*	0.67
Nitzschia vitrea	30.56	*Surirella comis*	0.67
Navicula lanceolata	24.00	*Trigonium alternans*	0.67
Diploneis littoralis	22.33	*Triceratium favus*	0.67
Actinoptychus senarius	20.53	*Campylodiscus echeneis*	0.66
Thalassiosira eccentrica	17.33	*Petroneis marina*	0.66
Tryblionella compressa	16.67	*Planothidium lanceolatum*	0.33
Podosira stelligera	11.96	*Biddulphia rhombus*	0.33
Pseudopodosira westii	11.33	*Cymatopleura solea*	0.33
Diploneis crabro	10.67	*Diploneis ovalis*	0.33
Diploneis interrupta	10.67	*Eunotia* sp.	0.33
Tryblionella navicularis	9.33	*Craticula halophila*	0.33
Opephora schwartzii	8.67	*Navicula palpebralis*	0.33
Pinalaria borealis	8.31	*Surirella brebissonii*	0.33
Cocconeis placentula	4.33	*Surirella capronii*	0.33
Petrodictyon gemma	4.32	*Caloneis ventricosa*	0.33
Hantzschia virgata	4.00	*Luticola nivalis*	0.33
Cosmioneis pusilla	4.00		
Nitzschia linkei	3.33		
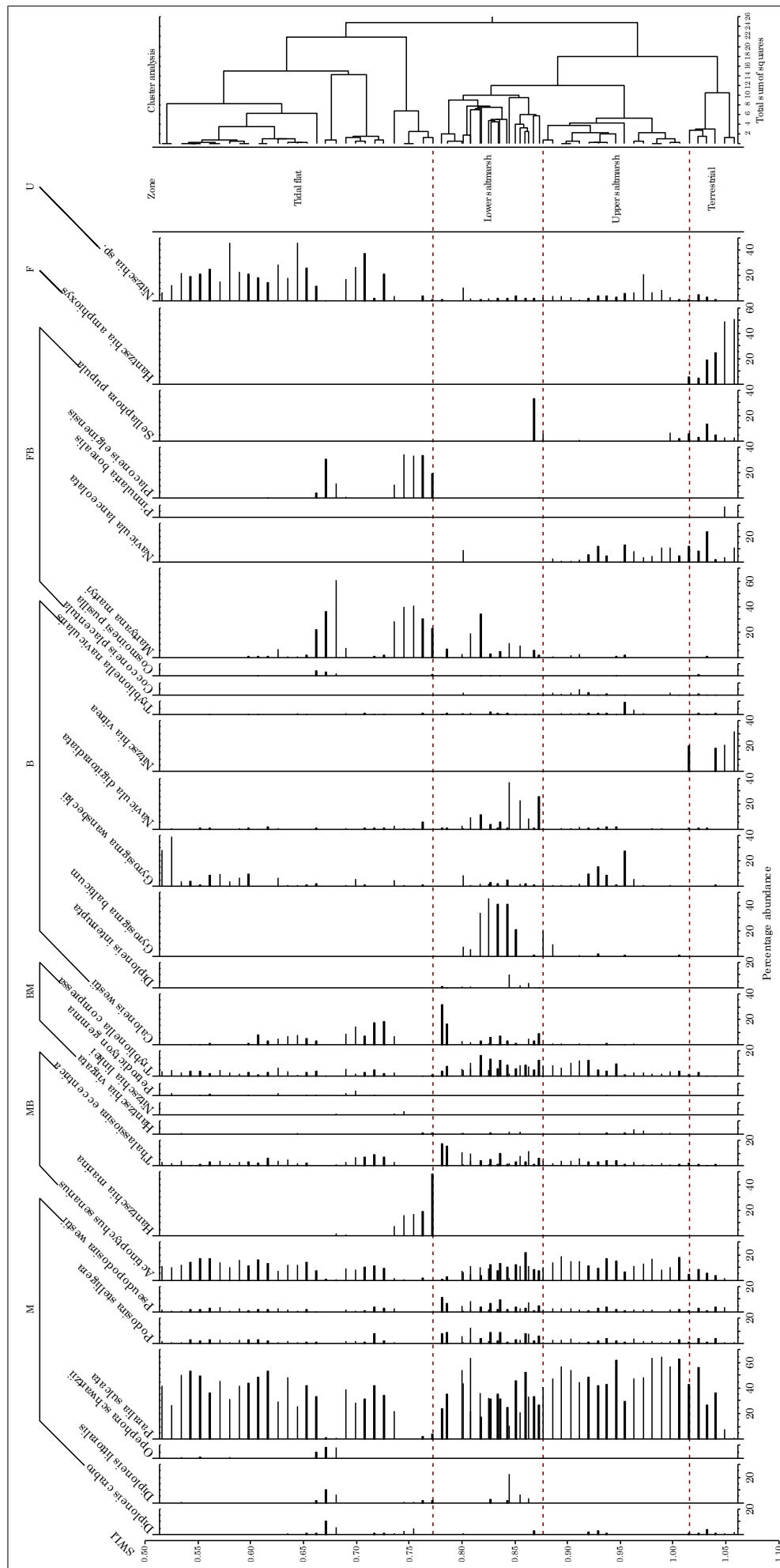
Figure 5.8: The diatom training set and results of cluster analysis. Species are grouped by their salinity classes. M = marine, MB = marine-brackish, BM = brackish-marine, B = brackish, FB = freshwater-brackish, F = freshwater, U = unknown.

ii The foraminifera training set

The foraminifera training set was composed of the dead assemblages of those samples that yielded counts of at least 100 tests, and species accounting for 3% or more of at least one of those samples. Figure 5.9 shows the foraminifera training set. The maximum percentage abundance of each species can be found in Table 5.3.

While species such as *Elphidium macellum* appeared to dominate some of the ST1 samples, having excluded samples with total counts lower than 100, the maximum abundance of some species in this filtered training set is now far lower. This is why *Elphidium macellum* was ultimately excluded from the foraminifera training set, despite apparent high *percentage* abundance in some samples.

Cluster analysis revealed two main zones in which foraminifera were present in sufficient numbers and two zones in which low numbers of tests were found. The lowest zone, identified as the tidal flat zone, ranged from the lowest sample to SWLI 0.662. Dominant species in this zone were calcareous, typically tidal flat-dwelling *Ammonia beccarii* and *Haynesina germanica*. The vertical range between SWLI 0.662 and 0.825 yielded counts too low to be of any statistical significance. The second zone inhabited by sufficient numbers of foraminifera ranged between SWLI 0.825 and 0.946 and was identified as the saltmarsh zone. This zone also contained a large proportion of *Ammonia beccarii* and the second and third most prominent species were *Jadammina macrescens* and *Haplophragmoides wilberti* respectively.

The intertidal foraminifera zones are presented schematically alonside the diatom zones in Figure 5.10.

Upwards of SWLI 0.946 the foraminifera were either present in insignificant numbers (often single digits) or were completely absent from the surface sediments analysed.

5.2 Quantifying the role of elevation in explaining intertidal microfaunal variation

This section presents the results of the ordination analysis, estimating the extent to which elevation is an important influence on diatom and foraminifera assemblage variation in the intertidal zone. Initially, results of DCA indicate which ordination methods are suitable for each of the training sets, then results of CCA, RDA and partial CCA and RDA are presented.

5.2.1 Linear or unimodal methods?

The DCA ordination analysis of the diatom training set showed the gradient length of the first axis to be 5.29 SD units, implying that unimodal ordination and regression methods, as
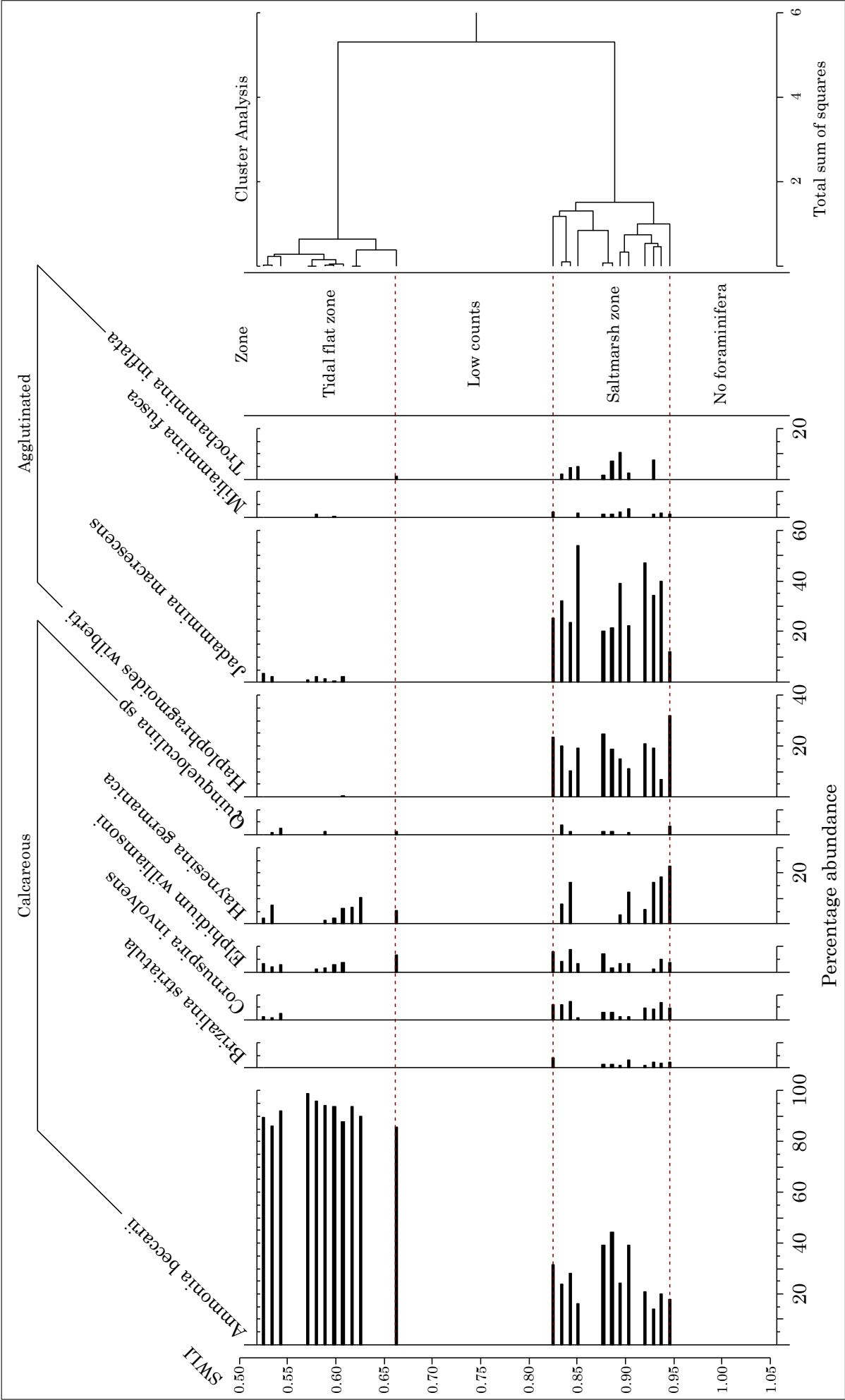
Figure 5.9: The foraminifera training set and results of cluster analysis.

Table 5.3: The maximum percentage abundance of the dead assemblage, in the samples that yielded a total count of at least 100 tests, of each species of foraminifera encountered in the modern training set. Those with less than 3% maximum abundance of the dead assemblage in those samples have been excluded from any further analysis.

Species	Max. %
Ammonia beccarii	98.84
Jadammina macrescens	54.03
Haplophragmoides wilberti	32.14
Haynesina germanica	22.62
Trochammina inflata	10.34
Elphidium williamsoni	8.82
Cornuspira involvens	7.35
Quinqueloculina sp	4.00
Brizalina striatula	3.92
Miliammina fusca	3.37
Elphidium macellum	1.30
Balticammina pseudomacrescens	1.14
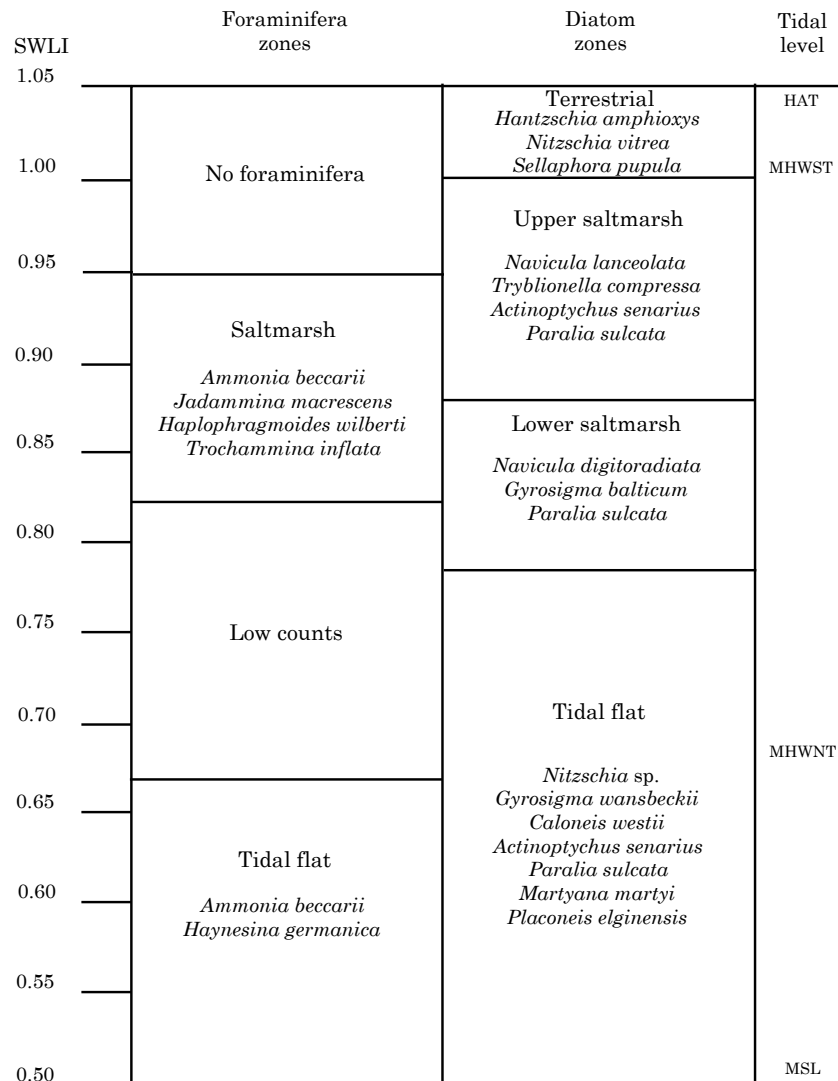
Figure 5.10: Microfaunal zones identified by cluster analysis of the diatom and foraminifera training sets, with respect to SWLI, and the dominant species of foraminifera and diatoms from each zone. MHWNT = mean high water neap tides.

opposed to linear methods, were the most appropriate for this data set.

Table 5.4: Results of DCA ordination of the four training sets.

	Axis 1 length	Axis 1 % variation explained
Diatom training set	5.29	73.72
Foraminifera training set	1.68	52.88
Combined training set A	1.98	32.68
Combined training set B	5.33	73.74
Combined training set C	5.13	71.05

The length of axis one in the foraminifera training set was 1.68 SD units. While a gradient length of less than 2 SD units is assumed to signify linearity in the species data (Birks, 1995), other researchers have applied both linear and unimodal regression techniques to those data sets with axis 1 gradient lengths that are close to 2 SD units (Gehrels *et al.*, 2001; Callard *et al.*, 2011; Ooms *et al.*, 2011). This approach was taken here, for both the foraminifera training set and combined training set A which had an axis 1 length of 1.98 SD units. The most appropriate transfer function models were subsequently chosen based on their relative predictive power and precision.

DCA ordination of combined training set B revealed an axis 1 gradient length of 5.33, implying that unimodal ordination and regression techniques were suitable for this combination of the foraminifera and diatom training sets. Similarly, the result of combined training set C is 5.13. These results are summarised, along with the percentage variation explained by the first ordination axis, in Table 5.4. The proportion of the variation in the data explained by the first ordination axis gives an indication of the success of the ordination procedure. The higher this value the more successful the ordination (Shi, 1993). The results in Table 5.4 indicate that ordination of the diatom and combined (B and C) training sets was more successful than those that only included the samples with greater than or equal to 100 foraminifera tests ('Foraminifera training set' and 'Combined training set A').

5.2.2 Direct ordination

The results of CCA and RDA ordination are presented for the five training sets in Figure 5.11. A key difference between in the amount of variation in the species data explained by the evironmental variables measured was apparent between the two proxies. CCA estimates that 19% of the diatom species variation was explained by SWLI, pH and LOI, while the value for the foraminifera training set was higher at 71%. For comparison, the linear ordination method RDA returned a slightly lower estimate of 60% for the foraminifera training set.
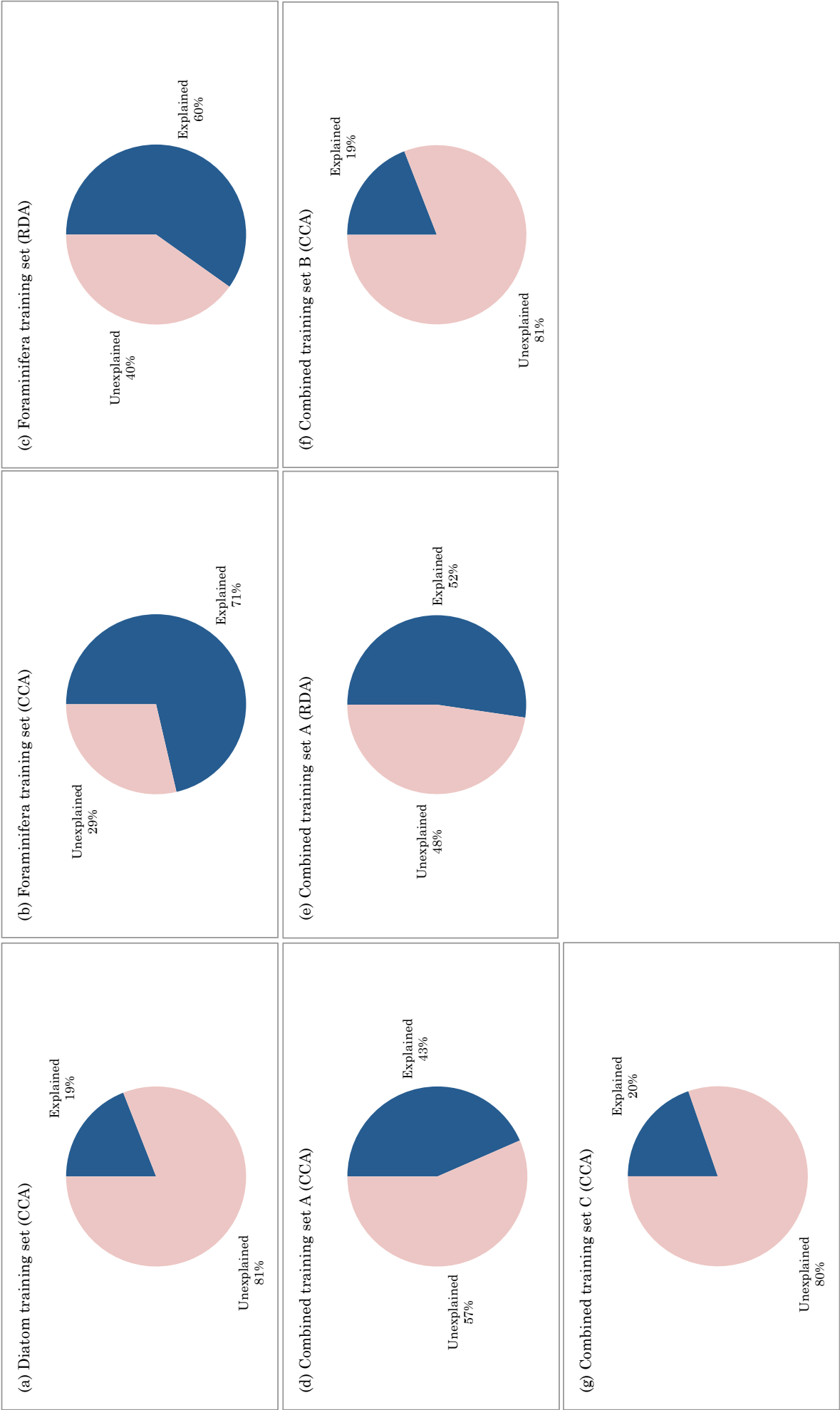
Figure 5.11: Pie charts showing the total variation in the diatom, foraminifera and combined training sets in portions explained and unexplained by the environmental variables measured, estimated by CCA and RDA.

The varying influence of the two groups of microorganisms when merging the data into combined training sets A, B and C was apparent in the CCA and RDA results. Combined training set A, which only contained the 23 samples that yielded at least 100 foraminifera tests, gave a similar result to the single proxy foraminifera training set; 43% of the variation in the species data was explained by the environmental variables when estimated by unimodal method CCA, and 52% when estimated using RDA.

Combined training set B, containing all 71 modern samples, returned the same result as the diatom training set alone; 19% of the variation was explained by change in the measured environmental variables. For combined training set C the percentage explained was slightly higher at 20%.

The contribution of each of the three environmental variables to the explained variation in each training set, estimated using partial constrained ordination methods partial CCA and partial RDA appear in Figure 5.12. The three variables measured contributed to almost equal proportions of the explained variation in the diatom training set, with SWLI and LOI both explaining 29% and pH explaining 27%. The remaining 15% was attributed to intercorrelation between the three measured variables (Horton and Edwards, 2000).

SWLI was estimated by CCA to account for 16% of the explained variation in the foraminifera training set, with LOI and pH accounting for relatively little variation (4% and 7% respectively), but with the majority of the explained variation (73%) being attributed to intercorrelation between the measured variables.

Linear ordination method RDA on the foraminifera training set gave significantly different results to CCA. Just 2% of the explained variation was attributed to SWLI, with pH estimated to be the most important of the three measured variables, and 66% of the explained variation attributed to intercorrelation between the three variables.

In contrast, similar results were given by CCA and RDA for combined training set A. Both ordination methods estimated SWLI to be the least important of the three variables, explaining 15% according to CCA and 17% according to RDA. RDA estimated that LOI and pH each accounted for 36% of the explained species variation. This result comes with the caveat that linear ordination methods are not appropriate for the diatom component of this combined training set.

Partial CCA on combined training set B (all 71 samples) showed SWLI to account for 31% of the explained variation, and for combined training set C, 30%.
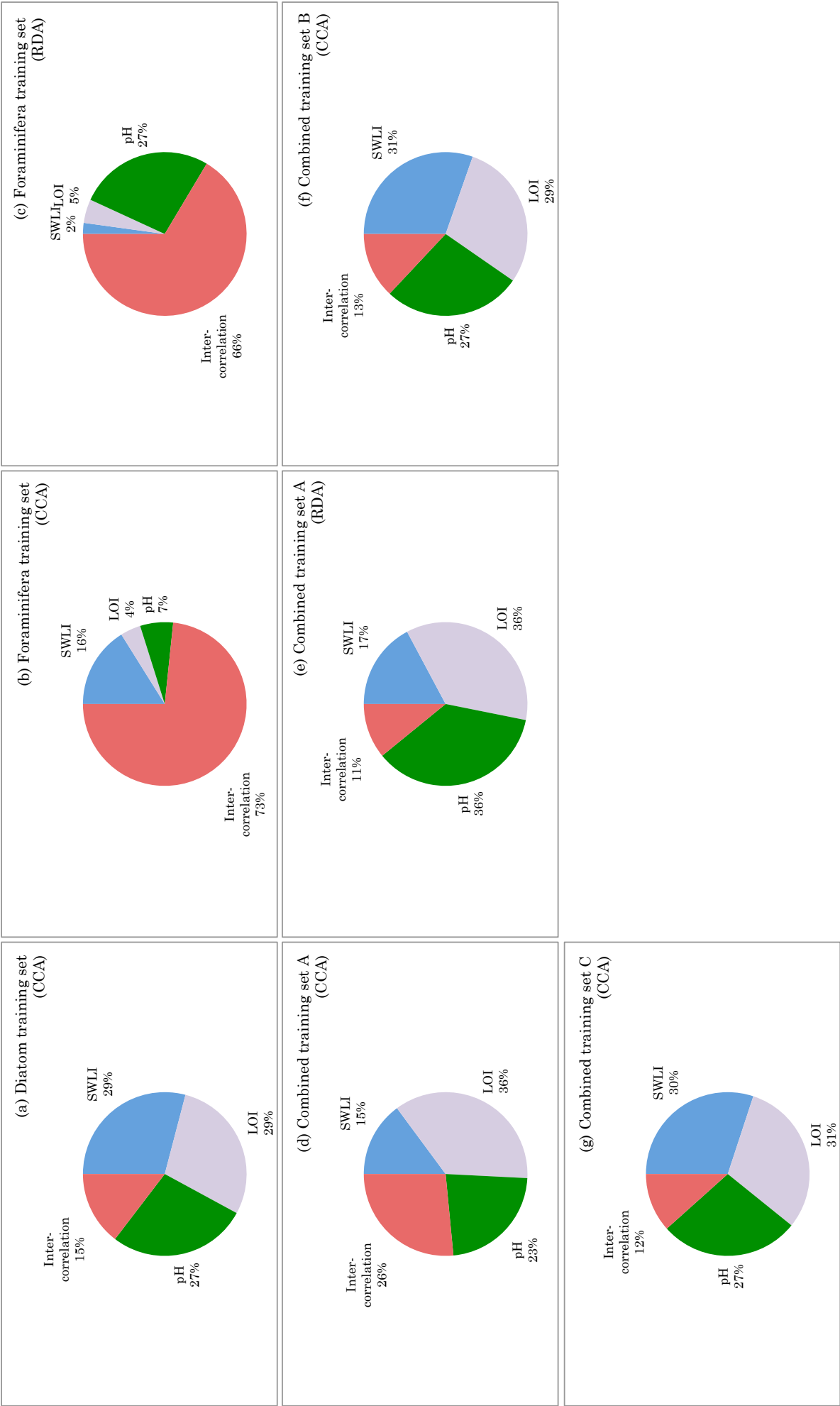
Figure 5.12: Pie charts showing the unique contributions of SWLI, pH and LOI, and the contribution of intercorrelation between those three variables, to the explained variation in the diatom, foraminifera and combined training sets, estimated by partial CCA and RDA.

5.3 Transfer function development: single and multi-proxy

The results of the direct and partial direct ordination showed that for the two individual training sets and the three versions of the combined training set, SWLI explained a significant, independent proportion of the species variation, with the exception of the foraminifera training set when analysed by RDA. All five training sets were taken forward to the transfer function development stage, but it is still unclear at this stage whether linear or unimodal methods are appoparite for the foraminifera training set.

Software package C2 (Juggins, 2007) was used to run multivariate regression models for each of the five training sets. The results of each model are summarised in Tables 5.5 and 5.6. In each case, the differences in r^2_{boot} and RMSEP between the classical and inverse versions of the WA and WA-Tol models were small, and for some of the models there was no difference.

Ter Braak (1995) found that classical methods are superior to the inverse methods when fossil samples are from the extreme ends of the environmental gradient being reconstructed (*i.e.* elevation in the tidal frame), and in this case the Holocene sediments at Steart are intercalated peats and silty clays, implying upper saltmarsh and tidal flat environments respectively. The classical models were therefore taken forward and compared in more detail with the PLS and WA-PLS models in Figures 5.13 to 5.16.

All four of the models based on the diatom training set presented in Figure 5.13 performed more accurately in the middle part of the intertidal zone but overestimated the SWLI at the lower end, underestimated towards the upper end and then overestimated the highest sampling point. The WA-PLS transfer function performed better than the WA and WA-Tol versions based on r^2_{boot} and RMSEP values (see Table 5.5). Using the rule of Brooks and Birks (2000), which is based on the principle of parsimony, the three component WA-PLS model was considered to be the best of its type because the reduction in RMSEP from one to two and from two to three components was greater than 5%, but not enough more precision was gained from adding a fourth component (see Table 5.7). In any case, (Barlow *et al.*, 2013) advises that no more than three components should be used.

Unimodal models based on the foraminifera training set predicted SWLI with more success than linear models (Figure 5.14). While all models overestimated slightly at the lower end and underestimated at the upper end of the intertidal zone, the linear models tended to be more erroneous and deviated particularly significantly from the observed SWLI in two places. The anomalous minimum in SWLI estimated by the foraminifera-based PLS models for sample S31 is likely to have been caused by linear extrapolation of the elevational range of *Ammonia beccarii*, which is unusually high in abundance in this sample. Similarly, the
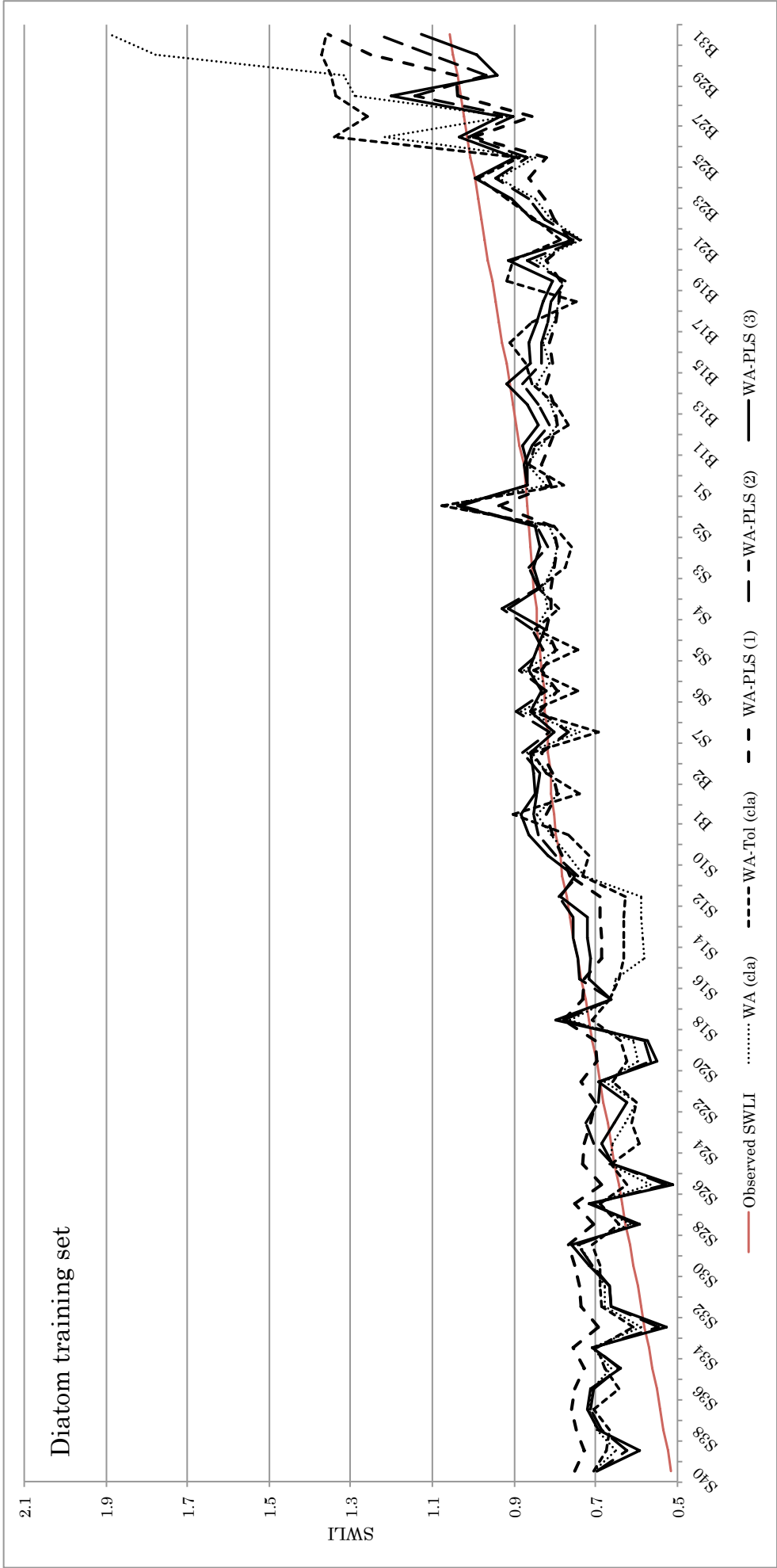
Figure 5.13: Sample elevations in the diatom training set, showing the predictions of WA, WA-Tol and WA-PLS (1 and 2 components) transfer functions against the observed SWLI values.
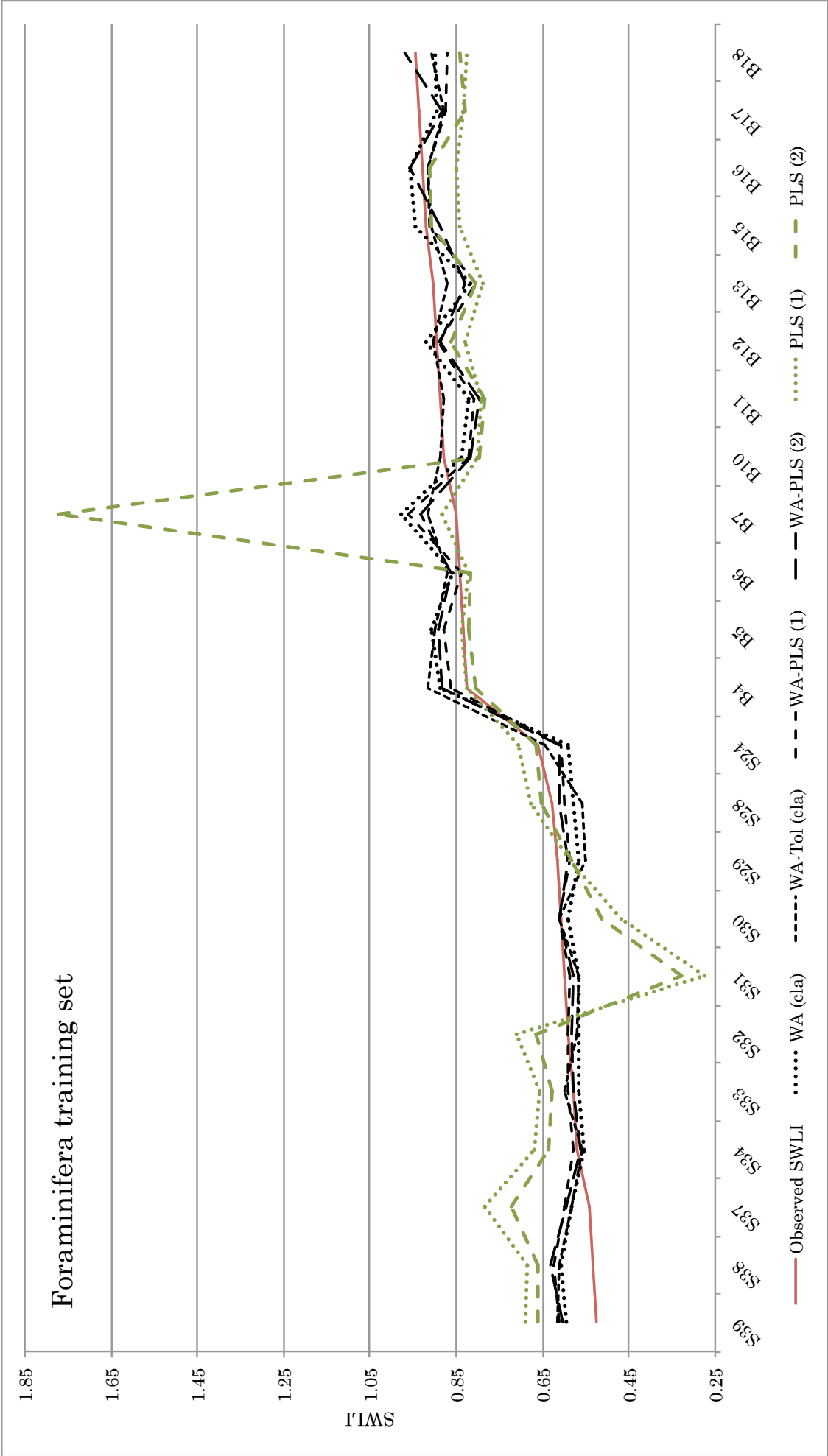
Figure 5.14: Sample elevations in the foraminifera training set, showing the predictions of WA, WA-Tol, WA-PLS (1 and 2 components) and PLS (1 and 2 components) transfer functions against the observed SWLI values.
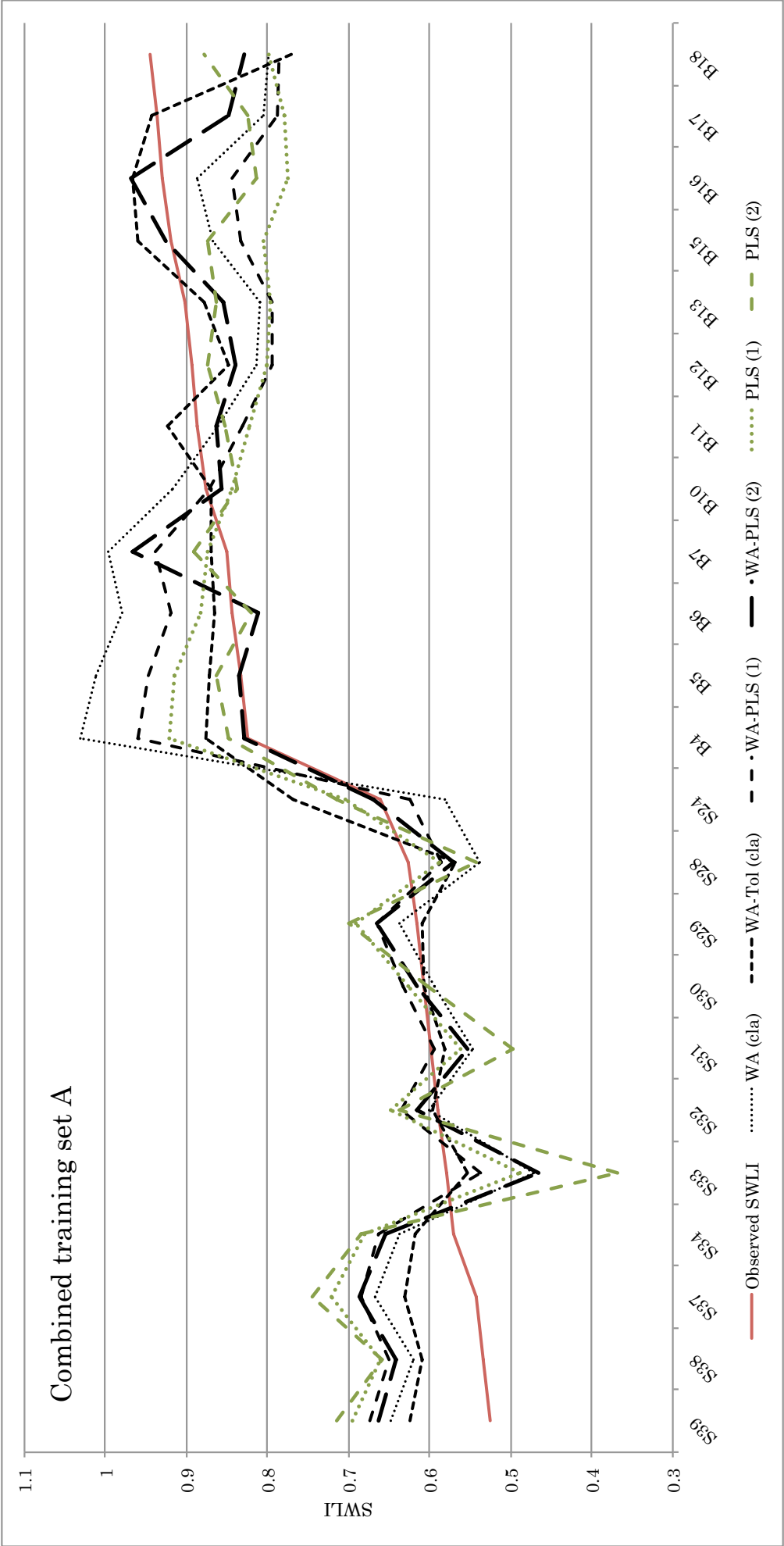
Figure 5.15: Sample elevations in combined training set A, showing the predictions of WA, WA-Tol, WA-PLS (1 and 2 components) and PLS (1 and 2 components) transfer functions against the observed SWLI values.
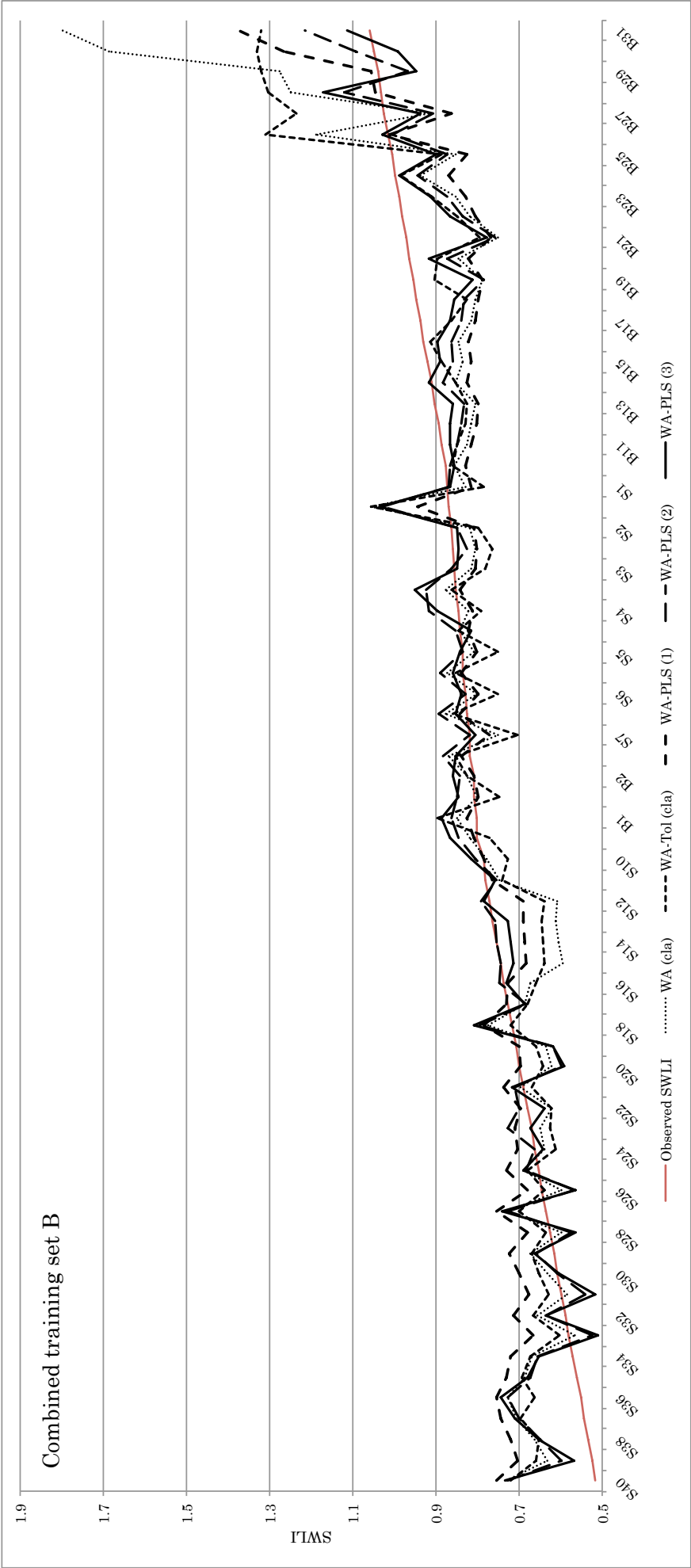
Figure 5.16: Sample elevations in the combined training set B, showing the predictions of WA, WA-Tol and WA-PLS (1 and 2 components) transfer functions against the observed SWLI values.
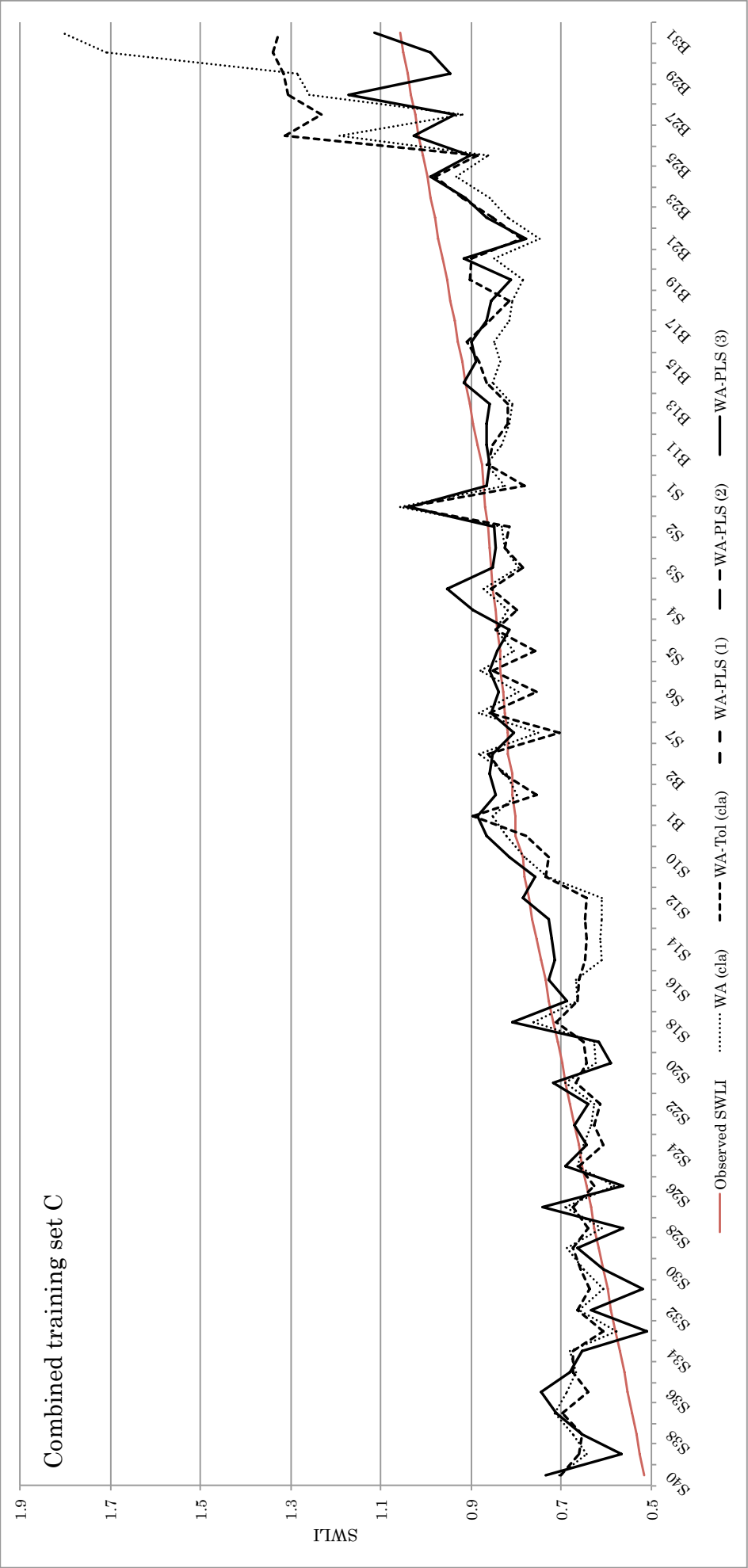
Figure 5.17: Sample elevations in the combined training set C, showing the predictions of WA, WA-Tol and WA-PLS (1 and 2 components) transfer functions against the observed SWLI values.

Table 5.5: Statistical parameters of the single proxy transfer functions based on the diatom and foraminifera training sets. N is the number of samples. n is the number of species. r^2 is the coefficient of determination. RMSE is the root mean squared error. r^2_{boot} is the coefficient of determination after bootstrapping cross validation. RMSEP is the root mean squared error of prediction. Numbers accompanying PLS and WA-PLS refer to the number of components. inv=inverse. cla=classical.

Training set	N	n	Regression model	r^2	RMSE	r^2_{boot}	RMSEP
Diatoms	71	29	WA (inv)	0.48	0.11	0.40	0.12
			WA (cla)	0.48	0.16	0.42	0.18
			WA-Tol (inv)	0.60	0.09	0.58	0.10
			WA-Tol (cla)	0.60	0.12	0.58	0.13
			WA-PLS 1	0.48	0.11	0.42	0.12
			WA-PLS 2	0.72	0.08	0.63	0.10
			WA-PLS 3	0.76	0.07	0.68	0.10
			WA-PLS 4	0.78	0.07	0.69	0.10
			WA-PLS 5	0.79	0.07	0.70	0.10
Foraminifera	23	10	WA (inv)	0.91	0.05	0.89	0.05
			WA (cla)	0.91	0.05	0.89	0.06
			WA-Tol (inv)	0.93	0.04	0.91	0.05
			WA-Tol (cla)	0.93	0.04	0.91	0.05
			WA-PLS 1	0.91	0.05	0.88	0.06
			WA-PLS 2	0.92	0.04	0.89	0.06
			WA-PLS 3	0.94	0.04	0.87	0.07
			WA-PLS 4	0.94	0.04	0.84	0.08
			WA-PLS 5	0.94	0.04	0.81	0.09
			PLS 1	0.56	0.10	0.44	0.13
			PLS 2	0.60	0.10	0.29	0.23
			PLS 3	0.74	0.08	0.39	0.21
			PLS 4	0.79	0.07	0.38	0.23
			PLS 5	0.80	0.07	0.37	0.24

abundance of *Jadammina macrescens* was unusually high in sample B7, causing the linear models to extrapolate far above the elevational range of that species encountered in the other 22 samples.

This set of transfer functions was based on a training set of only 23 samples and did not contain any samples from the middle of the intertidal zone (SWLI 0.662 to 0.825), where very few foraminifera were encountered, so at this stage it was not known how the transfer functions would respond to fossil samples that could represent past instances of that missing zone. Any reconstruction based on this transfer function would risk suffering from a lack of modern analogues for some samples. Based on the r^2_{boot} and RMSEP figures, the WA-Tol model performed best.

Transfer function models based on the combined training set A (again, only using 23 samples) tended to overestimate SWLI at the lower and upper ends of the gradient, and underestimated at the very top end (Figure 5.15). In terms of r^2_{boot} and RMSEP the classical WA-Tol model was the best, but based only on the plotted SWLI estimates, no one model

Table 5.6: Statistical parameters of the multi-proxy transfer functions based on the three different combinations of the diatom and foraminifera training sets. See Table 5.5 for an explanation of the column headings.

Training set	N	n	Regression model	r^2	RMSE	r^2_{boot}	RMSEP
Combined A	23	35	WA (inv)	0.74	0.08	0.62	0.10
			WA (cla)	0.74	0.09	0.64	0.11
			WA-Tol (inv)	0.88	0.05	0.86	0.08
			WA-Tol (cla)	0.88	0.06	0.86	0.08
			WA-PLS 1	0.74	0.08	0.63	0.10
			WA-PLS 2	0.88	0.05	0.78	0.08
			WA-PLS 3	0.92	0.04	0.74	0.10
			WA-PLS 4	0.94	0.04	0.71	0.11
			WA-PLS 5	0.95	0.03	0.71	0.12
			PLS 1	0.67	0.09	0.57	0.11
			PLS 2	0.76	0.08	0.62	0.11
			PLS 3	0.82	0.07	0.56	0.13
			PLS 4	0.87	0.06	0.58	0.13
			PLS 5	0.91	0.05	0.63	0.13
Combined B	71	39	WA (inv)	0.54	0.10	0.46	0.12
			WA (cla)	0.54	0.14	0.47	0.16
			WA-Tol (inv)	0.66	0.09	0.63	0.10
			WA-Tol (cla)	0.66	0.11	0.63	0.12
			WA-PLS 1	0.54	0.10	0.48	0.11
			WA-PLS 2	0.77	0.07	0.70	0.09
			WA-PLS 3	0.81	0.07	0.73	0.09
			WA-PLS 4	0.82	0.06	0.73	0.09
			WA-PLS 5	0.84	0.06	0.74	0.10
Combined C	71	39	WA (inv)	0.54	0.10	0.46	0.12
			WA (cla)	0.54	0.14	0.48	0.16
			WA-Tol (inv)	0.66	0.09	0.64	0.09
			WA-Tol (cla)	0.66	0.11	0.64	0.12
			WA-PLS 1	0.54	0.10	0.48	0.11
			WA-PLS 2	0.79	0.07	0.71	0.09
			WA-PLS 3	0.83	0.06	0.76	0.08
			WA-PLS 4	0.85	0.06	0.77	0.08
			WA-PLS 5	0.87	0.05	0.80	0.09

Table 5.7: Percentage change in RMSEP gained from adding further components to the diatom-based WA-PLS transfer function. Percentages are based on the difference between the RMSEP of that model and of the model with one fewer components.

WA-PLS components	r^2_{boot}	RMSEP	Change in RMSEP (%)
1	0.416232	0.119704	–
2	0.634126	0.098999	-17.297
3	0.675428	0.093750	-5.302
4	0.688459	0.095555	1.925
5	0.697707	0.102252	7.008

remained very close to the observed values throughout. The linear models were more variable than the unimodal models at the lower end but fitted slightly more successfully to the observed values around SWLI 0.8 to 0.9.

The models shown in Figure 5.16 for combined training set B followed a similar pattern to those based on the diatom training set alone. SWLI was generally overestimated for lower values, predicted well in the middle and underestimated for higher values. The very highest sample, which was overestimated by over half of the modelled elevation range again by the WA model, was likely to be poorly predicted because some diatom species only appeared in this one sample, and no foraminifera data were available to compensate for the lack of diatom information. The WA-PLS models performed best (see Table 5.6) and calculation of the increased precision gained by adding more components showed that two components was the ideal number, with less than 5% reduction in RMSEP gained from adding the third component (see Table 5.8).

Table 5.8: Percentage change in RMSEP gained from adding further components to the combined B WA-PLS transfer function. Percentages are based on the difference between the RMSEP of that model and of the model with one fewer components.

WA-PLS components	r^2_{boot}	RMSEP	Change in RMSEP (%)
1	0.478491	0.113284	–
2	0.695266	0.090073	-20.489
3	0.729106	0.085604	-4.962
4	0.733851	0.088803	3.737
5	0.735894	0.097200	9.456

Finally, the cross validated SWLI estimates given by the combined training set C transfer function models are plotted in Figure 5.17. The five models gave very similar estimates to the diatom training set and combined training set B, with all of the models overestimating the lower SWLI values, fitting well for the majority of the intertidal zone, underestimating some of the higher samples and overestimating the very highest samples. The classical WA model vastly overestimated the highest sample, and the WA-PLS models with two and three components fitted most closely to the observed SWLI plot, only slightly overestimating the upper samples. This is corroborated by the prediction statistics in Table 5.6. Table 5.9 shows that the second component improved the WA-PLS model considerably from one component and that just over 7% precision was gained by adding the third component.

The best model for each training set is listed in Table 5.10 and the relationship between the observed and predicted SWLI values for each of the five best models can be found plotted in Figure 5.18 These five models are discussed further in Chapter 6 before one of them is
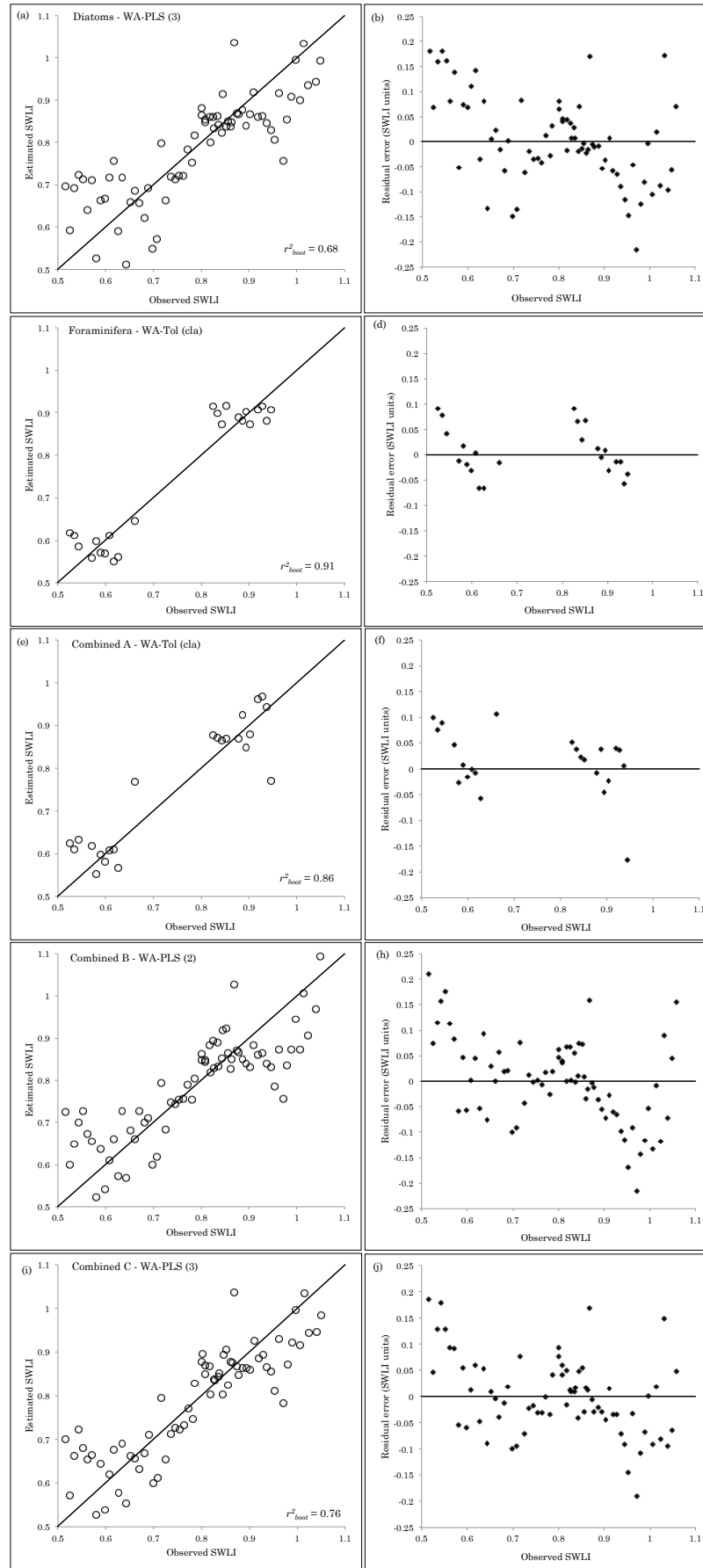
Figure 5.18: Observed SWLI and values predicted by the transfer functions, and the residual errors. (a) & (b) Diatoms - WA-PLS (component 3), (c) & (d) Foraminifera - WA-Tol, (e) & (f) Combined training set A - WA-Tol, (g) & (h) Combined training set B - WA-PLS (component 2), (i) & (j) Combined training set C - WA-PLS (component 3).

Table 5.9: Percentage change in RMSEP gained from adding further components to the combined C WA-PLS transfer function. Percentages are based on the difference between the RMSEP of that model and of the model with one fewer components.

WA-PLS components	r^2_{boot}	RMSEP	Change in RMSEP (%)
1	0.0478140	0.114093	–
2	0.714237	0.088764	-22.200
3	0.756645	0.082294	-7.289
4	0.766623	0.084611	2.815
5	0.777331	0.089446	5.714

Table 5.10: Statistical parameters for the transfer function with the most potential predictive power developed from each of the four training sets. See Table 5.5 for an explanation of the column headings.

Training set	N	n	Regression model	r^2	RMSE	r^2_{boot}	RMSEP
Single proxy							
Diatoms	71	29	WA-PLS (3)	0.76	0.07	0.68	0.10
Foraminifera	23	10	WA-Tol (cla)	0.93	0.04	0.91	0.05
Multi-proxy							
Combined A	23	35	WA-Tol (cla)	0.88	0.06	0.86	0.08
Combined B	71	39	WA-PLS (2)	0.77	0.07	0.70	0.09
Combined C	71	39	WA-PLS (3)	0.83	0.06	0.76	0.08

selected for the reconstruction in Chapter 8.

5.4 Chapter summary

- Two modern transects sampled from Stert Flats and Beachley Point spanned the intertidal zone from just above MSL (0.646m OD at Stert/SWLI 0.516) to MHWST (7m OD at Beachley/SWLI 1.058).

- The diatom training set was composed of 71 contemporary surface samples. Cluster analysis revealed four intertidal zones: tidal flat, lower saltmarsh, upper saltmarsh and terrestrial zones. DCA indicated that the diatoms responded unimodally to their environment, implying that weighted averaging regression methods were the most suitable methods for develping a diatom-based sea-level transfer function from this training set.

- The foraminifera training set was composed of 23 contemporary surface samples. Samples between SWLI 0.662 and 0.825 and those above SWLI 0.946 had insufficient numbers of tests to be included in the training set. DCA did not definitively confirm whether the foraminifera species responded linearly or unimodally to their environment, so both linear and weighted averaging regression methods were used to develop single-proxy foraminifera-based transfer functions.

- Foraminifera and diatom data were combined in three different ways.

  - Combined training set A was composed only of the 23 samples containing sufficient numbers of both foraminifera and diatoms to form the single-proxy training sets.

  - Combined training set B was composed of all 71 samples, with low foraminifera counts replaced by zero counts.

  - Combined training set C was composed of all 71 samples, with low foraminifera counts included.

- Constrained ordination indicated that elevation above MSL (expressed as SWLI) was a significant factor in explaining the variation in the diatom and foraminifera data.

- Unimodal transfer functions (WA, WA-Tol and WA-PLS) were developed from the diatom and combined B and C training sets.

- Unimodal (WA, WA-Tol and WA-PLS) and linear (PLS) transfer functions were developed from the foraminifera and combined A training sets.

- The transfer function with the best prediction statistics from 1,000 bootstrap cycles based on each training set is discussed in the next chapter, prior to the reconstruction stage. These five are:

  - Diatoms: WA-PLS (3 components), r^2_{boot}=0.68, RMSEP=0.10

  - Foraminifera: WA-Tol (classical), r^2_{boot}=0.91, RMSEP=0.05

  - Combined A: WA-Tol (classical), r^2_{boot}=0.86, RMSEP=0.08

  - Combined B: WA-PLS (2 components), r^2_{boot}=0.70, RMSEP=0.09

  - Combined C: WA-PLS (3 components), r^2_{boot}=0.76, RMSEP=0.08

Chapter 6

Sea-level transfer function analysis and discussion

This chapter presents a discussion of the findings presented in the previous chapter, in the context of using the new transfer functions for the Severn Estuary to reconstruct Holocene sea-level at the Steart Peninsula, and of the issues encountered in sampling in an extremely macrotidal environment with limited suitable intertidal sites and in attempting to combine two proxies together into a single model. Comparisons are made to results of previous research, and the limitations encountered, as well as possibilities for future research, are discussed within each section.

6.1   Diatom and foraminifera training sets

Analagous to previous studies both in the British Isles and elsewhere, intertidal diatom assemblages displayed greater species diversity than the assemblages of foraminifera did across the two modern transects surveyed in this study. The average number of species per sample in the diatom training set was 12.5, but only 6.3 in the foraminifera training set. Other authors have noted similar findings, such as Kemp *et al.* (2009a) whose comparative study in North Carolina saw the identification of 102 diatom species and 16 foraminifera species across four intertidal transects. In the UK Gehrels *et al.* (2001) identified 291 diatom species in a training set of 97 samples from three sites, but only 29 species of foraminifera from a training set of 90 samples from the same three sites.

The vertical zonation in diatom assemblages revealed by cluster analysis shares elements with other studies. While the particular species that dominate diatom zones might vary between sites, most authors tend to identify three or four main zones, whether based on floral changes (Woodroffe and Long, 2010), tidal levels (Zong and Horton, 1999) or by using

cluster analysis of the species data itself (Horton and Edwards, 2000; Szkornik *et al.*, 2006; Hill *et al.*, 2007), distinguishing between an unvegetated tidal flat zone dominated by marine and marine-brackish species such as *Paralia sulcata* and other, apparently site-specific species, and one or more saltmarsh zones. Hill *et al.* (2007) identify an additional upper mudflat zone characterised by a decline in marine species and an increase in brackish species. No such distinction emerged through cluster analysis in this study, where the tidal flat zone evolved straight into the lower saltmarsh zone. Horton and Edwards (2000), Szkornik *et al.* (2006) and Hill *et al.* (2007) then identify two marsh zones, each composed of increasingly less marine and more brackish and freshwater species.

Similar to this study, Zong and Horton (1999) identified an upland/supratidal zone characterised by freshwater and oligohalobous (indifferent in terms of salinity) diatom species, while Woodroffe and Long (2010) identified a terrestrial/upland zone devoid of any diatoms. Horton and Edwards (2000) used cluster analysis to divide the intertidal habitats of 10 sites into zones but none of the data sets reveals a terrestrial or upland zone. Instead, the middle and upper marshes are coupled together as one single zone. Vos and de Wolf (1988) identified a *Hantzschia amphyoxis* supratidal diatom group in the Netherlands that shares some of the species with the terrestrial zone identified in this study.

Some of the data collected throughout the modern diatom analysis on the cumulative number of species per 10 individuals is presented in Figure 6.1 for a representative selection of the transect samples. Three randomly selected samples from each modern diatom zone are presented, confirming that 300 diatoms was sufficient in representing the population at each sampling site. The full data are available on request.

Unlike diatoms, foraminifera tend to form intertidal assemblages of similar species at different sites, allowing for a more direct comparison between the foraminifera zonation found in this study and others. Previous authors have identified anywhere between one (Horton and Edwards, 2006) and four (Scott and Medioli, 1978) intertidal foraminifera zones. The lack of significant numbers of tests in the samples between SWLI 0.67 and 0.82 in this study makes comparison with other studies slightly more difficult, but most studies do identify one or two tidal flat zones characterised by calcareous species. *Haynesina germanica*, *Elphidium williamsoni* and *Ammonia beccarii* are the dominant species identified by Horton and Edwards (2000) as tidal flat dwellers at several UK sites, and the same genera and often the same species have been found to characterise the tidal flat zones in New Zealand (Hayward *et al.*, 1999), North America (Kemp *et al.*, 2009b), the Iberian Peninsula (Leorri *et al.*, 2008, 2010) and France (Rossi *et al.*, 2011), for example.
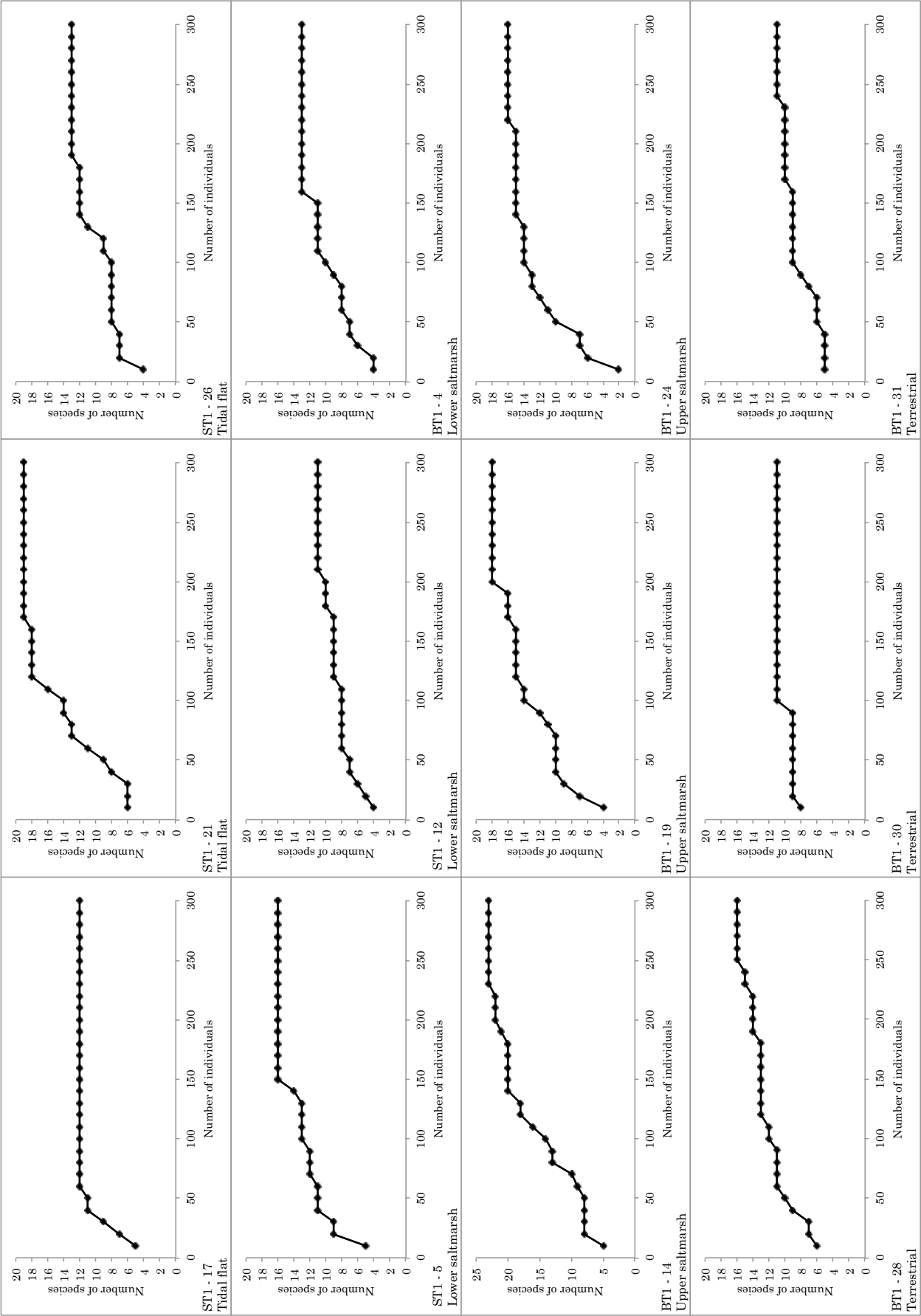
Figure 6.1: Cumulative species versus individuals plots for modern diatoms samples representing each modern diatom zone.

In a study at Oldbury-on-Severn Haslett *et al.* (1997) made a distinction between *H. germanica* and *A. beccarii* tidal flat zones, but in this study no division of the tidal flat zone was apparent, perhaps in part because of the low abundance of foraminifera above SWLI 0.67. This missing zone in the foraminifera training set represents the transition between the tidal flat and lower marsh environments, and was a disappointing result for the foraminifera- and multi-proxy-based transfer function development because a large amount of information is not available.

In their pioneering study in Novia Scotia, Canada, Scott and Medioli (1980) were able to identify four separate saltmarsh zones. The highest zone (1A) was composed entirely of *Trochammina macrescens*[1], which is a finding replicated in only some UK sites, such as Welwick Marsh in the Humber Estuary and Roundsea Marsh at Morecambe Bay (Horton and Edwards, 2000). In this study, while *Jadammina macrescens* was an important component of the saltmarsh zone, the assemblages were not monospecific, but included significant contributions of other species.

Zone 1B of Scott and Medioli (1980) is in the high and middle marshes and is more diverse, with *Trochammina comprimata* and *Haplophragmoides bonplandi* dominating alongside *T. macrescens*. These species are not generally found in UK salt marshes (Haslett, 1997; Gehrels *et al.*, 2001; Horton and Edwards, 2006). *Miliammina fusca* and *Trochammina inflata* appear in the low marsh in zone 2A (these are common UK species), and species of calcareous genus *Ammonia* are found in the low marsh zone (2B) of the Scott and Medioli (1980) classification.

Similar to this study, Scott and Medioli (1980) found no foraminifera above HHW, where terrestrial flora were noted. In the Severn Estuary, and in particular the Beachley site, where these upper samples were taken, the zone between MHWST and HAT was only inundated by the tide around once per year (Proudman Oceanographic Laboratory, 2012c), so it is possible that this slight marine influence is not sufficient to support foraminifera, which are marine organisms (Murray, 2002). In contrast to the three saltmarsh zones identified in the diatom data in this study, only one saltmarsh zone was idenitified in the foraminifera data, characterised by agglutinated species *J. macrescens*, *Haplophragmoides wilberti* and *T. inflata*, as well as a large proportion of *A. beccarii*. Haslett *et al.* (2001b) found a similar pattern at Oldbury-on-Severn, where calcarous, usually tidal flat-dwelling *A. beccarii* encroached on the zone otherwise dominated by *J. macrescens* and *T. inflata*. This may be because the minerogenic saltmarshes of the Severn Estuary are not as acidic as other, more organic saltmarsh environments, allowing calcareous species that normally suffer dissolution upwards of the

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[1]*Trochammina macrescens* has since been found to be composed of two separate species, *Jadammina macrescens* and *Balticammina pseudomacrescens*; both species were recorded in this study

tidal flat to inhabit the more elevated saltmarsh environment. This hypothesis is supported by the comparison of the maximum pH measured on the Beachley Point transect with other pH ranges from comparable UK studies (Table 6.1).

Table 6.1: Minimum and maximum intertidal pH values from UK sea-level transfer function studies.

Location	Min. pH	Max. pH	Citation
Otter Estuary, Devon	6.74	7.45	Allen (2000c)
Erme Estuary, Devon	5.35	6.96	Charman *et al.* (2002)
Brancaster, Norfolk	5.90	8.05	Charman *et al.* (2002)
Taf Estuary, South Wales	5.45	7.54	Charman *et al.* (2002)
Tees Estuary, Yorkshire	5.40	6.80	Horton (1999)
Severn Estuary, South Wales/Somerset	5.52	9.18	This study

While diatoms were abundant in every modern sample, foraminifera numbers were generally low across both transects. Gehrels (2002) advises that $2cm^3$ of sediment will usually suffice for counts of 200 to 250 tests, but although $4cm^3$ of sediment was prepared per sample in this study, some of them yielded very low numbers; tens or even single digits.

Gehrels and Newman (2004) also found relatively low foraminifera concentrations during a study of Kjelst Enge saltmarsh in western Denmark. Most samples only yielded counts of 50 to 70 tests and statistical anlayses (cluster analysis and CCA) were based on samples with 30 or more tests per $5cm^3$ of sediment. The authors do acknowledge that sample sizes such as these are not satisfactory but go on to propose that precise sea-level reconstructions could be possible following the development of a foraminifera-based sea-level transfer function, because height relative to tide levels was shown to be an important environmental control on species assemblages.

Kemp *et al.* (2012), citing Fatela and Taborda (2002), used samples with a mean average of 165 tests per sample to construct a sea-level transfer function, using the low species diversity to justify this approach. Gehrels (2002) also advises that if species diversity is low then smaller sample sizes may be used, but does not give any indication of what low species diversity might be. Table 6.2 compares sample sizes and species numbers in this study with those in other studies of intertidal foraminifera, indicating that species diversity in the Severn Estuary data is relatively low.

In a study that compares counts of 100 foraminifera with counts of 300 from the same set of samples, Fatela and Taborda (2002) conclude that the only significant differences between the assemblages in the two groups are in the less common species. They advise that samples of 100 foraminifera are sufficient for most studies, and that at least 300 tests should be counted if species that contribute to less than 3% of any one sample are included. Since those such

Table 6.2: Sample numbers, species diversity and sample sizes from selected intertidal foraminifera studies. The data from the Gehrels *et al.* (2005) is taken from Scott and Medioli (1980). N=number of training set samples, n=number of species. *Average number of species per site over 10 sites.

Location	Citation	N	n	Tests counted
Tasmania	Callard *et al.* (2011)	43	6	≥ 300
Connecticut, USA	Edwards *et al.* (2004)	86	11	not stated
Maine, USA	Gehrels (2000)	68	8	not stated
UK	Gehrels *et al.* (2001)	92	29	100–300
Denmark	Gehrels and Newman (2004)	27	16	≥ 30
Nova Scotia	Gehrels *et al.* (2005)	46	33	often over 1,000
Oregon, USA	Hawkes *et al.* (2010)	91	18	up to 300
Various, UK	Horton *et al.* (1999b)	Not given	17*	≥ 40
North Carolina, USA	Horton and Culver (2008)	47	21	≥ 40
North Carolina, USA	Kemp *et al.* (2009b)	145	22	≥ 200
New Jersey, USA	Kemp *et al.* (2012)	56	11	average 165
Alaska, USA	Kemp *et al.* (2013)	58	25	≥ 100
Northern France	Leorri *et al.* (2010)	43	16	not stated
Northern Spain	Leorri *et al.* (2010)	59	23	not stated
Northern Portugal	Leorri *et al.* (2010)	52	44	not stated
Southern Portugal	Leorri *et al.* (2010)	22	8	not stated
Southwest England	Massey *et al.* (2006a)	85	34	≥ 300
New Zealand	Southall *et al.* (2006)	31	5	≥ 300
Severn Estuary	This study	23	10	≥ 100

species have been excluded from the analysis in this study, there can be confidence in those samples with counts of at least 100 foraminifera.

Data collected on the cumulative number of species present per 10 tests for all of the samples used in the foraminifera training set is presented in Figures 6.2 and 6.3. The majority of the plots show that the number of species present plateaus within approximately 100 tests; with particular exceptions in samples 24, 32 and 33 from ST1 and samples 4 and 11 from BT1. Other micropalaeontologists have previously used this type of judgement to justify particular samples sizes (Woodland *et al.*, 1998; Hill, 2006). While this analysis is only based on the number of species present, and not on the relative proportions of the species within each sample, this result combined with the advice of Fatela and Taborda (2002) is sufficient to justify using samples of 100 tests or less.

Implementing a minimum value of 200 tests (Gehrels, 2002) would have resulted in a foraminifera training set of only 8 samples. This number is far too few to have any statistical significance (Leorri *et al.*, 2011). This situation highlights the usefulness of pilot studies, and further research into quantitative sea-level indicators in the Severn Estuary should perhaps involve a study into the volume of sediment required to reliably reach foraminifera counts of 200 or more.
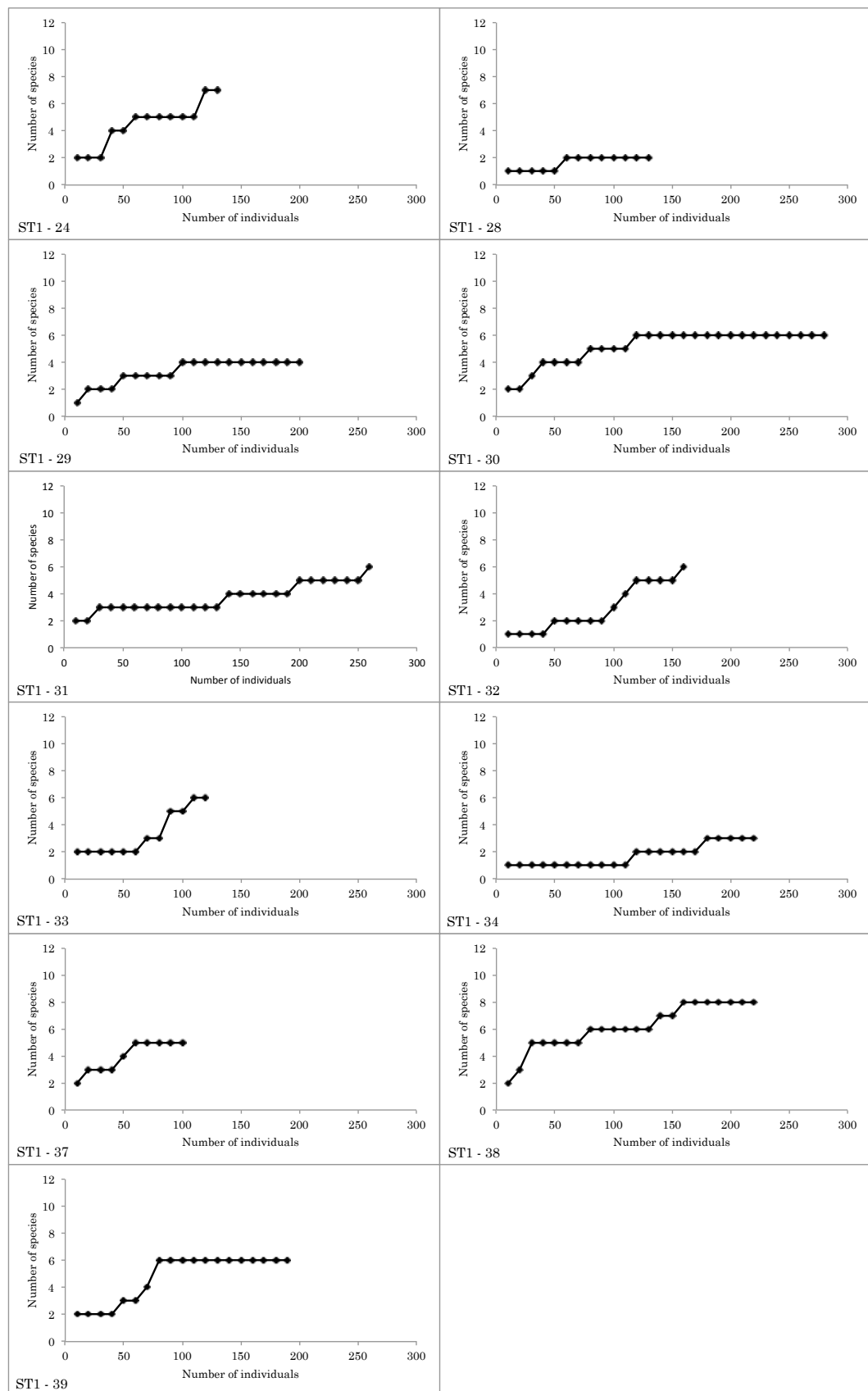
Figure 6.2: Cumulative species versus tests in ST1 samples included in the foraminifera training set.
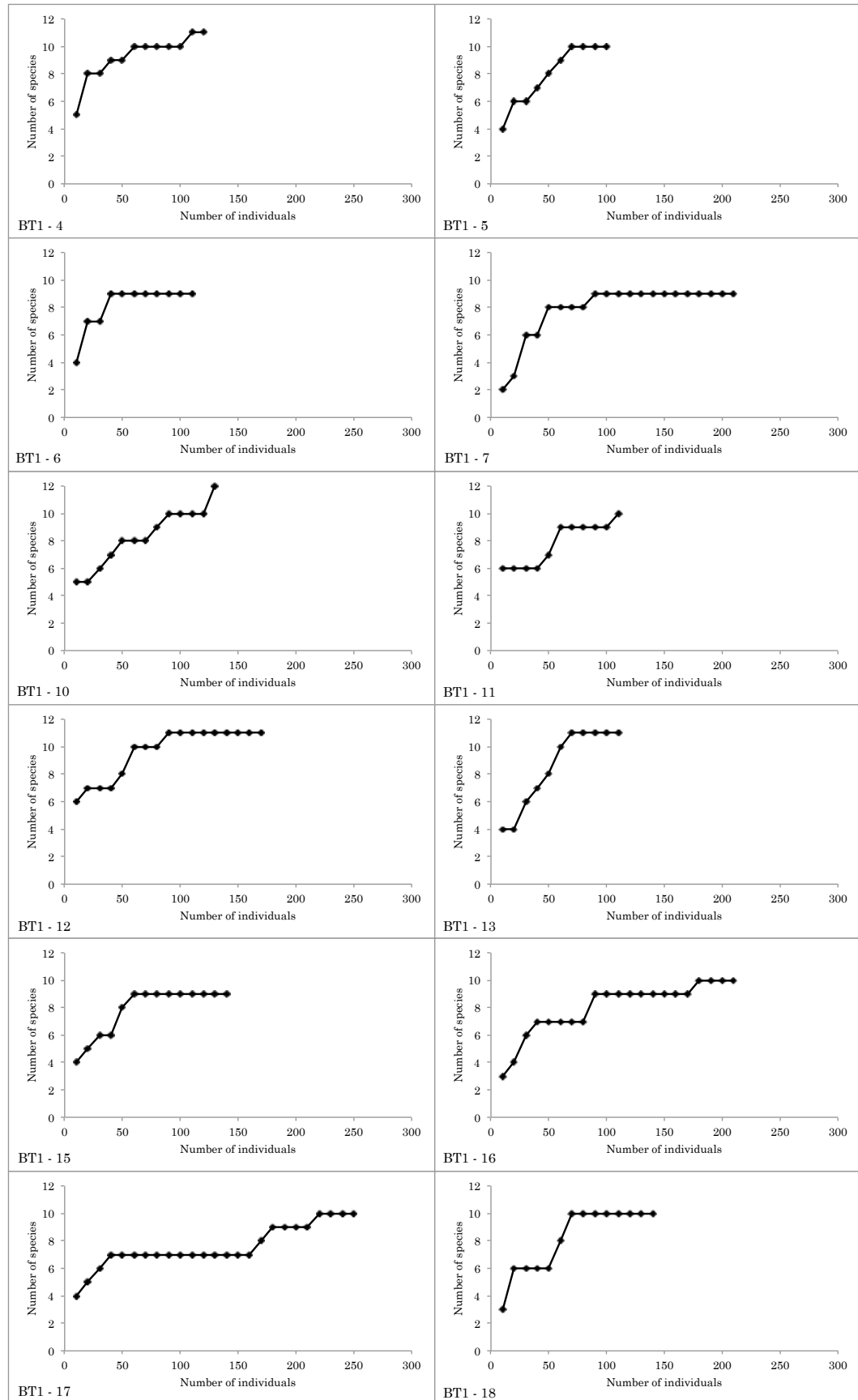
Figure 6.3: Cumulative species versus tests in BT1 samples included in the foraminifera training set.

The findings from the initial collection and discussion of the training set data so far corroborate the point highlighted by Kemp *et al.* (2009a), which is that while species assemblages of intertidal diatoms tend to be specific to particular sites, foraminifera species are more cosmospolitan, forming assemblages composed of the same or very similar species globally. While the foraminifera zones identified in this study are not necessarily identical in SWLI range or composition to others, there are many similarities, and one potential avenue of future research might be to supplement the patchy Severn Estuary foraminifera training set in this study with existing data from other sites, that might provide larger, more significant sample sizes and fill in some of the current gaps in the training data (see Section 8.11 of Chapter 8).

6.2 Combining proxies

The ordination analysis and transfer function development included a comparison between three different ways of combining two proxy data sets. There are two main studies that have looked at using more than one proxy to develop a sea-level transfer function. Gehrels *et al.* (2001) compared 11 combinations of foraminifera (live, dead and total assemblages), diatoms and testate amoebae in a UK study, while Kemp *et al.* (2009a) compared the performance of diatoms and foraminifera in North Carolina, USA as sea-level indicators and then attempted to combine the two proxies together to form a multi-proxy sea-level transfer function.

Gehrels *et al.* (2001) do not fully address the issues surrounding the manner in which data for two difference proxies can be or should be combined together. Before quantitative sudies of microorganisms were used to create transfer function and other numerical models, proxy data was treated qualitatively, and often different proxies used to reconstruct different aspects of the climate or an environmental system (Roberts, 1998). Combining two different proxies together to statistically reconstruct one variable raises questions about the relative importance of each proxy and how they should be combined together into one single data set.

Gehrels *et al.* (2001) excluded any sample from their data set of 121 samples from three sites that had low counts of any one proxy, apparently leaving 116 samples with significant numbers of all of the proxies. This approach appears to be similar to approach A taken in this study, whereby only samples with at least 300 diatoms and 100 foraminifera were included in combined training set A. However, Table 3 of Gehrels *et al.* (2001) gives the number of samples included in the 11 different iterations of the training sets, which ranges from 52 to 116 samples. More discussion around how these different data sets were compiled would

have been welcome, because it would appear either that not all 116 samples included full counts of each proxy, or that there was some other unexplained reason why some samples were excluded. This is important because in the research presented in this thesis, using only samples that yielded significant counts of both proxies (combined training set A) excluded 48 robust diatom samples and left a large part of the intertidal range without data.

Gehrels *et al.* (2001) were interested in the relative benefits of using more than one proxy, in terms of the accuracy and precision gained versus the time spent analysing the various proxies, but do not mention the notion that, in combining two or more proxies together in this way, useful data of one proxy might be discarded if the other is lacking in significant counts in some samples. One of the ways in which multi-proxy transfer functions might be useful is in situations where proxy X lacks acceptable abundance in one part of an environmental gradient and proxy Y can be used to fill this gap. This approach would not be possible if samples are only used when they produce significant counts of both proxies.

If it is preferable to retain samples that have sufficient counts of one proxy, there are two options. Should the poorer proxy be excluded from those samples altogether and all of the data come from the 'good' proxy (approach B)? Or, should the species counts for the poorer organism group be 'tacked onto' the better one (approach C), thus making the assumption that if significant counts of proxy Y have been found, adding on the species from proxy X is acceptable?

Later, Section 6.4 on transfer function development discusses the differences in the prediction statistics between the single proxy transfer functions and multi-proxy approaches A, B and C, and the potential performance of the different transfer functions. However, the decision about which approach should be implemented in the final reconstruction should be based on which gives the most robust training set in terms of sample size, and a fair representation of the real world, as well as which produces the most 'successful' transfer function statistically.

While approach A might be the most complete in terms of within-sample robustness, it falls down because, in this case, using two proxies actually results in fewer data points relative to the diatom-based transfer function, thus leaving a less complete training set from which to produce a transfer function.

The difference between approaches B and C are less clear cut, but intuitively, approach B is the more valid because, if the two proxies are to be treated as separate groups, allowing very low counts of, in this case foraminifera, is not robust, statistically. The minimum sample size of 100 tests is already relatively low, and adding in low counts of species that, when on

their own would not constitute adequate samples, does not seem like the correct thing to do. Approach B is a good compromise between retaining statistical significance within both microorganism groups and maximising the number of samples in the training set and the vertical gradient that it covers.

In the study in North Carolina, Kemp *et al.* (2009a) use existing modern data sets from Horton and Culver (2008) and Horton *et al.* (2006), which include significant counts of both proxies in all samples from the same sampling sites; therefore the question of how to combine the proxies did not arise, because approach A retains all of the samples in their case.

6.3 Species-environment relationships

The vertical optima and tolerance ranges of the diatom and foraminifera species comprising 3% or more of at least one of their respective training set samples, calculated as part of the transfer function development, can be found in Figures 6.4 and 6.5.

The diatom species had a diverse range of different tolerances, with those that had their optima in the middle of the SWLI gradient, such as *Paralia sulcata*, *Podosira stelligera* and *Pseudopodosira westii* having the largest estimated tolerance ranges. With a few exceptions such as *Gyrosigma wansbeckii* and *Tryblionella navicularis*, those species towards the upper and lower ends of the gradient had lower tolerance ranges of around 0.1 SWLI units, equating to about one metre at the Steart site. The fact that the species with the highest tolerance ranges coincided with the zone lacking in significant foraminifera assemblages is likely to have implications for the transfer functions in this part of the SWLI gradient. Zong and Horton (1999) noted a slightly different pattern, whereby the species in the lower part of the tidal range had larger tolerance ranges, decreasing gradually towards HAT.

In terms of the foraminifera, the calcareous species can be seen to have far wider tolerance ranges than the agglutainted, saltmarsh-dwelling forms. *A. beccarii*, *Quinqueloculina* spp. and *H. germanica* all had tolerance ranges of ~0.3 SWLI units (~3m) while *J. macrescens*, *H. wilberti*, *T. inflata* and *B. striatula* tolerated environments in ranges of 0.1 SWLI units (~1 metre) or less.

Similar findings on the northern coast of Spain and west coast of Portugal prompted Leorri *et al.* (2010) to experiment with removing all samples below a certain SWLI from their transfer function models for four different sites. They found that r^2_{boot} values were not affected significantly by this move, but that RMSEP was reduced, in one case by approximately 50%, indicating an increase in precision of the transfer functions when a smaller elevation range from the upper intertidal zone was used. This goes somewhat against the notion that it
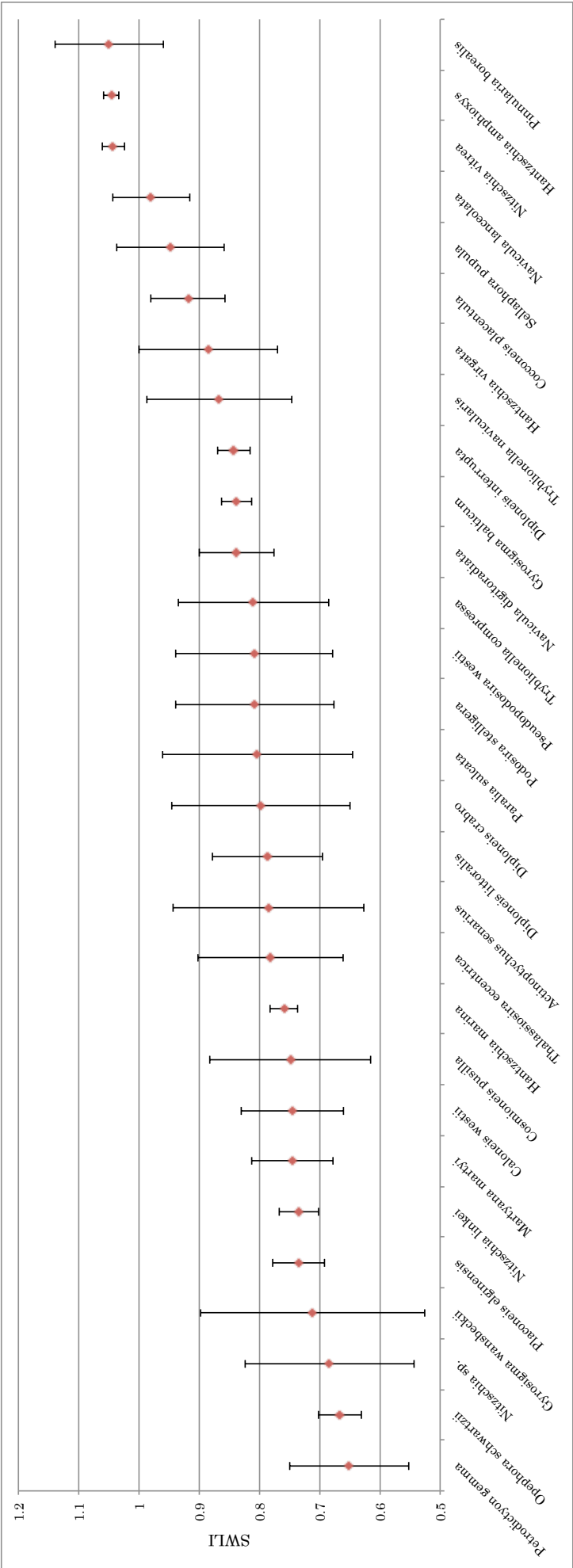
Figure 6.4: Optima and tolerance ranges of species in the Severn Estuary diatom training set in relation to SWLI, calculated by weighted averaging regression.
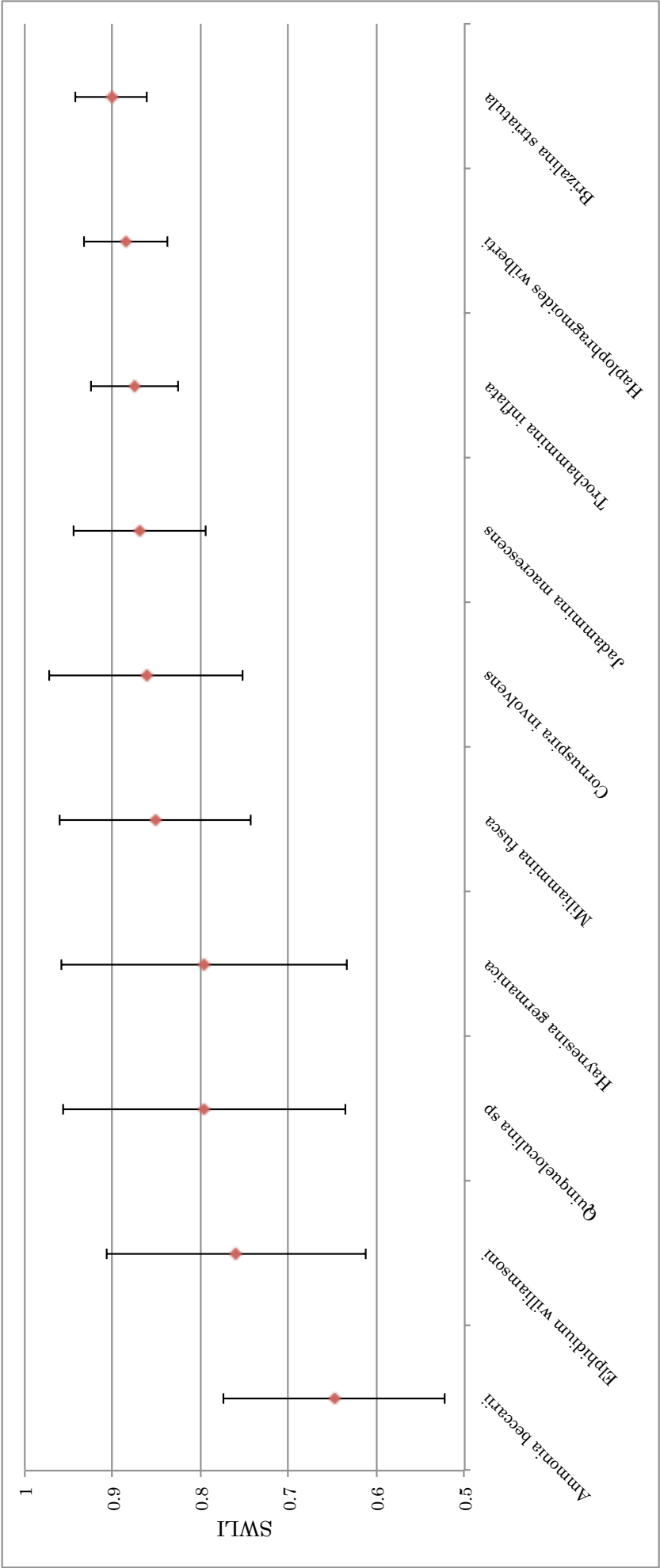
Figure 6.5: Optima and tolerance ranges of species in the Severn Estuary foraminifera training set in relation to SWLI, calculated by weighted averaging regression.

is important to sample from the intertidal zone in its entirety, so that the chances of fossil samples having good modern analogues is maximised, and so that the full tolerance ranges of, particularly low marsh to tidal flat, species can be established (Wright *et al.*, 2011b). Leorri *et al.* (2010) did not address this issue, and it is not known what the effect would be if core samples for a sea-level reconstruction contained high proportions of those assemblages excluded from the training set by removing the lower end of the gradient.

The diatom and foraminifera species with the smallest tolerance ranges with respect to SWLI were mainly in the upper saltmarsh and terrestrial habitats, so it is likely that reconstruction of these environments from the Steart cores would be more precise than for the lower, tidal flat deposits, where species in the modern environment tend to have broader environmental tolerance.

Ordination analysis to investigate the importance of SWLI on the variation in diatoms and foraminifera in the intertidal zone revealed some key differences between the two proxy groups.

In a very similar pattern to that found by Horton and Edwards (2000), CCA analysis showed that while a greater percentage of the *total* variation in the foraminifera data was estimated to be explained by the environmental variables measured than it was for the diatom data, a greater proportion of the *explained* varition was due to SWLI in the diatom data.

Hill *et al.* (2007) produced a similar result in a diatom study based on data from the Welsh and English sides of the Severn Estuary, and research by Zong and Horton (1999) across 7 sites in the UK showed that 22% of the explained variation in their contemporary diatom data set was explained by SWLI.

While it is possible to be confident that the transfer functions produced in this study can be at least as reliable as those in these existing studies, all of the results strongly suggest that there may be one or more factors influencing intertidal diatom distribution that have not been considered by most authors. Ng and Sin (2003) found that, along with water depth (linked to elevation), the calcium carbonate content of the sediments, pH, volumetric magnetic susceptibility and mean grain size explained the largest independent portions of diatom variation at their site in Hong Kong.

It is possible to reconstruct a variable from proxy data that is not the biggest influence on that data; indeed it is possible to reconstruct more than one variable from a single proxy data set, such as former temperature and precipitation from pollen records (Adam and West, 1983; Vincens *et al.*, 1993), but Birks *et al.* (2010) stresses that an environmental or climatic variable *must* be shown to account for a significant, independent proportion of species variation. While

that result for the diatom training set in this study is at least as strong as those cited above, with SWLI accounting for an overall 5.51% of the observed species variation (29% of the 19% variation explained by all of the variables measured), this is a fairly low proportion, and should be viewed as a limitation when interpreting the results of the sea-level reconstruction later.

Unimodal and linear methods implied two completely different scenarios for the foraminifera training set; one in which SWLI was the most influential of the measured variables (CCA) and one in which SWLI accounted for only a very small proportion of the variation explained by those variables (RDA). This posed the question of which of these results is most likely to represent the truth. While ecologists have more or less agreed that unimodal species-environment relationships are more common than linear relationships (Begon *et al.*, 2006), the large difference in the percentage of the explained variation accounted for by SWLI in this particular data set resulting from the two difference methods (16% of the 71% explained variation assuming unimodal relationships, and just 2% of the 60% explained variation in the linear version) is recognised as a significant limitation. In terms of actual percentages of the total variation, the unimodal and linear partial constrained ordination analyses return values of 11% and 1.2% respectively for the influence of SWLI.

The exceptionally low influence of SWLI on assemblages of foraminifera estimated by RDA indicated that there was no justification for pursuing further with linear methods in this study.

6.4 Transfer function development

Values of r^2 and RMSEP from cross-validation are two important indicators of the usefulness of an ecological transfer function (Gehrels *et al.*, 2001). These prediction statistics give an indication of the ability of the transfer function to predict small sub-sets of the original training set and therefore, of the potential for it to give meaningful results from fossil data.

Beginning with a comparison of the two single proxies, based solely on the prediction statistics, foraminifera were clearly the more accurate and precise microorganisms. The r^2 and RMSEP values compared favourably with previous studies (Table 6.3), while the prediction statistics for the diatom models suggested slightly less success than other studies have shown (Table 6.4). RMSEP for the best diatom-based transfer function in this study was actually comparable to other studies, and improved on some, but the r^2_{boot} value was low, and a high level of precision is not very meaningful when accuracy is relatively low. This result may be due to the ubiquitous species like *Paralia sulcata*, *Gyrosigma wansbeckii*,

Actinoptychous senarius and *Podosira stelligera* that have very wide tolerance ranges, so are not precise sea-level inidcators. Horton *et al.* (2006) have also noted the dominance of certain polyhalobous (marine) diatom species in their three marshes in North Carolina.

When presented as a percentage of the tidal range, RMSEP for the foraminifera-based WA-Tol transfer function (4.05%) indicates greater relative precision than some previous studies (Table 6.3). This suggests that perhaps, though intertidal habitats or zones are effectively stretched out at sites with greater tidal ranges, the banding of species optima and tolerances within those zones are more readily modelled in finer detail. The sampling strategy (10cm vertical intervals) implemented in this study means that greater detail in the microorganism training sets was achieved relative to the studies at sites with smaller tidal ranges that used the same or a similar sampling interval (Leorri *et al.*, 2010; Woodroffe and Long, 2010).

However, for reasons unknown, foraminifera counts were low in many samples, resulting in no representation for a large section of the intertidal zone. While previous authors have found a barren zone between MHWST and HAT in various estuaries (Scott and Medioli, 1980; Haslett *et al.*, 1998), the situation where counts are low in the middle portion is uncommon, and while the prediction statistics for the samples for which counts were available were strong, there is no information on how the foraminifera-based transfer function would behave in that missing section of the gradient.

Of the three versions of the multi-proxy training set, combined training set A produced the best prediction statistics. In comparison to the two existing multi-proxy sea-level transfer function studies published (Gehrels *et al.*, 2001; Kemp *et al.*, 2009a), this result was good, with a higher r^2_{boot} than either of them and a better RMSEP after accounting for the tidal range (Table 6.5). However, there are two reasons why this particular transfer function was not used to reconstruct sea-level from the Steart core. First, because the r^2_{boot} was lower and the RMSEP higher than those produced from the foraminifera training set alone, negating the value in merging the proxies in this way, and second, because this model suffered from the same issue as the single proxy foraminifera training set; samples from the entire intertidal range were not included due to low foraminifera counts in 48 of the 71 samples. The diatom-based transfer function alone covered the entire vertical range, so would have been a better choice of model than multi-proxy transfer function A.

Combined training set C performed slightly better than training set B, with a higher r^2_{boot} and the same RMSEP as combined training set A; 0.06 SWLI units, or 0.87 metres at Steart. This is likely to be due to the additional data in training set C gained from including the

Table 6.3: Comparison of the prediction statistics associated with the foraminifera-based transfer function developed in this study with previous studies. N is the number of samples in the training set. r_X^2 is the cross-validated r^2. MTR = mean tidal range. The data from Gehrels *et al.* (2005) are taken from Scott and Medioli (1980). Note that while the RMSEP values for models in this study were previously given in SWLI units, RMSEP here has been converted to metres in order to give RMSEP as a percentage of the mean tidal range and make direct comparisons between studies. C11=Callard *et al.* (2011), So06=Southall *et al.* (2006), G01=Gehrels *et al.* (2001), M06=Massey *et al.* (2006a), L10=Leorri *et al.* (2010), G et al 05=Gehrels *et al.* (2005), G00=Gehrels (2000), E04=Edwards *et al.* (2004), K12c=Kemp *et al.* (2012), K09c=Kemp *et al.* (2009c), H10=Hawkes *et al.* (2010).

Site	N	Model	r_X^2	RMSEP (m)	MTR	RMSEP/ MTR (%)	Citation
Tasmania	43	WA-PLS	0.66	0.10	0.60	16.7	C11
Catlins Coast, NZ	31	WA-Tol	0.49	0.05	1.50	3.1	So06
UK (average of 3 sites)	90	PLS	0.29	0.08	Not given	Unknown	G01
Southwest England	85	WA-PLS	0.93	0.29	3.45	8.3	M06
Severn Estuary	23	WA-Tol	0.91	0.55	13.58	4.05	This study
Brittany, France	43	PLS	0.52	0.12	3.50	3.4	L10
Northern Spain	59	WA-PLS	0.77	0.13	2.25	5.8	L10
Northern Portugal	52	WA-PLS	0.39	0.42	1.80	23.4	L10
Southern Portugal	22	PLS	0.22	0.14	2.00	7.1	L10
Nova Scotia	46	WA-Tol	0.46	0.06	1.50	3.7	G05
Maine	68	WA-PLS	0.76	0.08	3.11	1.0	G00
Connecticut	86	WA-PLS	0.72	0.14	1.36	10.3	E04
New Jersey	56	WA-PLS	0.79	0.14	1.20	11.7	K12c
North Carolina	46	WA-PLS	0.74	0.04	0.27	14.8	K09c
Oregon	91	WA-PLS	0.82	0.20	1.81	11.0	H10

Table 6.4: Comparison of the prediction statistics associated with the diatom-based transfer function developed in this study with previous studies. See Table 6.3 for an explanation of the column headings. ZH99=Zong and Horton (1999), G01=Gehrels *et al.* (2001), WL1=Woodroffe and Long (2010), Sz06=Szkornik *et al.* (2006), H07=Hill *et al.* (2007), K09=Kemp *et al.* (2009a), NS03=Ng and Sin (2003).

Site	N	Model	r_X^2	RMSEP (m)	MTR	RMSEP/ MTR (%)	Citation
UK (average of 6 sites)	88	WA-Tol	0.72	0.12	n/a	Unknown	ZH99
UK (average of 3 sites)	94	WA-PLS	0.75	0.054	Not given	Unknown	G01
Severn Estuary	61	WA-Tol	0.85	0.88	14.65	6.01	H07
Severn Estuary	71	WA-PLS	0.68	1.09	13.58	8.03	This study
West Greenland	135	WA-PLS	0.90	0.10	1.88	5.32	WL10
West Denmark	40	WA-PLS	0.90	0.14	1.5	9.33	Sz06
North Carolina (average of 3 sites)	46	WA-PLS	0.76	0.04	n/a	Unknown	K09
Double Haven (Hong Kong)	25	WA	0.73	0.39	1.7	22.94	NS03

Table 6.5: Comparison of the prediction statistics associated with the multi-proxy transfer function developed in this study with previous studies. See Table 6.3 for an explanation of the column headings. G01=Gehrels *et al.* (2001), K09a=Kemp *et al.* (2009a), P05=Patterson *et al.* (2005). *This r^2 value does not result from cross validation.

Site	N	Model	r^2_X	RMSEP (m)	MTR	RMSEP/ MTR (%)	Citation
UK (average of 3 sites)	99	WA-PLS	0.82	0.05	Not given	Unknown	G01
North Carolina (average of 3 sites)	46	WA-PLS	0.83	0.04	0.27	12.96	K09a
British Columbia, Canada	38	SMLR	0.96*	not given	-	-	P05
Severn Estuary	23	WA-Tol	0.86	0.87	13.58	6.41	This study (A)
Severn Estuary	71	WA-PLS	0.70	0.98	13.58	7.22	This study (B)
Severn Estuary	71	WA-PLS	0.76	0.87	13.58	6.41	This study (C)

lower foraminifera counts.

Refering back to the plots of observed versus estimated SWLI for the five best models (Figure 5.18), there is an observable effect of combining together the two proxies revealed by the patterns in the scatter plots. The diatom-based single proxy transfer function performs well in the centre of the gradient and less well at either end, while the foraminifera-based training set is missing data from the central part but performs well at the extremes, with lower errors than the diatom model. So in combining them together, the two proxies complement one another, with the accurate and precise diatom assemblages producing small prediction errors in the centre of the intertidal zone and the superior foraminifera data towards the ends of the gradient improving the accuracy and precision over the single-proxy diatom model.

At this point there are good indictions that both of the single proxy transfer functions and multi-proxy transfer functions B and C may be used to reconstruct Holocene sea-levels from the Steart core. The results of the analogue matching analysis are presented in Chapter 7 and give further indication of which of the five transfer functions is the most appropriate for reconstructing sea-level from the Steart Peninsula core.

The next chapter presents the stratigraphy, biostratigraphy and chronology of the core collected from the Steart Peninsula, the analogue matching between modern and fossil samples and a consideration of which is the most suitable transfer function model for reconstructing Holocene sea-level at the Steart Peninsula.

6.5   Chapter summary

- Diatom and foraminifera zonation in the intertidal zone at the two sites broadly reflected the findings of previous researchers. Diatoms were more diverse than foraminifera with regard to the number of species encountered, and similar environmental zones were identified by Hill *et al.* (2007), Woodroffe and Long (2010) (diatoms) and Scott and Medioli (1978) (foraminifera).

- Foraminifera abundance was generally low across both transects and further work on modern intertidal foraminifera in the region needs to take account of this. Samples were included in the analysis if at least 100 tests were identified, justified by the low species diversity and a similar approach taken by previous researchers.

- Of the three approaches to combining the proxies into multi-proxy training sets, approach B was considered to be the most robust. Approach B was therefore taken forward to the next stage of the research. Approach A excluded 48 useful diatom samples, while resulting in less significant prediction statistics than the single-proxy foraminifera transfer function alone, which uses the same 23 samples (foraminifera: r^2_{boot}=0.91, RMSEP=0.05; multi-proxy A: r^2_{boot}=0.86, RMSEP=0.08). Approach C produced more significant prediction statistics than approach B and was also taken forward to the next stage. However, it was recognised that approach C relies on low numbers of foraminifera in 41 of the 71 samples, and that those numbers would be deemed to be insufficient in a single-proxy transfer function.

- Both diatom and foraminifera species in the upper part of the intertidal zone (above SWLI 0.8-0.9) displayed narrower tolerance ranges with regard to elevation above MSL, in keeping with previous researchers' findings.

- Prediction statistics for the single- and multi-proxy transfer functions were comparable with previous multi-proxy studies. In particular the prediction statistics of the foraminifera-based transfer function were favourable when compared with other studies.

- The multi-proxy transfer functions B and C had slightly lower r^2_{boot} statistics than previous studies (Gehrels *et al.*, 2001; Kemp *et al.*, 2009a) but within the context of this study, the multi-proxy (B and C) transfer functions improved on the single proxy diatom-based transfer function in terms of the prediction statistics and on the single-proxy foraminifera-based transfer function in terms of the intertidal range accounted for.

Chapter 7

Palaeoenvironmental evidence from the Steart Peninsula

Fossil diatom and foraminifera assemblages from the Steart core are presented in this chapter, along with the sediment stratigraphy. A chronology for the sequence was compiled from calibrated radiocarbon dates and an age-depth model based on smoothing spline interpolation between those dates and results of the analogue matching exercises are then presented. The relative benefits and shortcomings of each of the four transfer function models brought foward from Chapters 5 and 6 are discussed, with multi-proxy transfer function B selected to reconstruct Holocene sea-level at the Steart Peninsula in Chapter 8.

7.1 Sediment stratigraphy and fossil microfauna

Descriptive statistics of the 11.22m long sediment core collected from the Steart Peninsula can be found in Table 7.1, including the number of diatom and foraminifera samples analysed, the number of species encountered, and the range in the percentage organic matter as given by LOI analysis.

7.1.1 Sediment stratigraphy

The sediment stratigraphy of the Steart core is presented in Figure 7.1 using the Troels-Smith sediment description system, alongside the variation in LOI. A thin basal peat occurred between 12.22 and 12.20m depth, with maximum LOI of 21%. Directly above the basal peat were grey-brown silty clays, containing plant stems and roots from 12.18-9.13m and 8.05-7.14m. Between 5.21 and 5.32 an organic unit occurred with maximum 63% organic carbon as measured by LOI, overlain by further grey clayey-silt. Between 4.49m and 4.39m the clayey-silts were intercalated by a peaty silty clay unit containing visibly abundant ostracod

Table 7.1: Basic descriptive statistics for the data collected from the Steart core.

Top depth (m beneath surface)	1.00
Top depth (m OD)	3.90
Bottom depth (m beneath surface)	12.22
Bottom depth (m (OD)	-7.32
Core length (m)	11.22
Number of diatom samples	122
- with at least 300 diatoms	95
Number of foraminifera samples	112
- with at least 100 foraminifera	33
Number of diatom species	46
Number of foraminifera species	10
Lowest sample LOI (%)	1.26
Highest sample LOI (%)	63.68

shells, with a maximum LOI of 18%. The silty clays directly above this peaty silty clay unit contained preserved plant stems and roots. A further organic unit with maximum LOI of 39% occurred between 2.87m and 2.79m, overlain to the top of the core by grey-brown silty-clays.

Outside of the four organic units the organic content remained at a consistent level of 5% to 8% LOI, with the exception of a deviation at 9.61m depth, but no organic material was identified in the stratigraphy at this depth, suggesting that a methodological error may have occurred in the process of measuring the LOI of this sample to produce this anomaly. The full Troels-Smith sediment description can be found in Table 7.2.

The stratigraphy shows many similarities to borehole 6P of Kidson and Heyworth (1976) (Figure 3.14). However, where Kidson and Heyworth (1976) recorded a peat unit at around -9m OD, with about 1m of estuarine clay between that and the Pleistocene surface below, the peat/bedrock boundary occurred at -7.32m OD in the core presented in this thesis, with no clay between the organic unit and the inpenetrable surface beneath it. The transect of Kidson and Heyworth (1976) begins to the south west of the core presented in this thesis and runs in a north easterly direction along the Steart Peninsula (Figure 3.11). The core presented in this thesis therefore sits part way along the Kidson and Heyworth (1976) transect, indicating that a basal organic unit lapping onto the bedrock or Pleistocene head occurs between boreholes 6P and 7D and was not recorded by the stratigraphic work of Kidson and Heyworth (1976). Instead Kidson and Heyworth (1976) recorded four intercalated peats and no basal peat in borehole 6P, highlighting the very local nature of thin peats in this area.

From the stratigraphy alone it is clear that organic units cannot be interpreted as genuine regional sea-level fluctuations but instead may represent variation in marine influence locally or in depositional factors. Similar patterns can be seen across the Severn Estuary Levels where lateral variation in intercalated peat units occurs on metre to kilometre scales (Allen,

2000c). Such variability in the stratigraphy of the Gwent Levels has been interpreted as a combination of vertical compaction above an uneven basement, the presence of barrier sands and tidal channel networks and post-depositional erosion (Allen, 2001). All of these factors are potentially relevant at the Steart Peninsula and in the subsequent interpretation of the results of this study.

7.1.2 Diatom biostratigraphy

In total, 122 samples from the Steart core were analysed for their diatom content and 31,280 diatoms were counted and identified in total. Forty-six species were encountered and the highest percentage abundance within the 122 samples of each of those species can be found in Table 7.3. The results of the diatom analysis are presented initially in Figures 7.2 (the upper 6m) and 7.3 (the lower 5.22m). Then, for the purposes of the transfer function reconstructions, samples with low counts (less than 300 diatoms within three microscope slides) were removed and only the species that account for at least 3% of one or more fossil samples were retained. Ninety-five samples and 27 species were retained in this reduced data set, which is presented in Figures 7.4 and 7.5.

Constrained cluster analysis on the fossil diatom dataset revealed eight distinct diatom zones. Figure 7.4 shows zones DZ4 to DZ8 in the upper 6m of the core, then zones DZ1 to DZ4 in the lower 5.22m are presented in Figure 7.5.

DZ1 was composed of the two samples in the basal peat and characterised by *Opephora schwartzii*, *Navicula phyllepta*, *Gyrosigma wansbeckii*, *N. digitoradiata*, *Cocconeis placentula* and *Sellaphora pusila*.

DZ2 occurred between 12.20m and 9.17m and was dominated almost entirely by *P. sulcata*, with low instances of *P. stelligera*, *P. westii*, *D. didyma*, *T. compressa* and *T. navicularis* forming the remainder of the assemblage.

DZ3 ranged from 9.17m to 8.21m and was characterised by decreasing abundance of *P. sulcata* and *T. navicularis* and increased importance of *P. westii*, *D. didyma* and *T. compressa* with elevation.

DZ4 was the largest zone, occurring between 8.21m and 5.25m depth. The assemblage was dominated by *P. sulcata*, *Podosira stelligera*, *P. westii*, *D. didyma*, *T. compressa* and *T. navicularis*. Other species occurred only in very low proportions.

DZ5 occurred between 5.25m and 5.01m depth and displayed a reduced dominance of marine species *P. sulcata* and *P. westii*, and increased importance of brackish and freshwater-brackish species such as *T. compressa*, *D. didyma*, *N. digitoradiata*, *T. navicularis* and *D.*

ovalis.

DZ6 occupied the section between 5.37m and 4.01m depth. As well as a large component of *T. navicularis*, *P. sulcata*, *D. didyma* and *T. compressa* occurred with 20-60% abundance in some samples.

DZ7 occurred between 4.37m and 3.01m depth and was dominated by *P. sulcata*, with lower abundances of *P. westii*, *D. didyma*, *T. compressa*, *Actinoptychus senarius* and other, less abundant species (see Figure 7.4). *T. navicularis* decreased with elevation after being an important component of DZ6.

DZ8 began at 3.01m and ended at 2.47m where diatom numbers became insignificant. The main species encountered in DZ8 were *P. sulcata*, *P. westii*, *Diploneis didyma* and *Tryblionella compressa*. *Diploneis interrupta*, *Navicula digitoradiata* and *T. navicularis* decreased with elevation throughout DZ8, with peak abundance at 2.87m.

The main components of the eight diatom zones can be found alongside a summary of the stratigraphy in Figure 7.9.
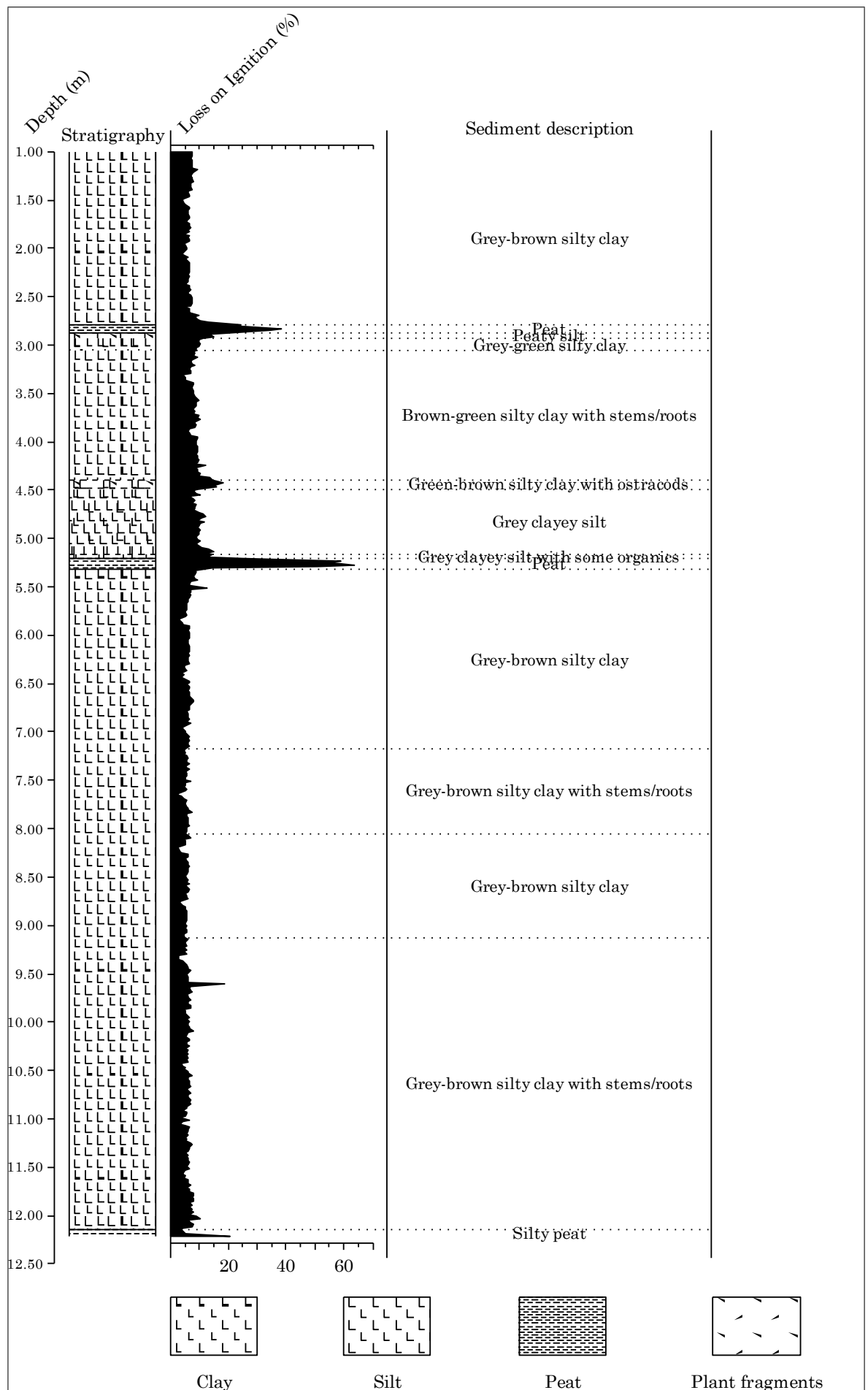
Figure 7.1: Troels-Smith sediment description of the stratigraphy of the Steart core, and the proportion of organic matter represented by percentage weight lost on ignition (LOI) at two centimetre intervals throughout the core.

Table 7.2: Steart core Troels-Smith sediment description

Description	Depth (m from surface)	Stratigraphy	Altitude (m OD)
Orange/grey/light brown silty clay; brown mottles reducing with depth	1.00-2.00	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.0; As.2; Ag.2	3.90-2.90
Orange/grey/light brown silty clay; no mottles	2.00-2.04	Nig.2; Strf.0; Elas.0; Sicc.2;Lim.0; As.2; Ag.2	2.90-2.86
Orange/brown/grey silty clay	2.04-2.54	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.1; As.2; Ag.2	2.86-2.36
Slightly darker grey silty clay	2.54-2.79	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.1; As.2; Ag.2	2.36-2.11
Peat	2.79-2.87	Nig.3; Strf.1; Elas.3; Sicc.2; Lim.1; Sh.4	2.11-2.03
Peaty silt	2.87-2.93	Nig.2; Strf.0; Elas.1; Sicc.2; Lim.1; Sh.1,Th.+; Dh.1; Ag.2	2.03-1.97
Silty clay, slightly darker grey than the layer above the peat	2.93-3.00	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.1; As.3; Ag.1	1.97-1.90
Silty clay, slightly darker grey than the layer above the peat	3.00-3.06	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.0; As.3; Ag.1	1.901.84
Grey/green silty clay	3.06-3.20	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.0; As.2; Ag.2	1.84–1.70
Brown/grey silty clay	3.20-3.27	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.1; As.2; Ag.2	1.70-1.63
Grey silty clay with plant stems/ roots	3.27-4.06	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.2; As.2; Ag.2	1.63-0.84
Grey silty clay with plant stems/ roots	4.06-4.18	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.0; As.2; Ag.2	0.84-0.72
Light brown silty clay with plant stems/ roots	4.18-4.30	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.0; Th.+; As.2; Ag.2	0.72-0.60
Green silty clay with plant stems/ roots	4.30-4.39	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.0; Th.+; As.2; Ag.2	0.60-0.51
Green and brown peaty silty clay with ostracods	4.39-4.49	Nig.3; Strf.1; Elas.2; Sicc.2; Lim.1; Th+; Ld.1; As.1; Ag.1	0.51-0.41
Grey clayey silt	4.49-5.06	Nig.2; Strf.0; Elas.1; Sicc.2; Lim.1; Th.+; As.1; Ag.3	0.41- -0.16
Grey clayey silt	5.06-5.16	Nig.2; Strf.0; Elas.1; Sicc.2; Lim.0; Th.+; As.1; Ag.3	-0.16- -0.26
Grey clayey silt with some organic matter	5.16-5.21	Nig.2; Strf.0; Elas.2; Sicc.2; Lim.0; Sh.1; Th.+; As.1; Ag.2	-0.26- -0.31

Description	Depth (m from surface)	Stratigraphy	Altitude (m OD)
Peat	5.21-5.32	Nig.3; Strf.1; Elas.3; Sicc.2; Lim.0; Sh.4;	-0.31- -0.42
Grey silty clay with rootlets	5.32-6.05	Nig.2; Strf.0; Elas.2; Sicc.2; Lim.1; As.2; Ag.2	-0.42- -1.15
Grey silty clay	6.05-6.10	Nig.2; Strf.0; Elas.1; Sicc.2; Lim.0; As.2; Ag.2	-1.15- -1.20
Grey silty clay	6.10-7.14	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.0; As.2; Ag.2	-1.20- -2.24
Grey silty clay	7.14-8.05	Nig.2; Strf.0; Elas.0; Sicc.2; Th.+; As.2; Ag.2	-2.24- -3.15
Grey/brown silty clay	8.05-9.13	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.0; As.2; Ag.2	-3.15- -4.23
Grey/brown silty clay with plant stems/roots	9.13-12.18	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.0; Th.+; As.2; Ag.2	-4.23- -7.28
Grey silty clay	12.18-12.20	Nig.2; Strf.0; Elas.0; Sicc.2; Lim.0; As.2; Ag.2	-7.28- -7.30
Peat	12.20-12.22	Nig.4; Strf.0; Elas.0; Sicc.2; Lim.1; Sh.4	-7.30- -7.32

Table 7.3: The maximum percentage abundance (Max. %) of each diatom species encountered in the Steart core samples.

Species	Max. %	Species	Max. %
Diploneis interrupta	75.78	*Nitzschia amphibia*	2.61
Paralia sulcata	75.00	*Rhopalodia gibberula*	2.00
Pseudopodosira westii	68.40	*Nitzschia bilobata*	1.00
Diploneis didyma	59.29	*Eunotia* spp.	1.00
Tryblionella navicularis	56.59	*Diploneis bombus*	0.67
Caloneis westii	32.33	*Rhopalodia gibba*	0.67
Tryblionella compressa	29.00	*Sellaphora pupula*	0.66
Navicula digitoradiata	28.67	*Petroneis latissima*	0.60
Podosira stelligera	27.00	*Diploneis littoralis*	0.33
Diploneis ovalis	26.67	*Hantzschia virgata*	0.33
Navicula phyllepta	24.67	*Placoneis elginensis*	0.33
Cocconeis placentula	15.28	*Psammodictyon panduriforme*	0.33
Petroneis marina	13.92	*Nitzschia tryblionella*	0.33
Caloneis ventricosa	13.65	*Martyana martyi*	0.33
Gyrosigma wansbeckii	11.33	*Surirella comis*	0.33
Cosmioneis pusilla	8.97	*Achnanthes longipes*	0.33
Rhopalodia musculus	8.97	*Surirella brebissonii*	0.33
Opephora schwartzii	8.64	*Navicula peregrina*	0.33
Nitzschia sigma	7.67	*Nitzschia socialis*	0.32
Actinoptychus senarius	7.33		
Surirella striatula	7.10		
Campylodiscus echeneis	6.77		
Nitzschia sp.	3.99		
Thalassiosira eccentrica	3.97		
Rhaphoneis amphiceros	3.33		
Triceratium favus	3.33		
Anomoeoneis sphaerophora	3.17		

7.1.3 Foraminifera biostratigraphy

Foraminifera analysis was carried out on 112 samples from the Steart core, revealing 10 distinct species (Figures 7.6 and 7.7 and Table 7.4). In total, 9,815 foraminifera were counted and identified. The number of tests identified in each 2cm^3 sample fluctuated between zero and over 400. Excluding samples that yielded fewer than 100 tests, and species with maximum percentages not reaching 3% of one or more of those samples, the final fossil foraminifera data set contains 33 samples and 8 species (Figure 7.8).

Cluster analysis revealed five zones in the fossil foraminifera data. FZ1 (9.17m to 8.45m) was composed of *J. macrescens*, *T. inflata* and *A. beccarii*. Only samples with very low numbers of tests were encountered deeper than 9.17m, and thus have been excluded from any further analysis.

FZ2 (8.45m to 5.09m) was dominated by *J. macrescens* but also contains instances of high

Figure 7.2: Diatom biostratigraphy of the upper 6m of the Steart core. Species are grouped by salinity class. M = marine, MB = marine-brackish, BM = brackish-marine, B = brackish, BF = brackish-freshwater, FB = freshwater-brackish. For the stratigraphic key see Figure 7.1.
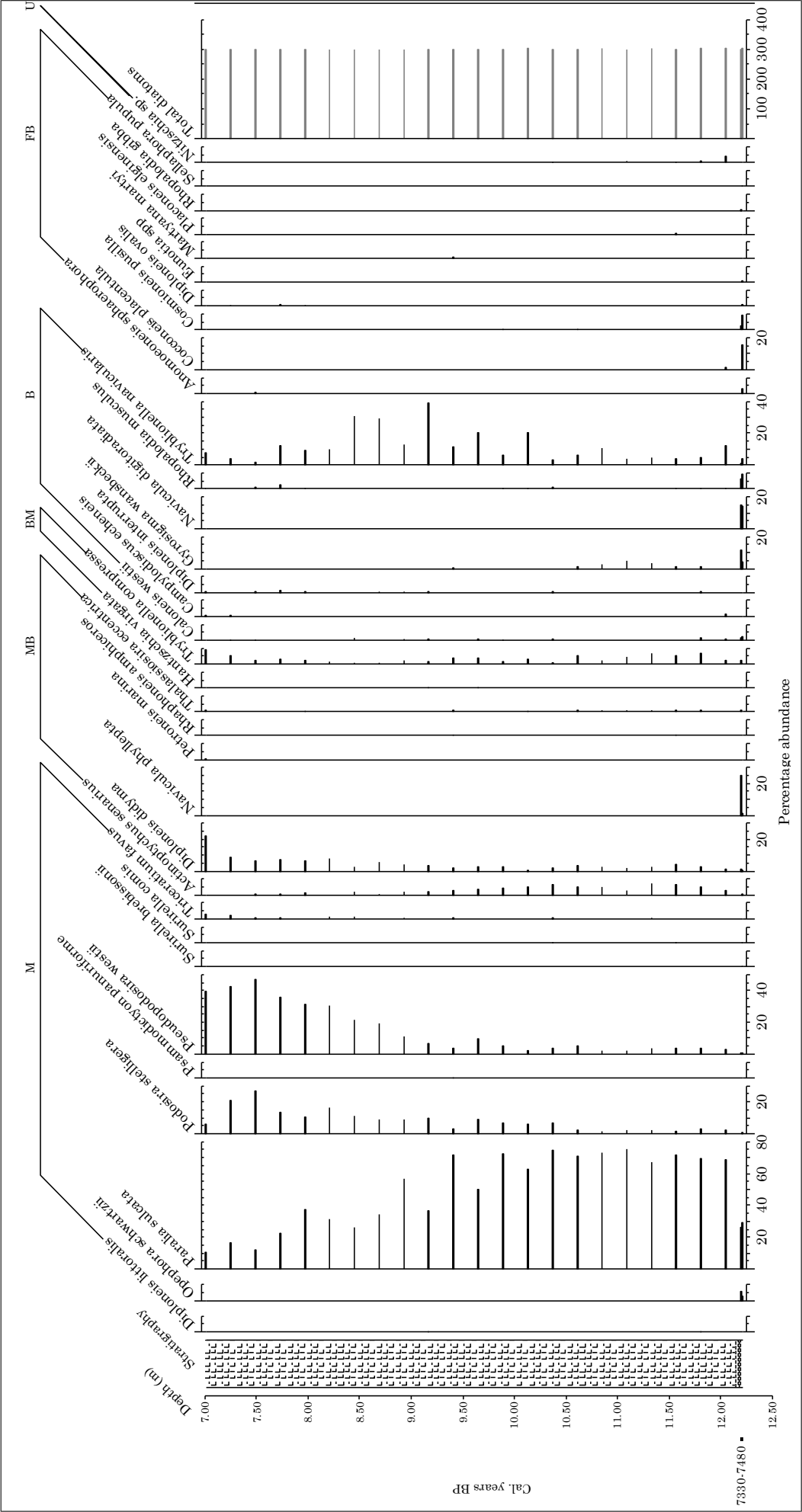
Figure 7.3: Diatom biostratigraphy of the lower 5m of the Steart core. Species are grouped by salinity class. M = marine, MB = marine-brackish, BM = brackish-marine, B = brackish, BF = brackish-freshwater, FB = freshwater-brackish. For the stratigraphic key see Figure 7.1.
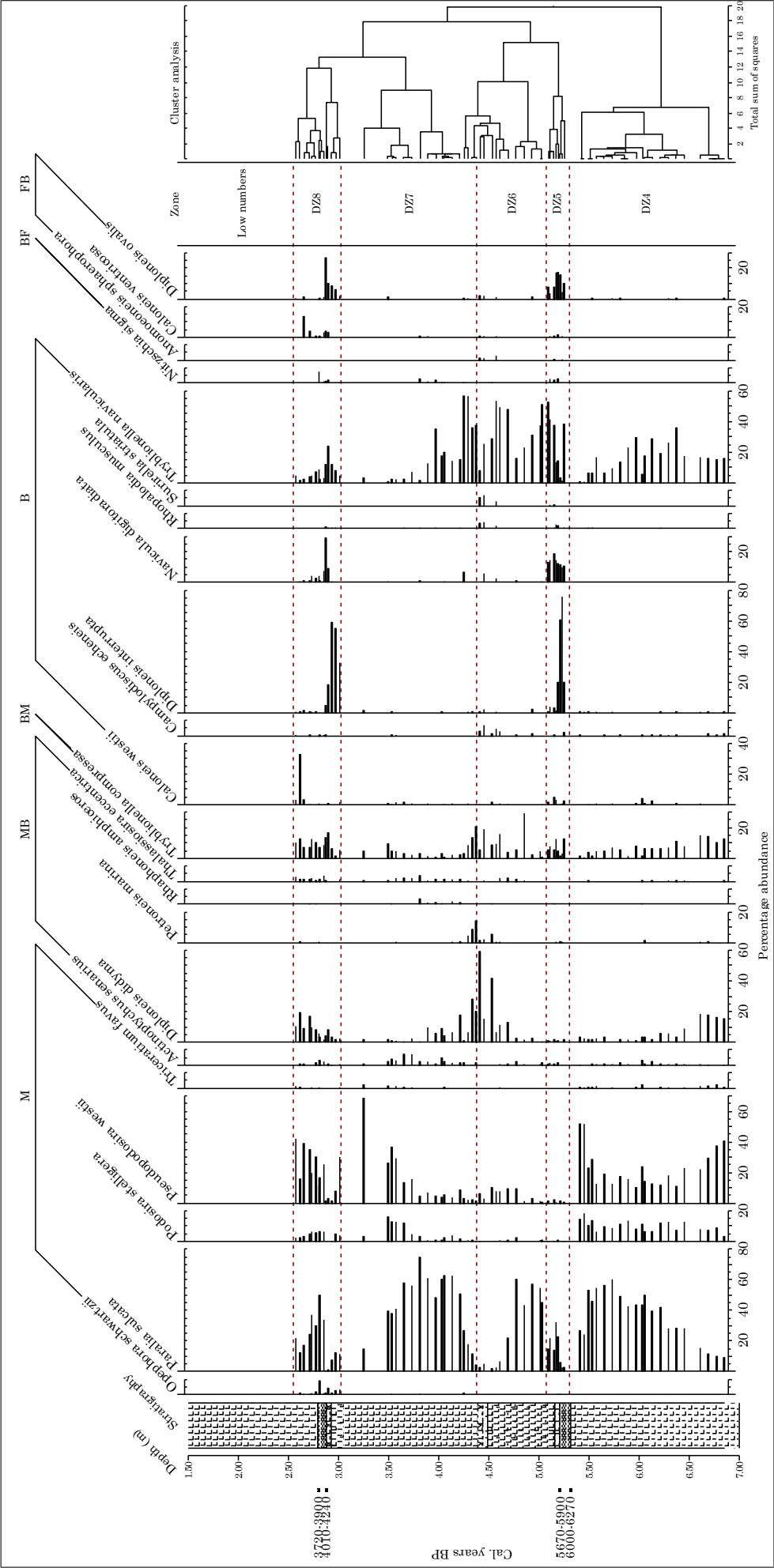
Figure 7.4: Diatom biostratigraphy of the upper 6m of the Steart core, excluding samples yielding fewer than 300 diatoms and excluding species occurring with less than 3% abundance in any of the core samples with at least 300 diatoms. Cluster analysis reveals diatom zones one to five. DZ = diatom zone. Species are grouped by salinity class. M = marine, MB = marine-brackish, BM = brackish-marine, B = brackish, BF = brackish-freshwater, FB = freshwater-brackish. For the stratigraphic key see Figure 7.1.
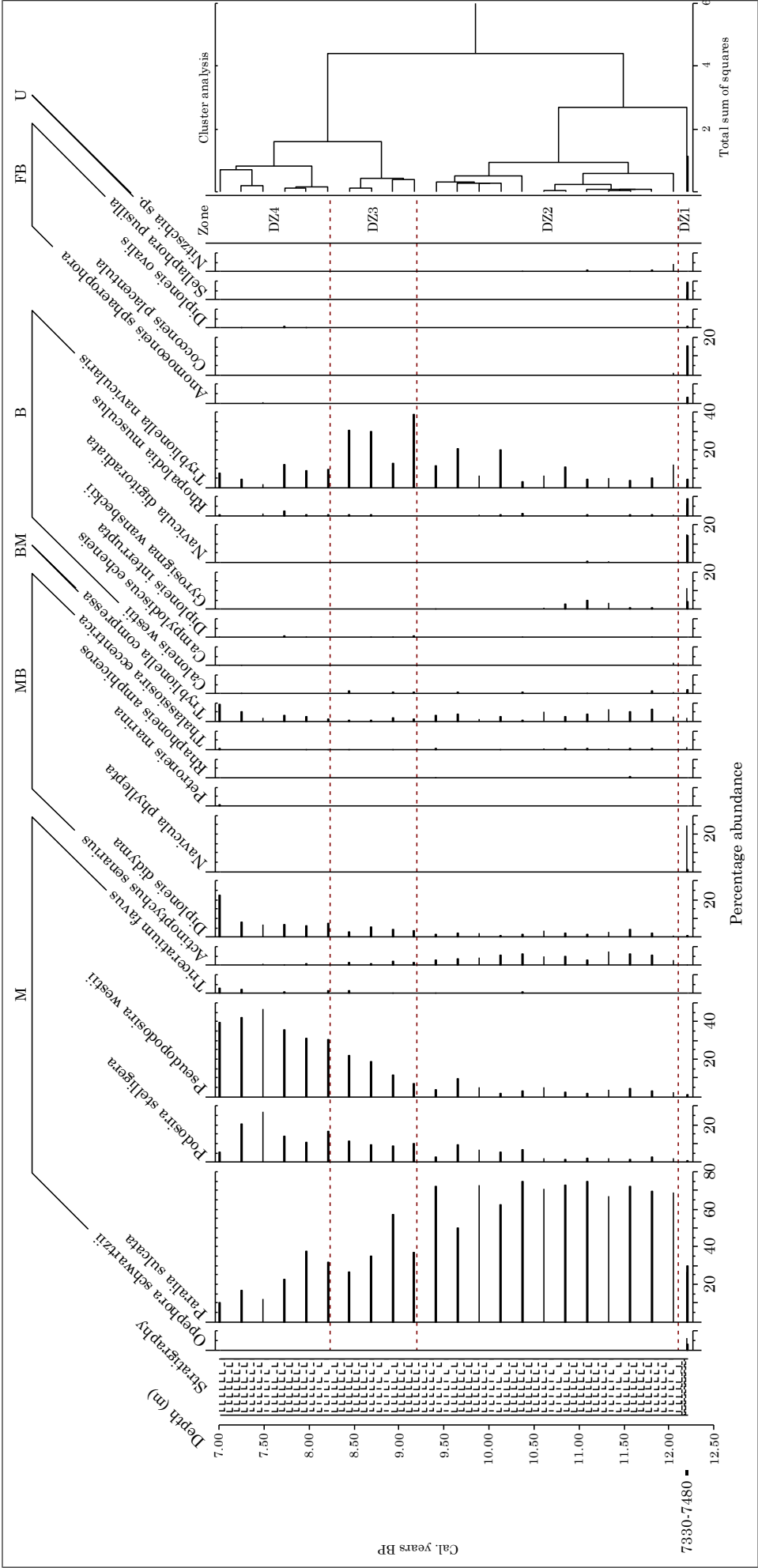
Figure 7.5: Diatom biostratigraphy of the lower 5.22m of the Steart core, excluding samples yielding fewer than 300 diatoms and excluding species occurring with less than 3% abundance in any of the core samples with at least 300 diatoms. Cluster analysis reveals diatom zones five to eight. DZ = diatom zone. Species are grouped by salinity class. M = marine, MB = marine-brackish, B = brackish, BF = brackish-freshwater, FB = freshwater-brackish. For the stratigraphic key see Figure 7.1.
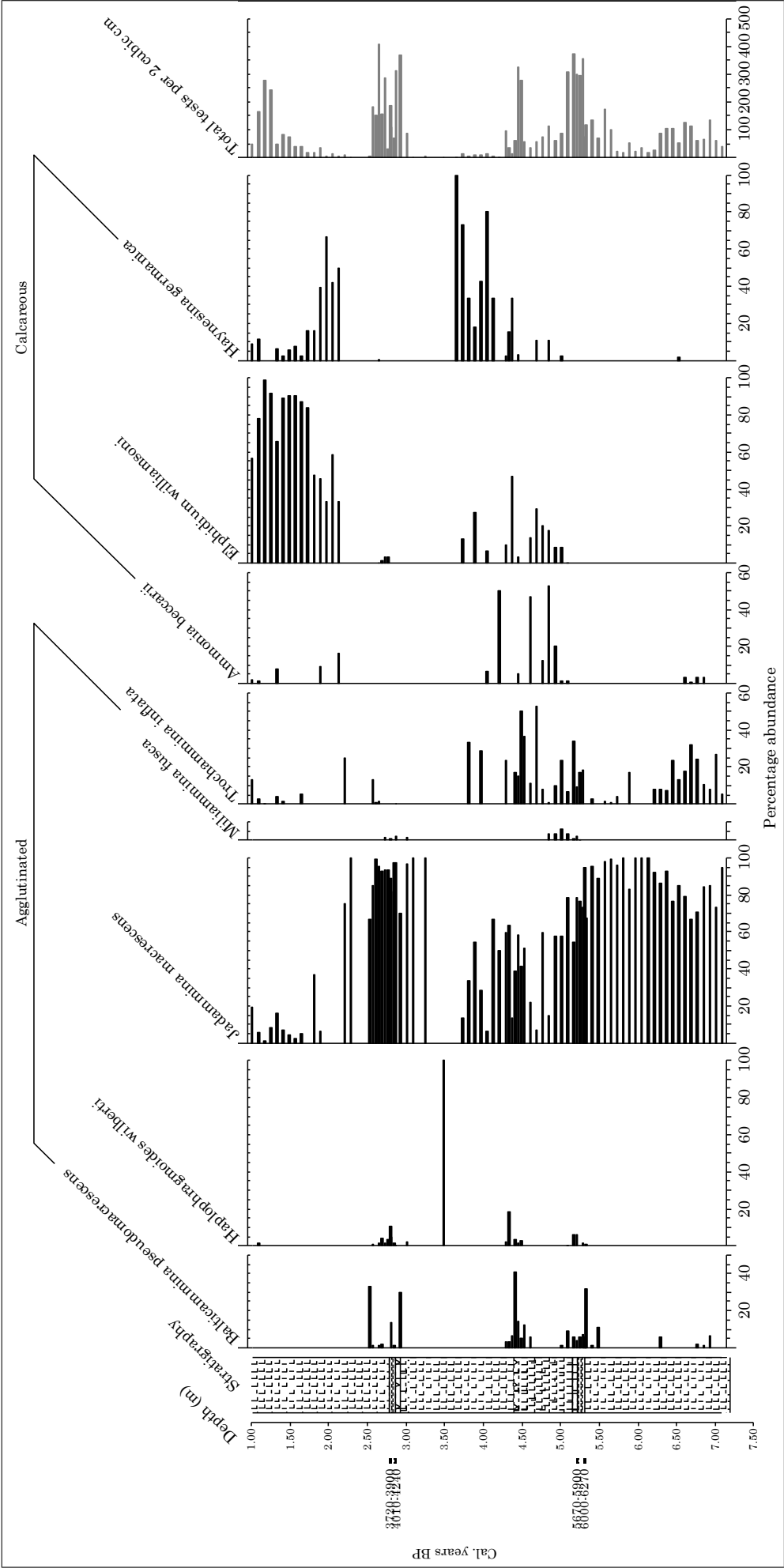
Figure 7.6: Foraminifera biostratigraphy of the upper 6m of the Steart core. For the stratigraphic key see Figure 7.1.
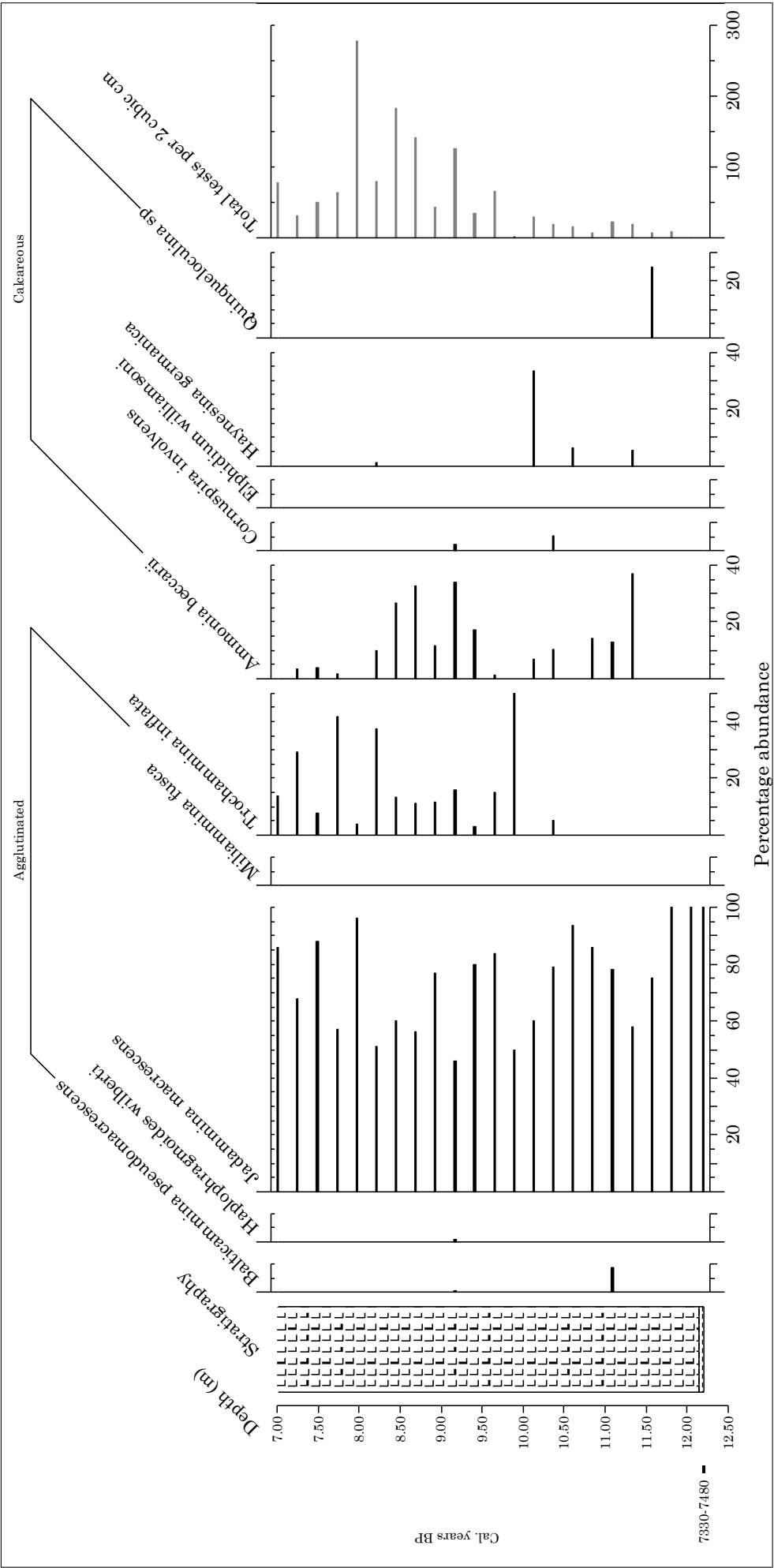
Figure 7.7: Foraminifera biostratigraphy of the lower 5.22m of the Steart core.For the stratigraphic key see Figure 7.1.
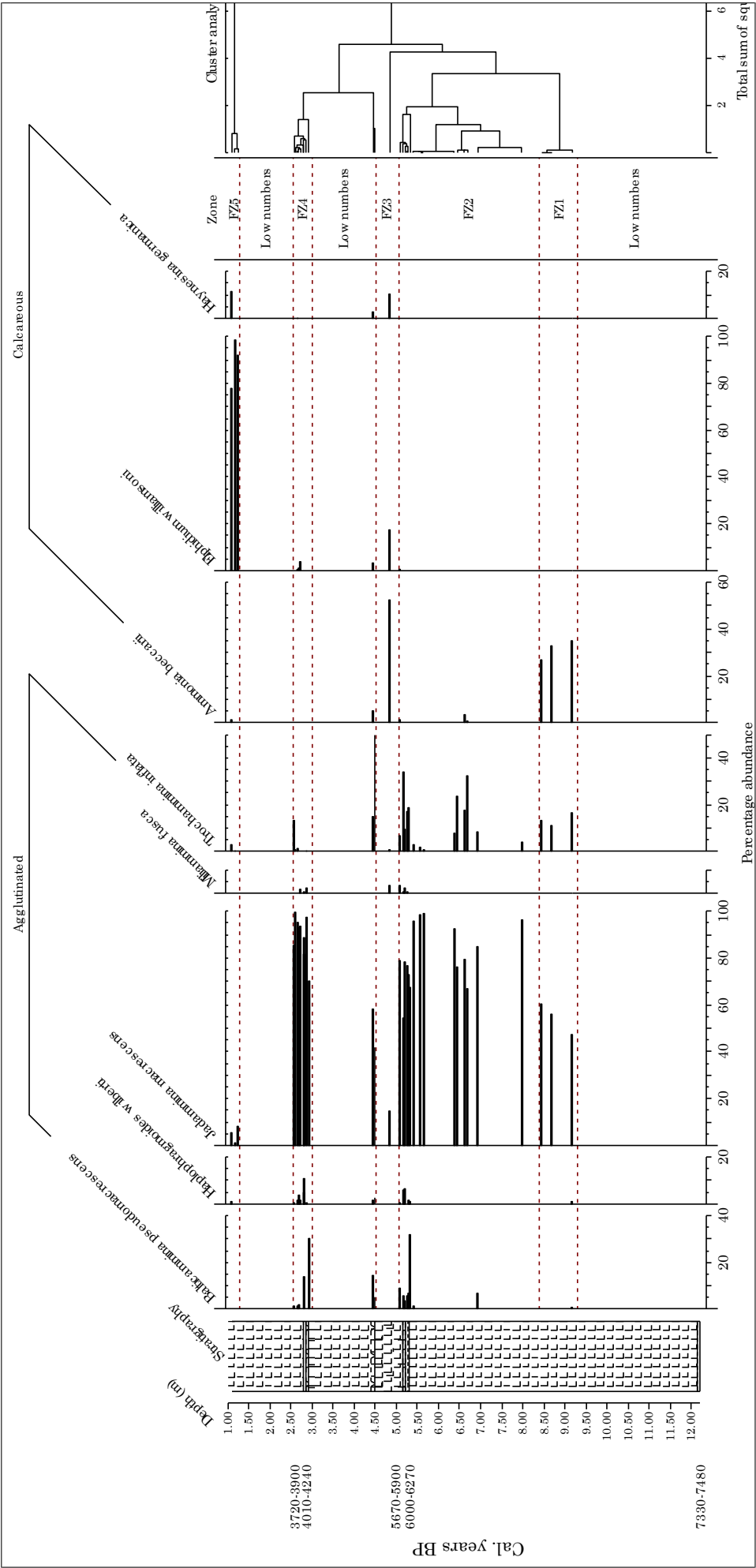
Figure 7.8: Foraminifera biostratigraphy of the whole Steart core, excluding samples yielding fewer than 100 tests and excluding species occurring with less than 3% abundance in any of those samples. Cluster analysis reveals foraminifera zones one to five (FZ1-5). For the stratigraphic key see Figure 7.1.

Table 7.4: The maximum percentage abundance (Max. %), in the Steart core samples that yielded a total count of at least 100 tests, of each species of foraminifera identified.

Species	Max. %
Jadammina macrescens	99.34
Elphidium williamsoni	98.56
Ammonia beccarii	52.63
Trochammina inflata	50.00
Balticammina pseudomacrescens	31.93
Haynesina germanica	11.38
Haplophragmoides wilberti	10.75
Miliammina fusca	3.51
Cornuspira involvens	2.38

proportions of *T. inflata*, and very few *Ammonia beccarii*. *B. pseudomacrescens*, *Miliammina fusca* and *H. wilberti* were also present in some samples.

FZ3 (5.09m to 4.49m) was composed mainly of *Ammonia beccarii, E. williamsoni* and *H. germanica*.

FZ4 (4.49m to 2.57m) was dominated mainly by *J. macrescens*, but with high proportions of *Balticammina pseudomacrescens* in some samples. *Trochammina inflata* and *Haplophragmoides wilberti* were also present. A section with low numbers of tests occurred within FZ4, between 4.45m and 2.93m.

FZ5 was composed of three samples between 1.25m and 1.09m deep and dominated by *Elphidium williamsoni*, with *Haynesina germanica* and *Jadammina macrescens* also present. The region from 2.57m to 1.25m deep was devoid of significant numbers of tests.

7.1.4   Steart core stratigraphy: summary

Figure 7.9 summarises the sediment stratigraphy and microfaunal zones revealed in the Steart core, showing equivalent depths and altitudes of the zones with respect to OD. An 11.22m sequence of silty clays was interbedded with three organic units and underlain by a thin basal organic unit. Cluster analysis revealed eight diatom zones and five foraminifera zones, based on the relative abundance of species encountered throughout the core.

7.2   Core chronology

Five samples were selected for radiocarbon dating, representing the transitions between organic and minerogenic deposition, indicating potential times of change in the environment and the rate or direction of sea-level change. Samples were taken from the upper and lower boundaries of the upper and lower of the three interbedded organic units, and from the upper boundary of the basal unit.
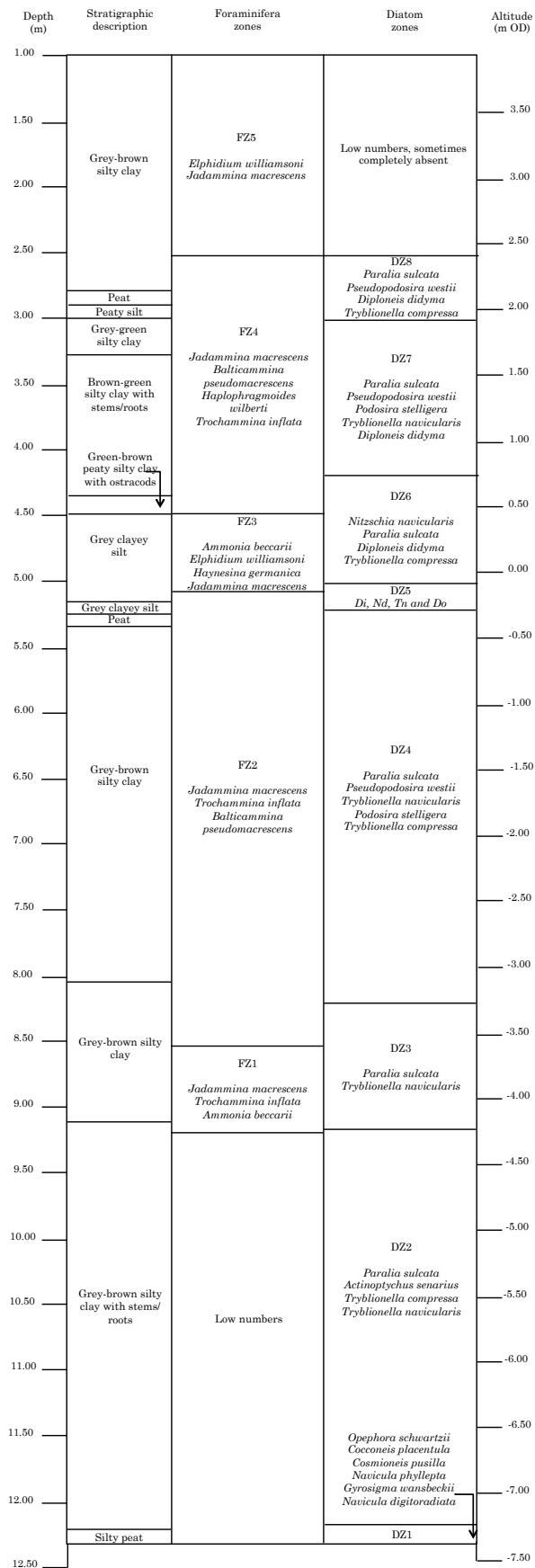
Figure 7.9: Schematic summary of the stratigraphy, foraminifera and diatom zones idenitified in analysis of the Steart core, and the typical species assemblages found in each zone. In diatom zone DZ4 *Di = Diploneis interrupta*, *Nd = Navicula digitoradiata*, *Nn = Tryblionella navicularis* and *Do = Diploneis ovalis*.

Results of the AMS radiocarbon analysis by Beta Analytic (Beta Analytic, 2013) are presented in Table 7.5. Conventional radiocarbon ages were calibrated using the INTCAL09 database (Heaton *et al.*, 2009; Reimer *et al.*, 2009; Stuiver and Braziunas, 1993; Oeschger *et al.*, 1975).

Figure 7.10 shows an estimated chronology for the Steart sequence based on smoothing spline interpolation between the five radiocarbon dated points and the surface.

The estimated chronology suggests that sediment deposition was rapid from ~7,500 cal. years BP, declining slightly around 7,000 cal. years BP and then slowing continuously until the present day. The nature of the sediment stratigraphy means an absence of organic sediments that could provide radiocarbon dates after around 3,800 cal. years BP. The model can only suggest a linear pattern of deposition between the most recent radiocarbon date and the present day surface, which may or may not be an accurate representation of the pattern of deposition that took place over the past 3,800 years.

7.3 Modern analogues

Results of the two analogue measures proposed by Birks (1998) can be found in Table 7.6 and Figures 7.11 and 7.12.

The analysis indicated that every fossil diatom sample contained some data from species that are not represented at all in the modern training set, and that in general, the fossil foraminifera species are better represented in the modern training set than the fossil diatom data.

In contrast to the two measures of comparison between modern and fossil species above, analogue matching using the Bray-Curtis dissimilarity indicated that the fossil foraminifera data set is not so well represented in the modern training set. A summary of the number of samples with good, fair and poor modern analogues is given in Table 7.7. All 33 samples in the fossil foraminifera data set lacked good or fair modern analogues in the corresponding training set, compared with 70 of the 95 fossil diatom samples.

Multi-proxy fossil data sets B and C each contained several samples with good and fair modern analogues. The number of samples with poor modern analogues was similar in each, but data set B contained more samples with good modern analogues than data set C; 23 samples compared with just four.

Plots of the minimum dissimilarity value for each sample in the four fossil data sets (*i.e.* the coefficient of the difference between each fossil sample in the core and its closest analogue

Table 7.5: Results of the AMS radiocarbon dating as returned by Beta Analytic.

Lab code	Depth	Altitude	Description	Pre-treatment	^{14}C age	Intercept	Calibrated age cal. years BP	
	m	m OD			cal. years BP	cal. years BP	2σ	1σ
Beta - 321509	2.80	2.10	Organic sediment	Acid washes	3,520–3,580	3,840	3,880–3,830	3,900–3,820 3,790–3,760 3,750–3,720
Beta - 321510	2.87	2.03	Organic sediment	Acid washes	3,730–3,800	4,150 4,110 4,100	4,220–4,210 4,160–4,140 4,130–4,090	4,240–4,080 4,030–4,010
Beta - 321511	5.21	-0.31	Plant material	Acid/alkali/acid	5,010–5,070	5,840 5,830 5,750	5,890–5,820 5,820–5,810 5,760–5,740	5,900–5,710 5,670–5,670
Beta - 321512	5.31	-0.41	Plant material	Acid/alkali/acid	5,320–5,380	6,180	6,200–6,180 6,150–6,120 6,080–6,070 6,040–6,030	6,270–6,240 6,210–6,170 6,160–6,100 6,080–6,000
Beta - 321513	12.20	-7.30	Plant material	Acid/alkali/acid	6,470–6,550	7,430	7,440–7,420	7,480–7,410 7,390–7,370 7,360–7,330

Figure 7.10: Steart core chronology as given by age-depth model based on five radiocarbon dates and smoothing spline interpolation between them.

Table 7.6: Descriptive statistics based on the calculation of the percentage of each fossil sample comprised of species that are absent from or poorly represented in the modern training sets. N is the number of samples in the fossil dataset. Percentages are to the nearest whole number.

	N	% of each sample composed of species absent in the training set			% of each sample composed of species poorly represented in the training set		
		Maximum	Minimum	Mean	Maximum	Minimum	Mean
Diatoms	95	76	0	11	84	4	28
Foraminifera	33	32	0	4	99	0	14
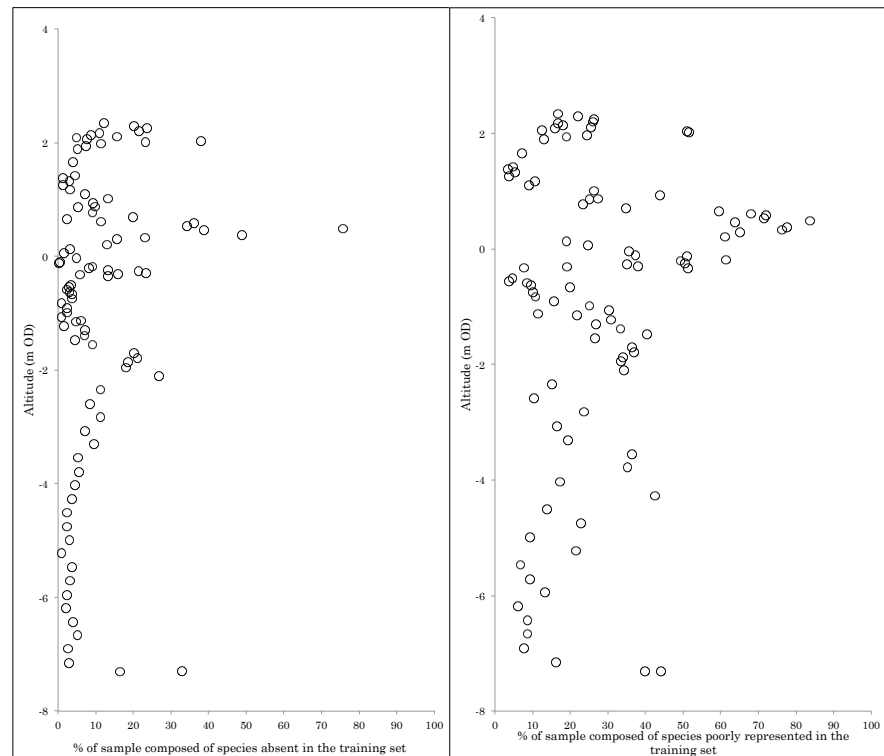
Figure 7.11: Percentage of each fossil diatom sample that is (a) absent from and (b) poorly represented in the training set. Poorly represented is defined as a maximum abundance of 10% in any one modern sample.
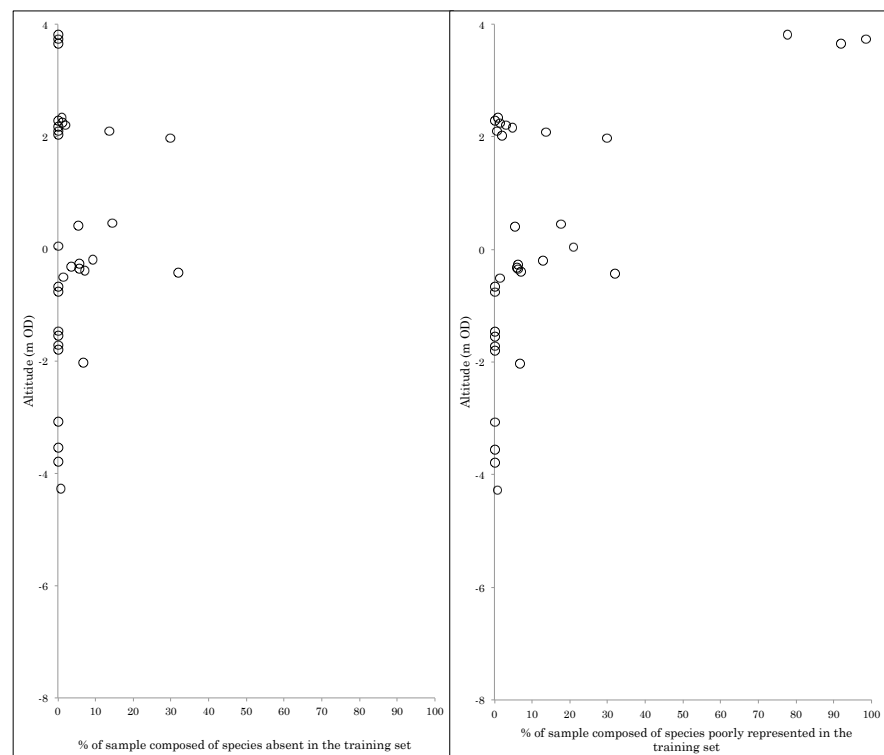
Figure 7.12: Percentage of each fossil foraminifera sample that is (a) absent from and (b) poorly represented in the training set. Poorly represented is defined as a maximum abundance of 10% in any one modern sample.

Table 7.7: Number of samples in the fossil data sets that have good, fair and poor analogues in the modern training data, as estimated using the analogue matching method. N is the number of samples in the fossil dataset.

Training set	N	Analogues		
		Good	Fair	Poor
Single-proxy				
Diatoms	95	10	15	70
Foraminifera	33	0	0	33
Multi-proxy				
B	102	23	21	58
C	102	4	36	62

in the corresponding modern training set) are presented in Figures 7.13 to 7.16. Sample depths have now been converted to altitudes with respect to OD.

Gaps between 3.65m and 2.33m OD indicate that neither proxy occurred in significant abundance in this vertical zone. Fossil samples between 2m OD and OD and the lower 4m of the sequence tended to have better modern analogues than those in the central 4m. Across all four data sets the dissimilarities ranged from 0.169 to 0.932.
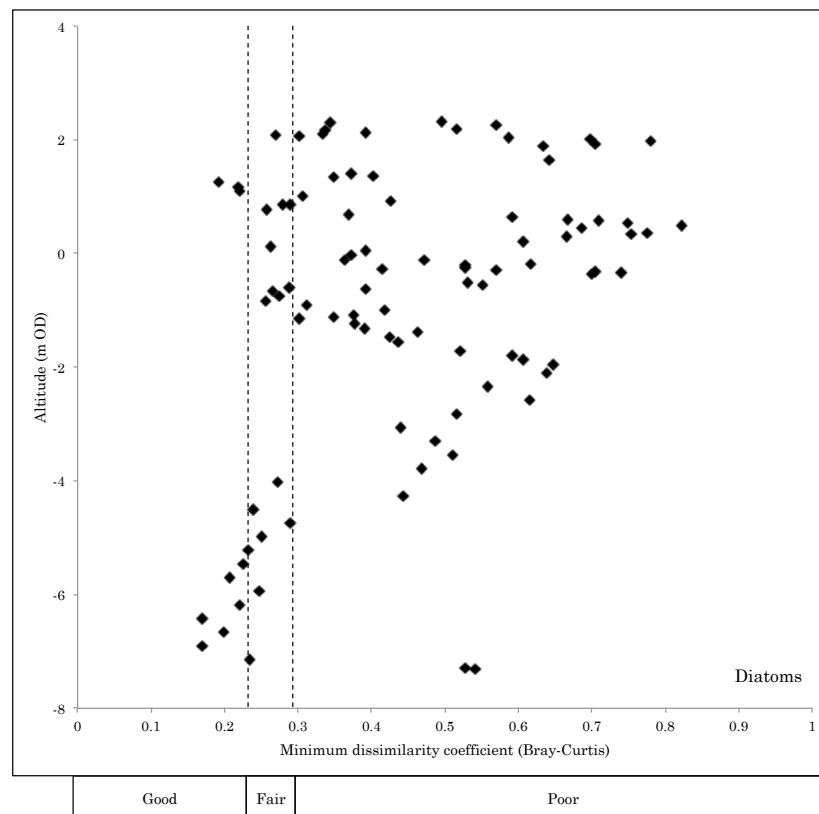
Figure 7.13: Dissimilarity measures for fossil diatom samples in the Steart core and estimates of the strength of analogy with samples in the modern training data.
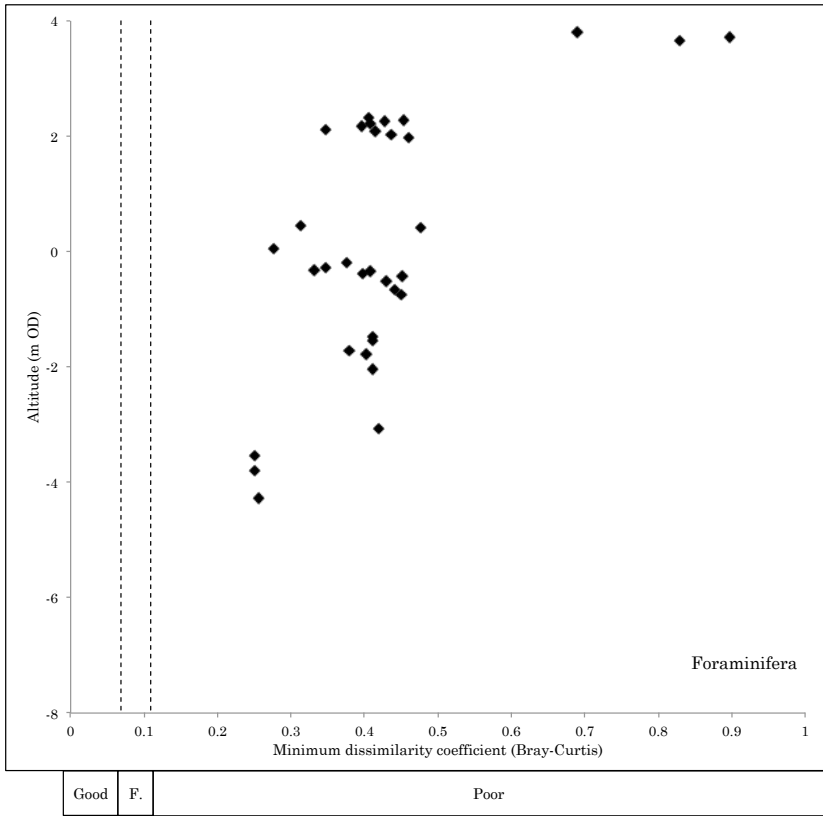
Figure 7.14: Dissimilarity measures for fossil foraminifera samples in the Steart core and estimates of the strength of analogy with samples in the modern training data.
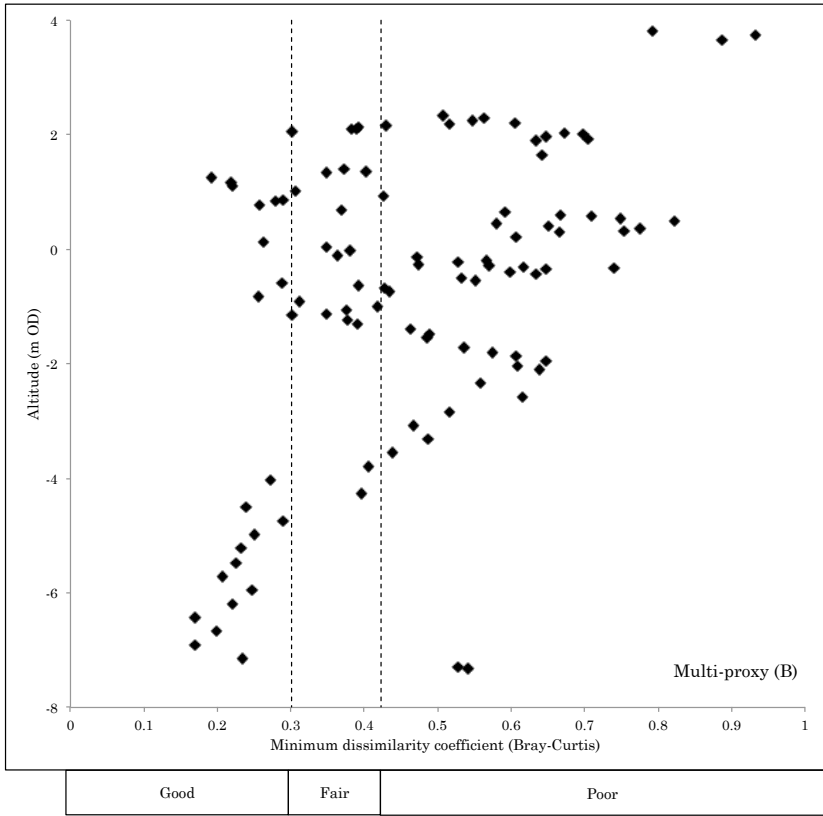
Figure 7.15: Dissimilarity measures for fossil multi-proxy (B) samples in the Steart core and estimates of the strength of analogy with samples in the modern training data.
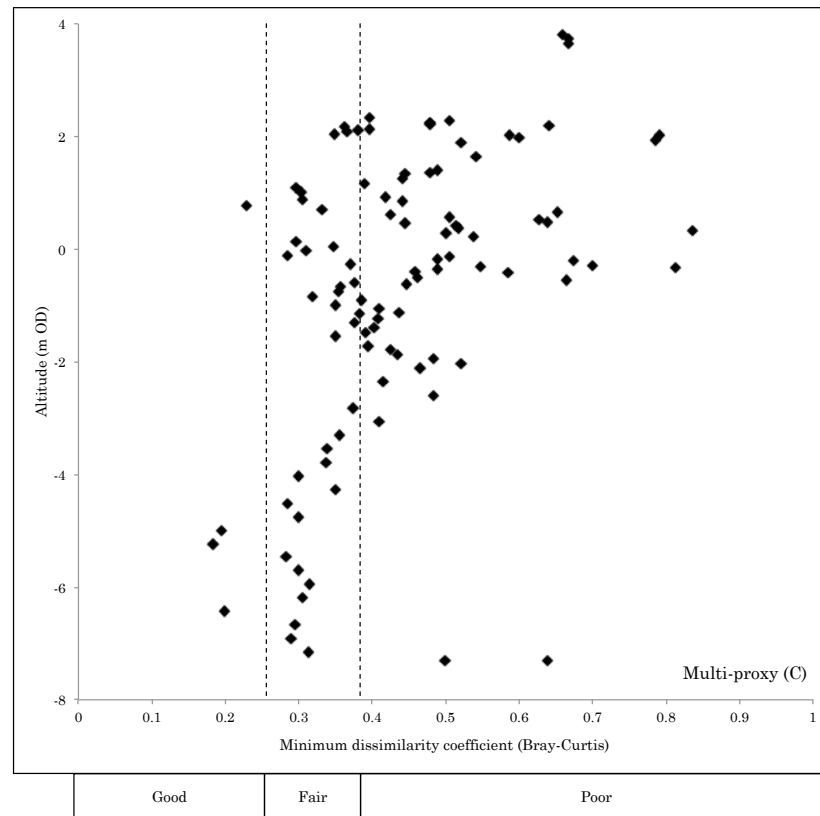
Figure 7.16: Dissimilarity measures for fossil multi-proxy (C) samples in the Steart core and estimates of the strength of analogy with samples in the modern training data.

7.4 Selecting the most appropriate transfer function

The following discussion considers the suitability of each of the four single- and multi-proxy transfer functions for reconstructing Holocene sea-level at the Steart Peninsula from the data extracted from the sediment core.

7.4.1 Single versus multi-proxy transfer functions

The relative benefits of using two proxies to create alternative sea-level transfer functions compared with the diatom- and foraminifera-based single proxy versions were discussed in Chapter 6, in terms of the prediction statistics and the strength of using different proxies when one microorganism group may be low in abundance in a particular part of the modern environmental gradient. Some of these points also apply to the application of the multi- versus single-proxy transfer functions to fossil micropalaeontological data.

Similar to the modern intertidal transects that had gaps in the foraminifera data when abundance was low or zero, the core contained certain sections in which one of the two proxies was absent or too low in abundance to use in a single proxy transfer function. The benefit of the multi-proxy approach in this specific case then, is that when data on one proxy are insufficient, there is a possibility that the other can provide data with which to estimate

former sea-levels.

There were large sections of the sedimentary sequence that did not yield sufficient foraminifera, and most of these were supplemented in multi-proxy transfer functions B and C by diatom data. The cases where diatom numbers were low were fewer, and foraminifera data were available in some of these cases. For example, the low abundance of diatoms between 1.09m and 1.25m depth was compensated for by the significant occurrence of foraminifera, while the converse was the case between depths of 9.53m and 12.33m. A gap in both proxies occurred between 2.33m and 3.65m OD.

It is difficult to make direct comparisons of the apparent low and zero abundances of the two proxies due to ecological and methodological differences. $2cm^3$ is generally assumed to be enough sediment to make counts of 200 foraminifera or more (Gehrels, 2002). In this study, this was often not the case, and it was not possible to assign more material to the foraminifera analysis at the risk of not having sufficient volume remaining for the other analyses.

In the case of the diatoms, $1cm^3$ was prepared per sample, as per Palmer and Abbott (1986), which in many cases would have been enough to prepare far more slides per sample than required. The majority of the samples yielded counts of 300 diatoms within one slide (84 of the 117 samples analysed), while 16 of them required two or three full slides to reach that number. A rule was imposed whereby if 100 diatoms were not found within two slides, the sample was abandoned. This was considered to be a good compromise between time spent on poor diatom samples and the benefit gained from doing so, and 28 samples were not completed as a result.

While, theoretically, full diatom counts *may* have been possible from these poor samples, given more time for analysis, no further analysis could have been carried out on the small foraminifera samples due to restrictions on the amount of core sediment available. It was assumed that if no or very few foraminifera were found in $2cm^3$ of sediment, analysing another $2cm^3$ would probably not have provided a large enough assemblage. With the diatoms it was a case of being strategic about the amount of time spent analysing particular samples.

Figure 7.17 shows species numbers plotted against foraminifera counts for a selection of the core samples (every 4th sample used in the reconstruction as a representative sample). One hundred foraminifera is a low minimum count and in some cases, such as 0.19m OD and -0.51m OD, the total number of individuals counted may not have been enough to represent the true population. Low foraminifera abundance has been a major limitation in this study, indicating that a multi-proxy approach may be beneficial, because of an overall increase in the amount of fossil data available.

While there are several examples in the literature of transfer functions based on training set samples with foraminifera counts lower than 100 (see Table 6.2, Chapter 6), there are no examples of the application of a sea-level transfer function to core samples with counts of less than 100.

The manner in which the two proxies were combined in the modern setting was discussed in Chapter 6. Method A was discounted at that point and was not used to combine the fossil data or considered for the sea-level reconstruction, for the reasons discussed previously. Method B was concluded to be the more robust, because if the two proxy groups are still to be treated as separate assemblages, as in the analogue matching discussion above, then "tacking on" extra species from a second proxy in a sample where significant numbers of that second proxy are not identified is not in keeping with the ecological and statistical importance of ensuring that samples are large enough (Patterson and Fishbein, 1989; Fatela and Taborda, 2002).

7.4.2 Combining proxies

For the ordination and transfer function development analyses it was possible to use raw species counts and simply use raw count data for both sets of proxies. However, the analogue matching method specifically required data to be in proportions rather than raw counts (Simpson, 2007). This posed a particular problem for combining two different microorganisms groups together into one data matrix.

There is only one example in the literature of an attempt to use the modern analogue technique to match fossil and modern assemblages in a multi-proxy study. Kemp *et al.* (2009a) simply combined their diatom and foraminifera data sets by taking percentages of the total counts of both proxies together in each sample. Simpson (2012) describes this approach as a naïve way to merge two different sets of proxy data together. An artificial link is created between the two microorganism groups where one may not exist in reality. In any data set where values are converted to percentages or proportions a change in the value of one data point affects the values of the others, causing an effect called matrix closure (Mekik and Loubere, 1999) where artificial correlation is created between species (Leorri *et al.*, 2010). This same effect will occur if foraminifera and diatoms are treated together as one assemblage, meaning that the proportions of a species in one microorganism group will depend on the relative size of each group. Here, all diatom samples have around 300 individuals whereas the foraminifera sample sizes vary, which would introduce some false variability if percentages had been taken of each whole assemblage. This issue prompted Mitchell *et al.* (2013) to give
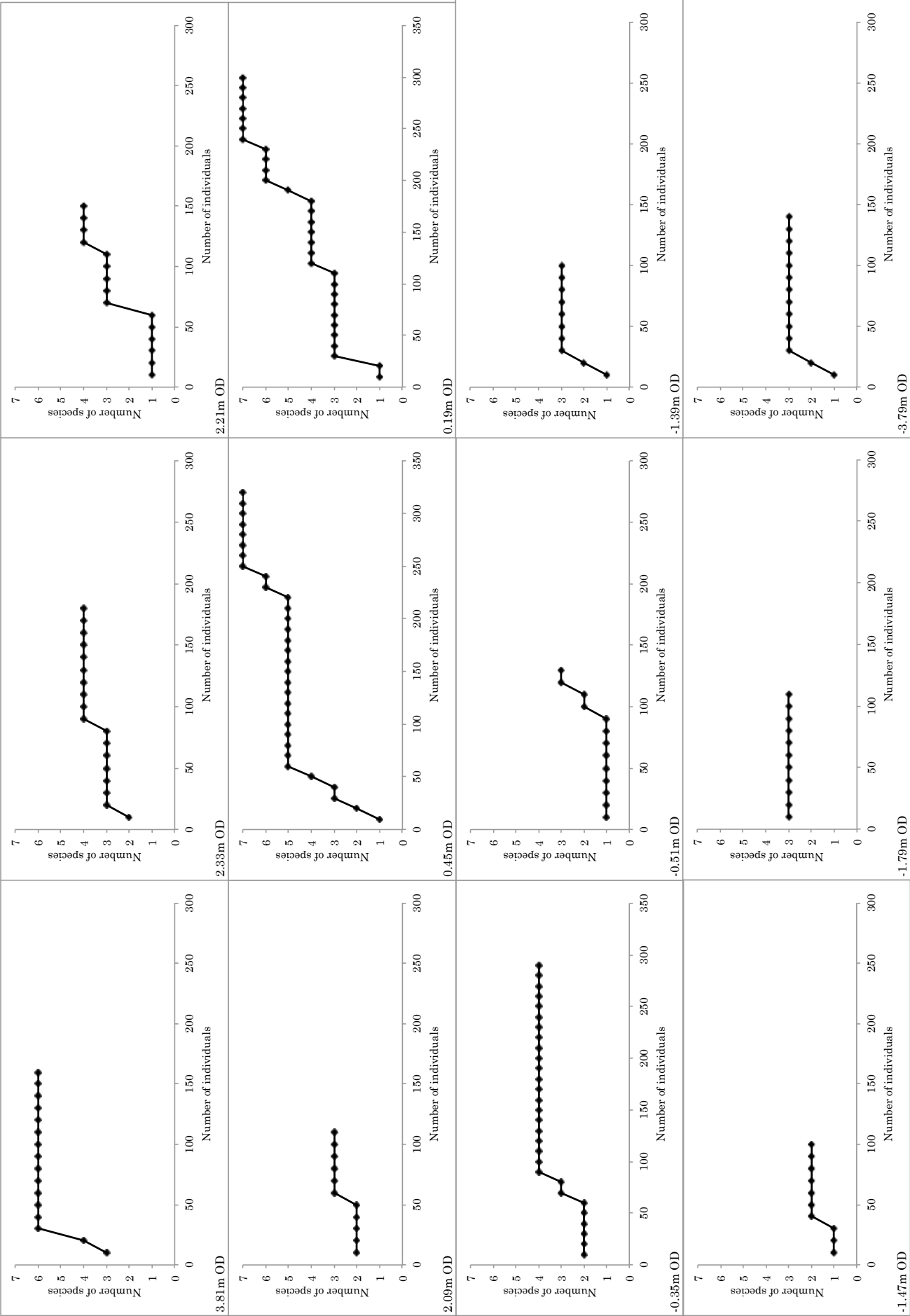
Figure 7.17: Cumulative species versus individuals plots for core foraminifera samples representing the whole sedimentary sequence.

equal weight to each of their proxies (testate amoebae, bryophytes and vascular plants) by taking percentages within each group and then adding them together so that each sample totalled 300%, and this was the approach taken in this study for analogue matching.
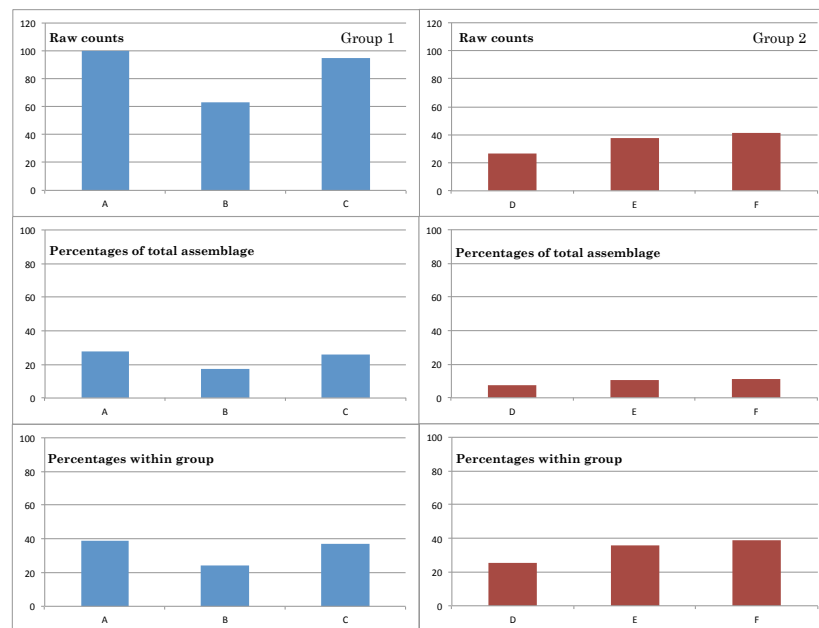
Figure 7.18: Comparison of the effect of taking percentages of species in two microorganism groups from the total assemblage versus taking percentages within the two groups.

For a simple comparison, Figure 7.18 shows, for some fictional data, the difference between these two approaches. The species in Group 2 are given less weight than the species in Group 1 when percentages are taken of the combined assemblage total, because the sample in Group 2 is smaller. Further work might compare the effect of the two different approaches on a whole data set.

7.4.3 The significance of modern analogues

Several authors have put great emphasis on the representation of fossil assemblages in the modern training sets used to reconstruct former sea-levels (Kemp *et al.*, 2009a; Wright *et al.*, 2011b; Wilson and Lamb, 2012), reflecting the notion that while prediction statistics associated with transfer functions are informative about the strength of the contemporary relationships between species' distributions and, in this case, elevation above MSL, there needs to be some acknowledgement of the ability of transfer function models to predict former sea-level from fossil species assemblages, which may be very different in composition to those in the training set.

Reconstructing sea-level on longer timescales increases the likelihood of encountering assemblages that are not well represented in local and extra-local modern training sets, so analogue matching in this study is particularly important (Barlow *et al.*, 2013).

The analogue matching exercise revealed some interesting patterns. Beginning with the two simpler measures that calculated the percentage of each fossil sample composed of speices (a) absent from the training set and (b) poorly represented in the training set, both proxies tended to be slightly better accounted for in the modern data in the lower 6m; particularly in the foraminifera data where the percentage derived from both methods was close to zero for all five samples.

In the lower 6m of the core diatom samples were almost entirely composed of species present in the modern training set, though the percentage of samples composed of species that were poorly represented is consistently higher, and tended to increase with altitude.

In the upper 5m the highest percentages are seen for both proxies and from both methods at the three intercalated organic sedimentary units, indicating that the species typically found in the minerogenic units are better represented in the diatom and foraminifera training sets than those encountered in the peat units. In contrast, the second test sees a spreading out of the pattern seen in the first test, with the maximum percentage value increasing from 76% to 84%.

The pattern in the foraminifera data was very similar in both tests, with the majority of points beneath 10% and the highest percentage the same in each (32%). This suggests that in the foraminifera data, species in the fossil samples were either well represented or not represented at all in the training set, whereas in the diatom data some species that dominate the core assemblages were in the minority in the training set. There are no examples of these measures being applied in sea-level studies with which to compare these results.

While it is intuitive to conclude from this first exercise that fossil foraminifera assemblages were better represented in the modern training set than diatoms, the more sophisticated analogue matching exercise indicates otherwise. Based now on whole assemblages and the relative proportions of the species within them, the fossil foraminifera samples were estimated to have poor modern analogues throughout. This is in contrast to a similar exercise by Kemp *et al.* (2009a) who found their foraminifera assemblages to be very well represented in the modern transect data in North Carolina, USA. Only one of their 18 fossil foraminifera assemblages was not well represented in the training set.

Many of the samples in the fossil diatom data had poor modern analogues. While the closest modern analogues to the fossil foraminifera assemblages were closely bunched between 0.3 and 0.5 on the dissimilarity gradient, with the exception of the three highest samples (Figure 7.15), the diatom data was more widely spread, particularly in the upper 5m of the sequence (Figure 7.13).

The diatom samples with good and fair modern analogues were characterised by high proportions of marine planktonic *Paralia sulcata* (up to 70% abundance), moderate numbers of marine planktonic *Pseudopodosira westii* and brackish *Tryblionella navicularis* (∼10-20%) and low proportions (5-10%) of marine *Podosira stelligera*, marine-brackish *Actinoptychus senarius* and *Diploneis didyma*, and brackish-marine *Tryblionella compressa* (Figures 7.4 and 7.5). Those assemblages with higher proportions of *P. westii*, *P. stelligera* and *T. navicularis*, and those with significant numbers of *Diploneis didyma*, *Diploneis interrupta*, *Diploneis ovalis* and *Navicula digitoradiata* were not well represented. Peaks in these marine-brackish to freshwater-brackish species coincided with the first and third organic units, suggesting that this particular palaeoenvironment was not covered in the modern environment by the sampling strategy, or that the environment they represent is now characterised by different species.

Considering the two proxies together as combined assemblages was effective in increasing the number of good and fair modern analogues in one case (multi-proxy B), but not in the other (multi-proxy C). Similar to the case of multi-proxy C, Kemp *et al.* (2009a) noted that combining their diatom and foraminifera data together did not result in an improved analogue situation. In this study, combination B (samples with significant numbers of at least one of the proxies, with the entries for species in the other proxy replaced by zeros if the total is insignificant) improved the number of good samples from 10 to 23 and the number of fair samples from 15 to 21.

In the lower 5m of the core dissimilarity decreased with depth, with the lowest 2.5m containing only samples with good modern analogues. Finally, the two very deepest samples, representing the organic unit at the base of the sequence, had poor modern analogues.

In combination B the fossil assemblages with good and fair modern analogues (Figures 7.19 and 7.20) included *Diploneis didyma* (up to ∼10%), *Caloneis ventricosa* (∼5% in some samples) and higher values of *Tryblionella compressa* (up to 15%), as well as those mentioned above in the diatom-only case. Foraminifera species *Jadammina macrescens* (up to 90%) and *Ammonia beccarii* (up to 60%) dominated the combined assemblages with good modern analogues in those with a foraminifera component (Figure 7.21). *Elphidium williamsoni* and *Trochammina inflata*, while present in the modern training set data, did not dominate any of the modern intertidal zones, so the fossil samples with high components of these species were not well represented in the training set.

While the effect of combining the two proxies together in both the modern and fossil contexts resulted in an improved analogue sitation, there was a high number of samples
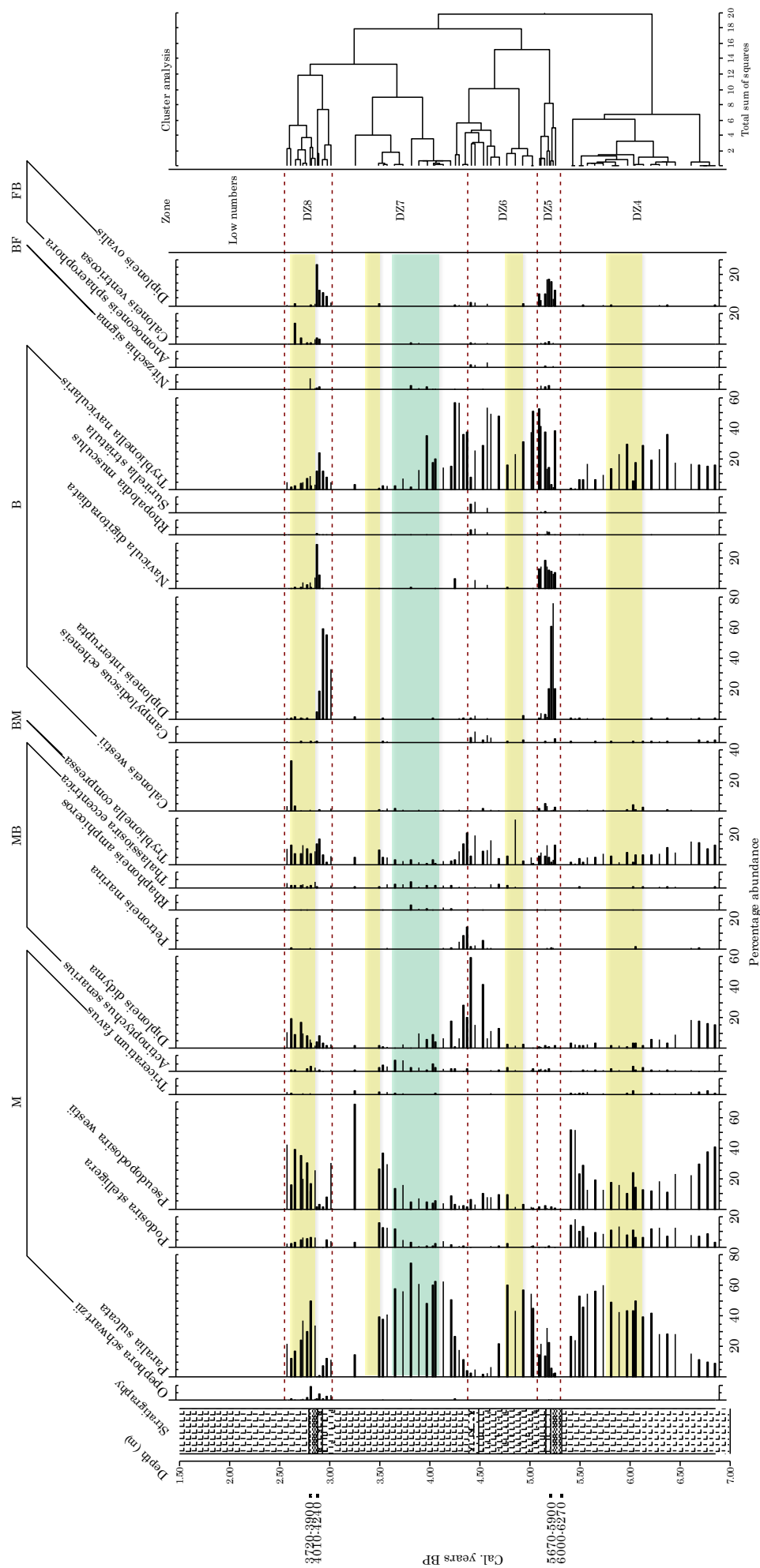
Figure 7.19: Sections of the upper 6m of the Steart core containing samples with good (green) and fair (yellow) modern analogues, as calculated by analogue matching of fossil multi-proxy samples with combined training set B, overlaid on the diatom data.
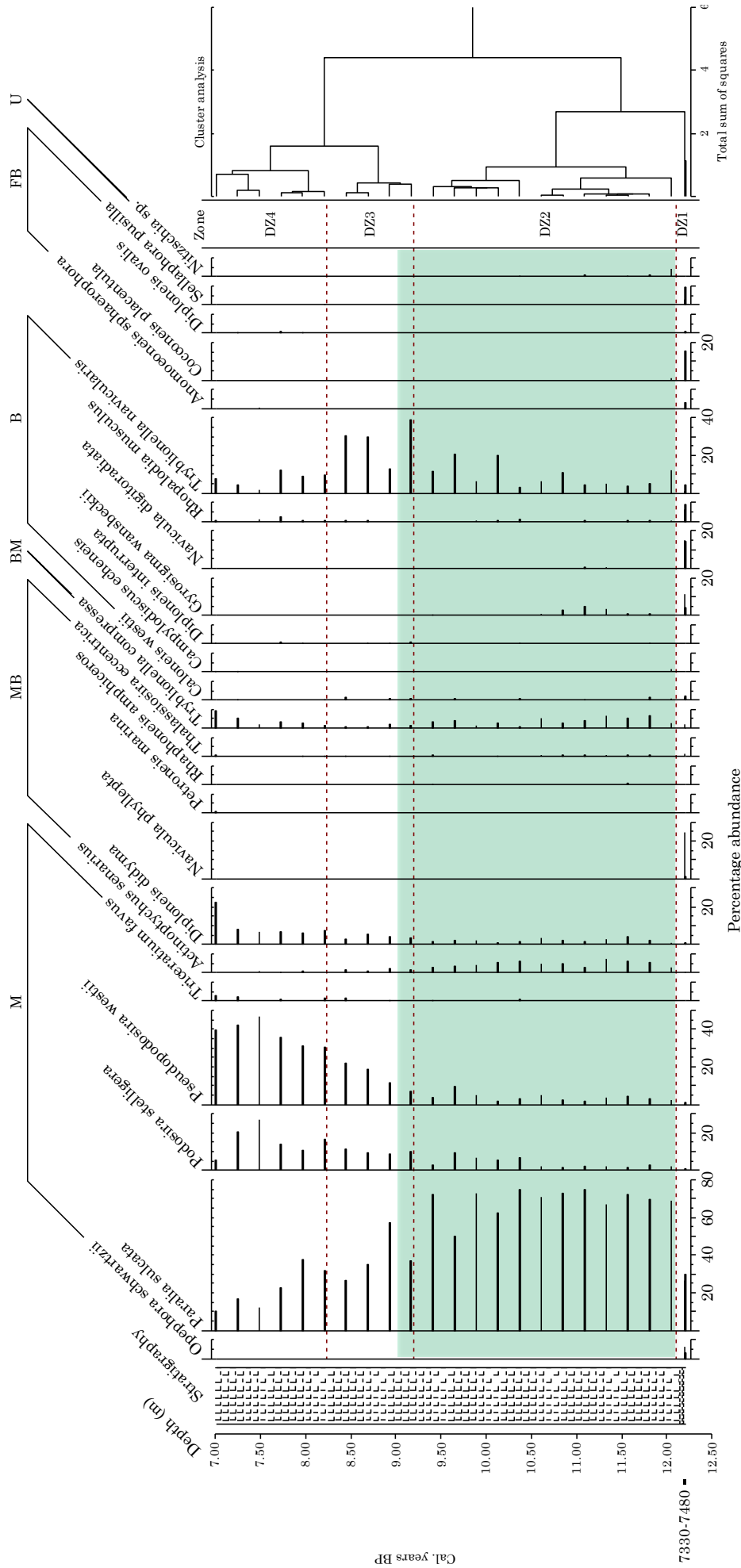
Figure 7.20: Sections of the lower 5m of the Steart core containing samples with good (green) and fair (yellow) modern analogues, as calculated by analogue matching of fossil multi-proxy samples with combined training set B, overlaid on the diatom data.
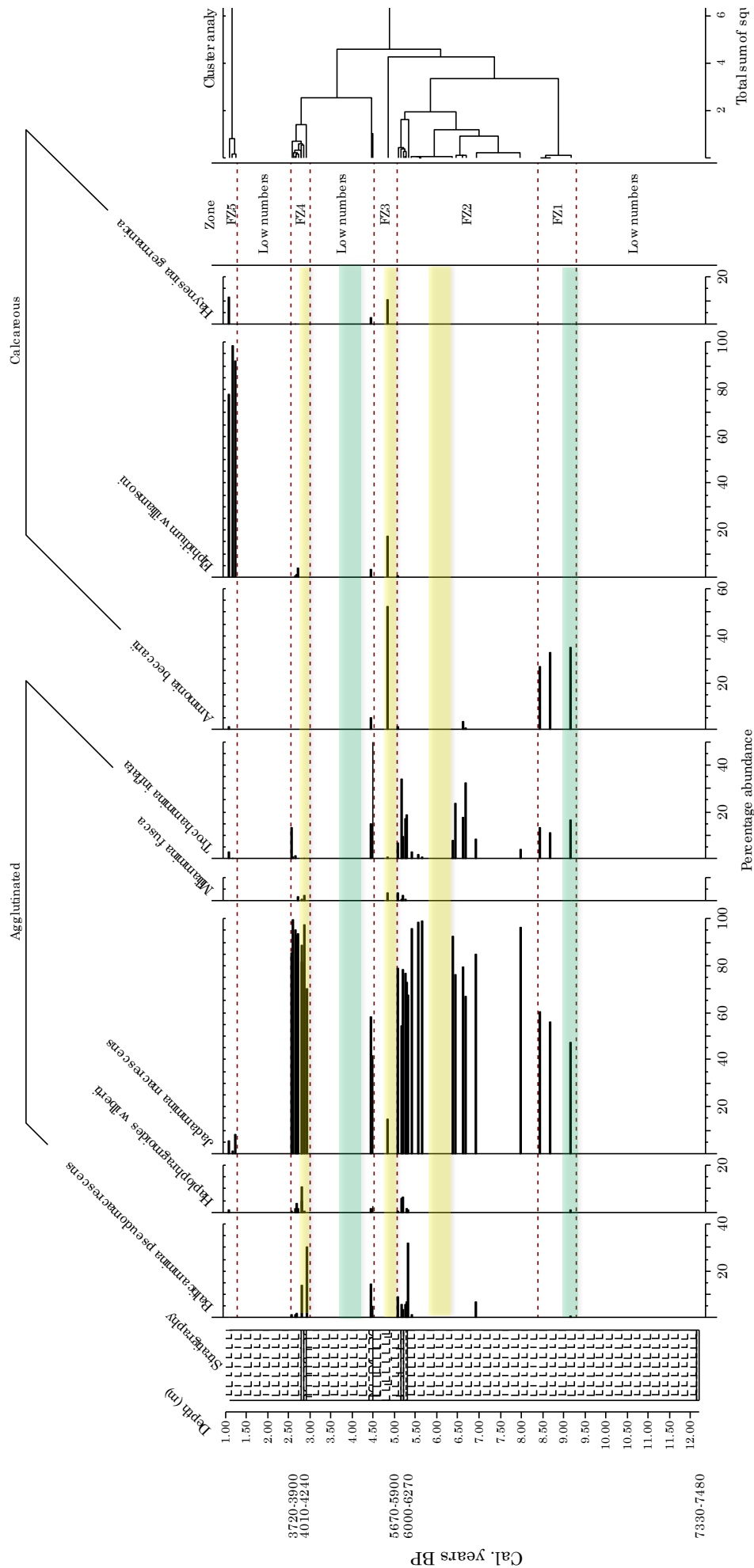
Figure 7.21: Sections of the Steart core containing samples with good (green) and fair (yellow) modern analogues, as calculated by analogue matching of fossil multi-proxy samples with combined training set B, overlaid on the foraminifera data.

still without good modern analogues (52 out of 102, or 57%). Two previous studies have compared the effect of including non-local sites in the modern training set on the level of analogy between fossil and modern assemblages, with contrasting results.

While Horton and Edwards (2005) found that only 9 of their 22 fossil foraminifera assemblages from north Northfolk, UK, had good analogues (critical value = 10th percentile; dissimilarity measure not provided) when a local training set was used, all of the fossil samples had good analogues in a regional training set that included data from 13 UK sites.

Wright *et al.* (2011b), however, found that fossil material from their cores taken from a site in Connecticut, USA, is very similar to both local and regional contemporary intertidal surface sediments in terms of foraminifera assemblages.

The results of this study, in contrast to Horton and Edwards (2005) and Wright *et al.* (2011b), indicate that a single-proxy, foraminifera-based transfer function for the Severn Estuary might only be successful if regional training data were used in addition to the extra-local data collected and used in this study, given the overall lack of suitable extra-local intertidal sites.

The arguments for using local training data in this study, as outlined in Chapter 4, were the most compelling, but given the less than satisfactory analogue situation, future research could involve adding data from sites further afield to the training sets in order to address the issues (Wright *et al.*, 2011b), and to fill the gap in the foraminifera training set, as discussed in Chapter 6.

The weighted averaging regression methods used to develop the transfer functions (WA-PLS and WA-Tol) are known to perform well in poor analogue situations (Birks *et al.*, 2010), but the analogue matching work provides a strong argument for choosing multi-proxy transfer function B for the sea-level transfer function at Steart.

7.4.4 Conclusion

Taking all of the above points into consideration, it was concluded that in this location and under the specific circumstances of this study, the multi-proxy approach was preferable to the single-proxy approach, and that method B of combining the modern and fossil diatom and foraminifera datasets together was the more robust.

Therefore, multi-proxy transfer function B was taken forward and applied to the fossil microorganism data to reconstruct palaeo-sea-level at the Steart Peninsula (see Chapter 8).

7.5   Chapter summary

- The 11.22m long sequence from the Steart Peninsula reflected a typical Holocene transgressive sequence. The core was composed primarily of grey, grey-brown and grey-green silty clays, intercalated by two organic units each approximately 10cm thick, and one 10cm thick peaty silty clay unit. The sequence rested upon a thin basal organic unit.

- Cluster analysis of the biostratigraphy revealed eight diatom zones and five foraminifera zones.

- Radiocarbon dating and age-depth modelling revealed that the sediment sequence was deposited between 7,345-7,582 and 1,442-1,543 cal. years BP. Therefore the sequence represents approximately 6,000 years of deposition.

- Simple comparison of the species found in the modern and fossil data indicates that foraminifera *species* tended to be better represented in the modern training set than the diatom species.

- In terms of *assemblages*, fossil diatom samples generally had better modern analogues than the foraminifera samples. This means that while the same species of foraminifera appeared in both the modern and fossil data, the relative abundance of those species tended to be different.

- Combining the two proxies resulted in better analogy between modern and fossil assemblages.

- Following a discussion of the relative merits and shortcomings of the four remaining transfer function models (single-proxy diatoms, single-proxy foraminifera, multi-proxy using method B and multi-proxy using method C), multi-proxy transfer function B was concluded to be the most suitable for estimating the Holocene sea-level change at Steart Peninsula.

Chapter 8

Holocene environment and sea-level reconstruction at the Steart Peninsula

The selected sea-level transfer function was applied to the fossil data from the Steart core to give five SLIPs and 102 other estimates of former sea-level. In this chapter the palaeoenvironmental interpretations of the stratigraphic, micropalaeontological and transfer function-derived results are presented and the quantitative reconstruction at the Steart Peninsula is evaluated with reference to the palaeoenvironments implied by all of the lines of evidence analysed, and with reference to previous research. The results are then placed into the context of current understanding of Holocene environmental and sea-level change in Bridgwater Bay and the wider Severn Estuary region. Finally the key areas for possible future research are put forward. It is recognised throughout the discussion that regional sea-level changes may not be the only possible cause of the environmental changes seen in the Steart sequence, particularly in the context of the influence of localised factors such as the shingle ridge evolution at Steart during the Holocene (Kidson, 1960; Kidson and Heyworth, 1976).

8.1   Application of the prefered transfer function

Multi-proxy transfer function B (WA-PLS model with 2 components; r_{boot}^2=0.70; RMSEP=0.09) was applied to 107 fossil multi-proxy samples, where at least one proxy had significant counts and insignificant counts were replaced with null values. The results provided estimates of each fossil sample's palaeo-elevation above MTL (indicative meaning) at the time of sediment deposition, and sample-specific estimates of prediction error. Both sets of values were converted from SWLI units to metres relative to MTL and palaeo-sea-level (m OD) was calculated by subtracting indicative meaning from sample altitude.

8.1.1 Former sea-levels

Estimates of palaeo-sea-levels given by the multi-proxy transfer function are plotted against sample altitude in Figure 8.1.

The samples with good and fair analogues are concentrated in the top and bottom sections, and an overall rise in sea-level of ~14m is indicated over the course of the sequence. Fluctuations in marine influence are implied between -1m and 0.5m OD and again at 2m OD, but cannot be interpreted as genuine oscillations in MTL given the mean prediction error of 1.08m as a minimum error margin.

The transfer function produced estimates of sudden lowering in MTL of several metres for the two outliers at -3m and -2m OD. However, at most these points may be interpreted as periods of locally reduced marine influence, due to the large vertical error bars, poor modern analogues and inconsistency with the overall trend.

The error bars tend to be smaller in the lower samples (-7m to OD) compared with the samples from the upper 4m of the core. In particular, the three points just below 4m OD have large error bars in both plots, of about ±1.65m. These three fossil samples had the poorest analogy with the modern training sets (Figure 7.15). The average prediction error of all of the fossil samples in the reconstruction is ±1.09m. This is comparable to the average prediction error recorded by Hill *et al.* (2007) in a diatom transfer function-based reconstruction of sea-level change at Gordano Valley, North Somerset.

8.1.2 Sea-level index points

Five SLIPs based on calibrated radiocarbon dated samples, transfer function-derived indicative meanings, indicative ranges and sea-level tendencies are set out in Table 8.1.

The fourth SLIP, from 5.31m deep (-0.41m OD), did not yield significant numbers of either diatoms or foraminifera. While the sample was included in the quantitative reconstructions, it is highlighted here as a less reliable data point, and was not included in the analogue matching exercises. 107 diatoms were identified from this sample, and 72 foraminifera tests.

8.1.3 Transfer function-based sea-level reconstruction

Combining the radiocarbon dated SLIPs and age-depth modelled palaeo-sea-level estimates, Figure 8.2 gives a plotted Holocene sea-level history for the Steart Peninsula site based on the preferred multi-proxy transfer function model. Vertical and horizontal error bars are placed only on the "real" SLIPs to avoid cluttering the chart. Figure 8.3 includes vertical and horizontal error bars.
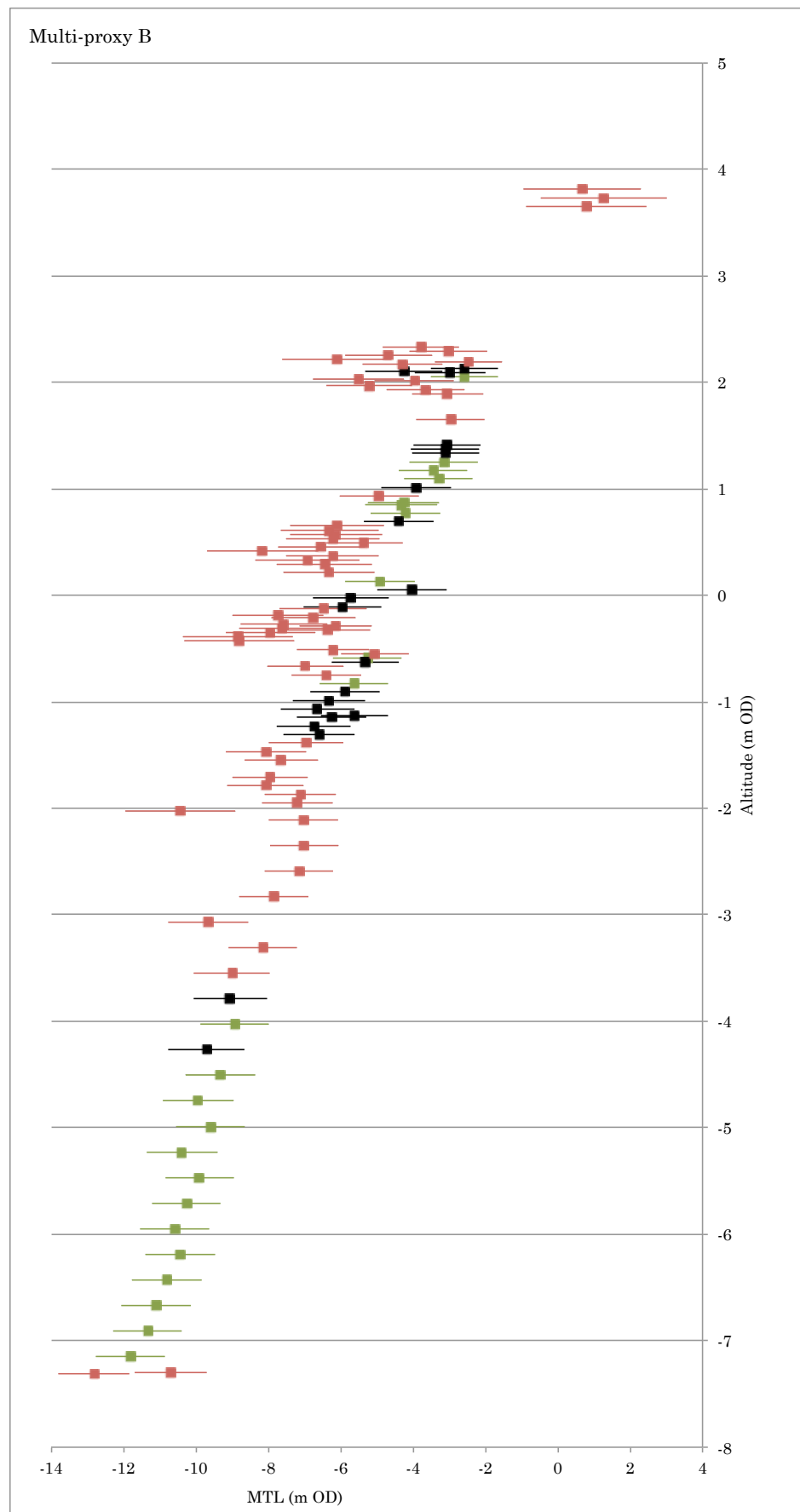
Figure 8.1: Palaeo-sea-level as estimated by the multi-proxy transfer function, against altitude in the Steart core sequence. The colour of the points refers to the level of analogy in the modern training set. Green = good analogues, black = fair analogues, red = poor analogues, as calculated in Section 7.3 of Chapter 7.

Table 8.1: Details of five radiocarbon dated SLIPs from the Steart sequence.

Lab code	Depth	Altitude	Description	^{14}C age	Calibrated age (2σ)	Indicative meaning	Indicative range	Indicative meaning	Sea-level tendency
	m	m OD			cal. years BP	m > MTL	m > MTL	tidal level	
Beta - 321509	2.80	2.10	Organic sediment	3,520–3,580	3,900–3,720	6.36	5.38–7.34	MHWST–HAT	Negative
Beta - 321510	2.87	2.03	Organic sediment	3,730–3,800	4,240–4,010	7.52	6.54–8.50	HAT	Negative
Beta - 321511	5.21	-0.31	Plant material	5,010–5,070	5,900–5,670	7.26	6.28–8.24	HAT	Negative
Beta - 321512	5.31	-0.41	Plant material	5,320–5,380	6,270–6,000	4.98	4.00–5.96	MHWST	Positive
Beta - 321513	12.32	-7.30	Plant material	6,470–6,550	7,480–7,330	3.42	2.44–4.40	MHWST	Positive
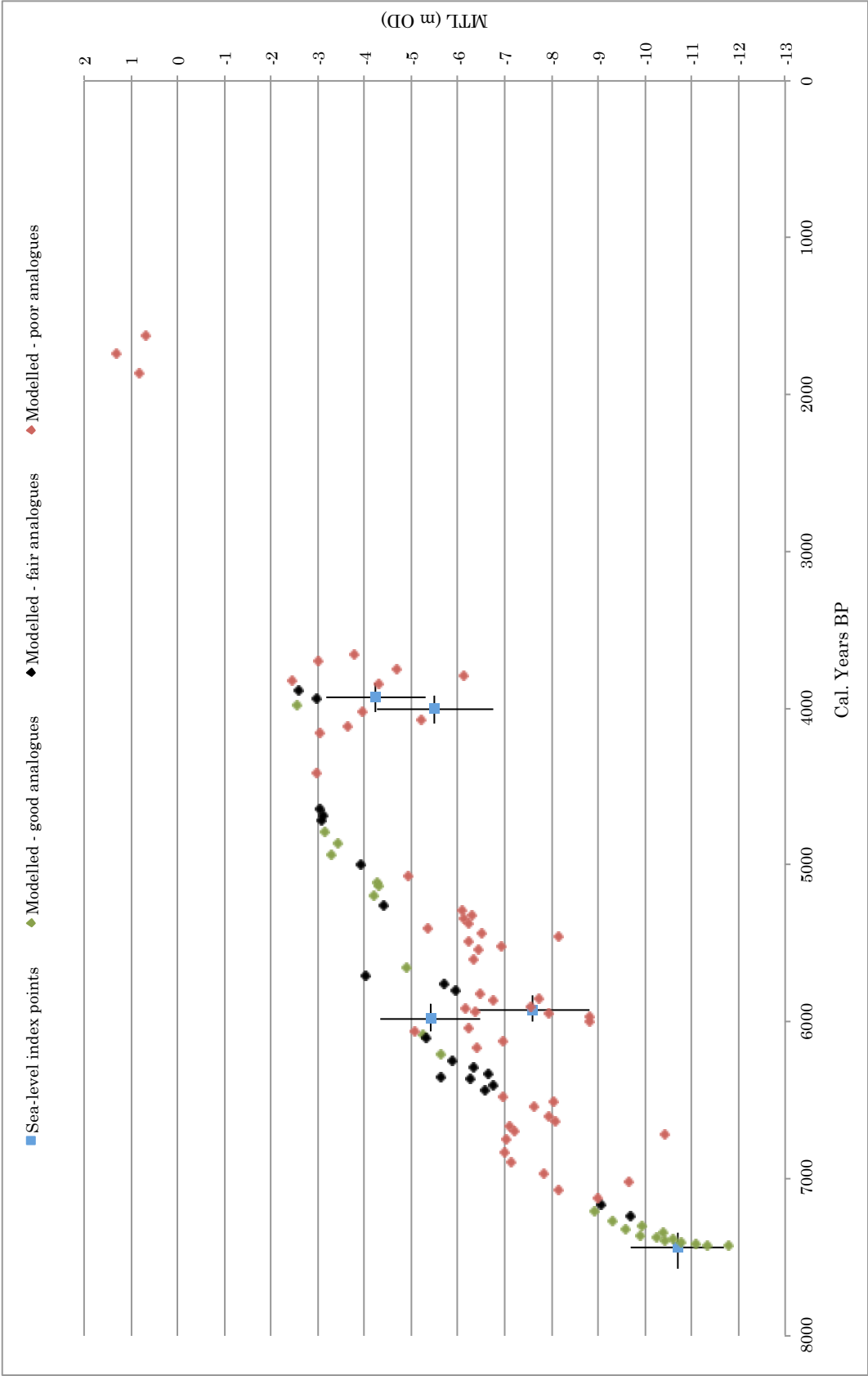
Figure 8.2: Reconstructed relative sea-level at the Steart Peninsula based on five sea-level index points, inferred ages of 97 other points in the Steart sequence and multi-proxy B WA-PLS (2 components) transfer function.
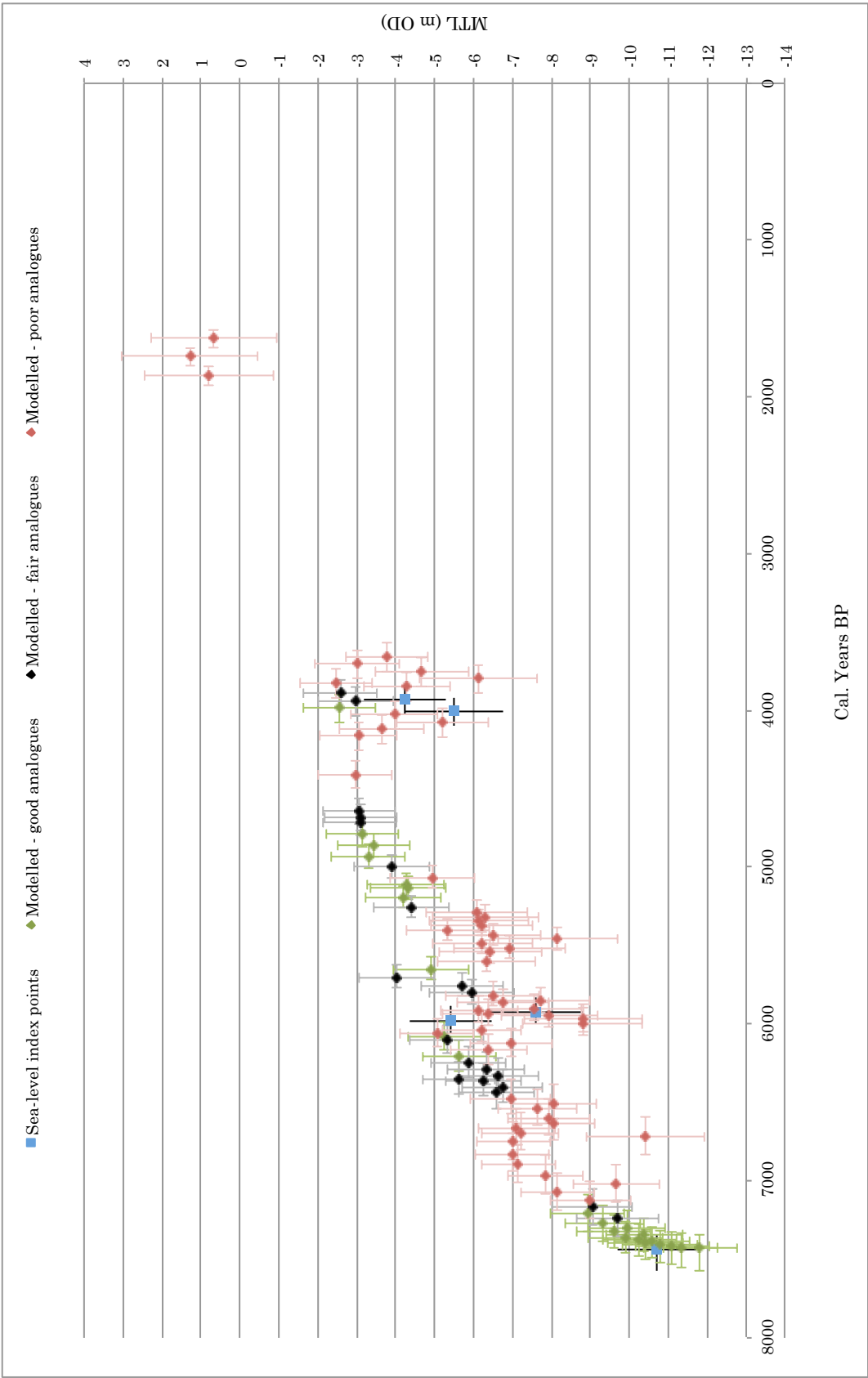
Figure 8.3: Reconstructed relative sea-level at the Steart Peninsula based on five sea-level index points, inferred ages of 97 other points in the Steart sequence and multi-proxy B WA-PLS (2 components) transfer function, including vertical prediction error and horizontal 2-sigma radiocarbond dating error.

A steep rise in sea-level was implied from -12m OD 7,450 cal. years BP to -8.2m OD 7,100 cal. years BP. This average rate of 11mm per year is comparable to the 12mm per year recorded by Kidson and Heyworth (1976) for the Bristol Channel, implying that the factors influencing sea-level at Steart during this period were likely to be regional drivers.

The rate of rise gradually levelled off over the next 3,000 cal. years, and MTL stood at -2.5m OD 3,900 cal. years BP. A gap in the data occurred between 3,900 and 1,800 cal. years BP, where MTL was estimated to be 1m OD ±1.7m by the transfer function. These three points have the largest of all the vertical error bars and also had among the highest dissimilarity measures in the analogue matching exercise, so cannot be used for a precise interpretation of MTL 1,800 cal. years BP.

The section between 7,000 and 5,100 cal. years BP contained a lot of variability in estimated MTL. Again, the most widely spread points were those based on samples with poor modern analogues, and differences of about 4m in estimated MTL were noted in samples 100 years apart in some places, meaning that only a broad interpretation of a rise in MTL can be taken, with possible variation in marine influence on a centennial timescale.

Samples deposited between 5,100 and 4,600 cal. years BP had good or fair contemporary analogues and were less vertically spread than the previous period. Some further possible local fluctuation in marine influence occurred between 4,200 and 3,700 cal. years BP, but again, given the margin of vertical error involved, it is not possible to derive an interpretated of genuine oscillation in MTL from the data.

8.2 Stratigraphic interpretation

The Holocene sedimentary sequence at Steart is characteristic of many UK coastal palaeo-sequences (Horton and Edwards, 2006), beginning with a thin basal organic unit between -7.30 to -7.32m OD, followed above by about 12 metres of grey, brown and green silty clays intercalated with three organic units. There were some remains of vegetation in parts of the silty-clay units of the core and the middle organic unit contained numerous ostracod tests. The average proportion of organic matter in the four organic layers, from top to bottom, was 28%, 16%, 57% and 21% respectively, while the average organic content of the silty-clay units was 7%.

Based solely on the sediment stratigraphy and radiocarbon dates, the sequence is interpreted as a typical post-glacial transgression (Horton and Edwards, 2006; Kidson and Heyworth, 1976), with the basal organic unit representing early Holocene water logging and peat formation and the silty-clays representing Holocene sea-level rise.

Sedimentation appeared to keep pace with sea-level rise throughout the majority of the sequence, implying a high sediment load in the estuary throughout the Holocene (Kidson and Heyworth, 1973), and the three thin organic units were interpreted as periods of marine regression, either due to sea-level fall, to increase protection from the open water, or because sedimentation outpaced the rate of sea-level rise during these times, allowing peats to develop. The two periods of peat accumulation that were dated each lasted about 300 years before the return of the transgressive regime. Following the initial peat formation ~7,440 cal. years BP six metres of silty clay sediments were deposited in just over 1,000 years. The average rate of deposition during the first 1,000 years was 6mm per year, slowing dramatically to 1.8mm per year from 6,440 to 5,440 cal. years BP. This rate continued to drop, to 1.2mm per year to 4,440 cal. years BP, then 0.9mm per year, 0.08cm per year, and finally 0.7mm per year between 2,440 and 440 cal. years BP. This exponentially decreasing rate of sediment deposition over time broadly indicates the pattern of change in the rate of Holocene sea-level rise (Allen, 1990a).

8.3   Foraminifera-based interpretation

The foraminifera data for the Steart sequence is patchy in places due to low numbers of tests in the core sediments.

The foraminifera that were present throughout the majority of the sequence were common saltmarsh species and the most common assemblage, composed mainly of *Jadammina macrescens*, *Trochammina inflata* and *Balticammina pseudomacrescens*, occurred in both the minerogenic and organic units. Given how patchy the data is, a brief return to the un-screened foraminifera data, shown in Figures 7.6 and 7.7 and displaying all samples and species regardless of sample sizes or maximum species percentages, confirms that agglutinated saltmarsh dwelling taxa dominate throughout. There are two periods when calcareous, typically low marsh to tidal flat-dwelling species *Elphidium williamsoni*, *Haynesina germanica* and *Ammonia beccarii* increased, from 3.89m to 3.17m OD and 0.45m and -0.19m OD. These sections represent approximately 1,460 to 2,550 cal. years BP and 5,430 and 5,850 cal. years BP respectively.

The long-term sea-level rise over several millennia may have resulted in the immature minerogenic marsh continually accumulating mobile sediment from the Severn Estuary, increasing in elevation over time (Pratolongo *et al.*, 2009). The prevalence of calcareous tidal-flat species in the two periods mentioned above signify times when sea-level rise out-paced the rate of minerogenic saltmarsh sedimentation and upper tidal flat conditions prevailed.

The modern foraminifera zonation revealed by cluster analysis (Chapter 5) corroborates this general claim, as the silty-clay saltmarsh sediments found towards MHWST contained mainly *J. macrescens* and *T. inflata* as well as *Haplophragmoides wilberti* which is not as common in the fossil assemblages, and calcareous *A. beccarii*. The modern tidal flat zone did not correspond so closely with the fossil assemblages that were assumed to represent a tidal flat environment because they contained calcareous species (Gehrels, 2002). While the modern tidal flat zone was dominated by *A. beccarii*, with low numbers of *E. williamsoni* and *H. germanica*, the fossil equivalent was composed mainly of *E. williamsoni* with a large component of *H. germanica* in only some samples, and low numbers of *A. beccarii*.

8.4   Diatom-based interpretation

This section provides a diatom-based palaeoenvironmental interpretation of the Holocene sequence at Steart, beginning at the base, dated at ~7,440 cal. years BP. Diatom zones refer to those in Figures 7.4 and 7.5 in Chapter 7. Dates estimated by the age-depth model are given to the nearest 10 years.

The basal organic unit was characterised by two species typical of the lower saltmarsh zone identified in the modern transects; *Paralia sulcata* and *Navicula digitoradiata*. However, the other species in this basal unit that did not dominate any of the modern assemblage zones were mainly marine-brackish, brackish and freshwater-brackish forms. The unit is therefore more likely to signify a higher saltmarsh environment or a transition period between lower and higher saltmarsh development.

A transition straight into a zone dominated by marine, marine-brackish and brackish species occurred above the basal unit, representing the period from 7,435 to 7,240 cal. years BP. Just under three metres of sediments were deposited in this 200 year period, and towards the top there is evidence for an increasingly brackish environment, with a higher proportion of *Tryblionella navicularis* and declining dominance of marine species.

DZ6 revealed the establishment of a higher intertidal environment, signifying a marine regression or slowing down of sea-level rise, a higher rate of sediment input or the presence of barrier protection as brackish *T. navicularis* increased in relation to marine species from 7,240 to 7,060 cal. years BP.

This saltmarsh environment was then inundated once more as marine *Pseudopodosira westii*, *P. sulcata* and *Podosira stelligera*, marine-brackish *Diploneis didyma* and brackish-marine *Tryblionella compressa* increased and brackish *T. navicularis* declined from 7,060

throughout DZ5 from 7,060 to 5,950 cal. years BP, signifying a lower saltmarsh or tidal flat environment.

A brief return to a higher saltmarsh environment was implied between 5,950 and 5,820 cal. years BP in which DZ4 was dominated by brackish, brackish-freshwater and freshwater-brackish species, namely *N. digitoradiata* and *T. navicularis*, as well as *Diploneis interrupta* and *Diploneis ovalis* which were not well represented in the modern diatom zonation but are well-known saltmarsh indicators (Vos and de Wolf, 1988). This short, organic-rich (see Section 8.2) period of saltmarsh development abruptly ended 6,380 cal. years BP with a return to a marine-brackish environment of lower marsh or upper tidal flat. Marine species were present but did not dominate as they did between 6,680 and 5,800 cal. years BP. Instead the assemblage was characterised by *D. didyma*, *T. compressa* and *T. navicularis*.

Marine species increased again around 5,260 cal. years BP, signifying a further marine transgressive period in which marine species were the only species present in any significant proportion in the diatom assemblage.

The final unit before diatom numbers fell significantly was deposited between 4,160 and 3,660 cal. years BP, and the assemblages indicated a marine-brackish to brackish environment similar to that found in DZ3, with contributions from most of the salinity groups, including brackish-freshwater and freshwater-brackish species, indicating perhaps a transition to higher marsh conditions as sea-level stabilised. The transition into the section containing low diatom numbers was gradual, suggesting that significant erosion did not occur here.

The diatom biostratigraphy revealed more changes in palaeoenvironmental conditions than were suggested by analysis of the sediment stratigraphy alone; particularly in the lower 6m where the sequence was almost entirely composed of grey silty clays, representing the period between 7,440 and 6,485 cal. years BP.

8.5   Transfer function-based interpretation

Figure 8.4 shows the indicative meanings of the core sampling points as estimated by the multi-proxy transfer function. The indicative meanings are plotted against time and micro-faunal zones based on the modern diatom zonations revealed in Chapter 5, indicating the palaeoenvironment over the timescale being reconstructed.

The multi-proxy transfer function reconstruction predicted a tidal flat to lower saltmarsh environment between ~7,440 and ~7,300 cal. years BP, followed by upper saltmarsh for ~630 years and then a period of fluctuation between upper saltmarsh and terrestrial environments lasting about 1,670 years. Lower saltmarsh returned just after 5,000 cal. years BP, lasting

for ~590 years. After this, decreasing marine influence over time was implied by the upper saltmarsh and then terrestrial environments until 3,600 cal. years BP, followed by a period where no information was available due to low assemblage counts. The three most recent samples (1,860 to 1,620 cal. years BP) were then assigned to the tidal flat zone by the transfer function, with the lowest indicative meanings of all the samples.
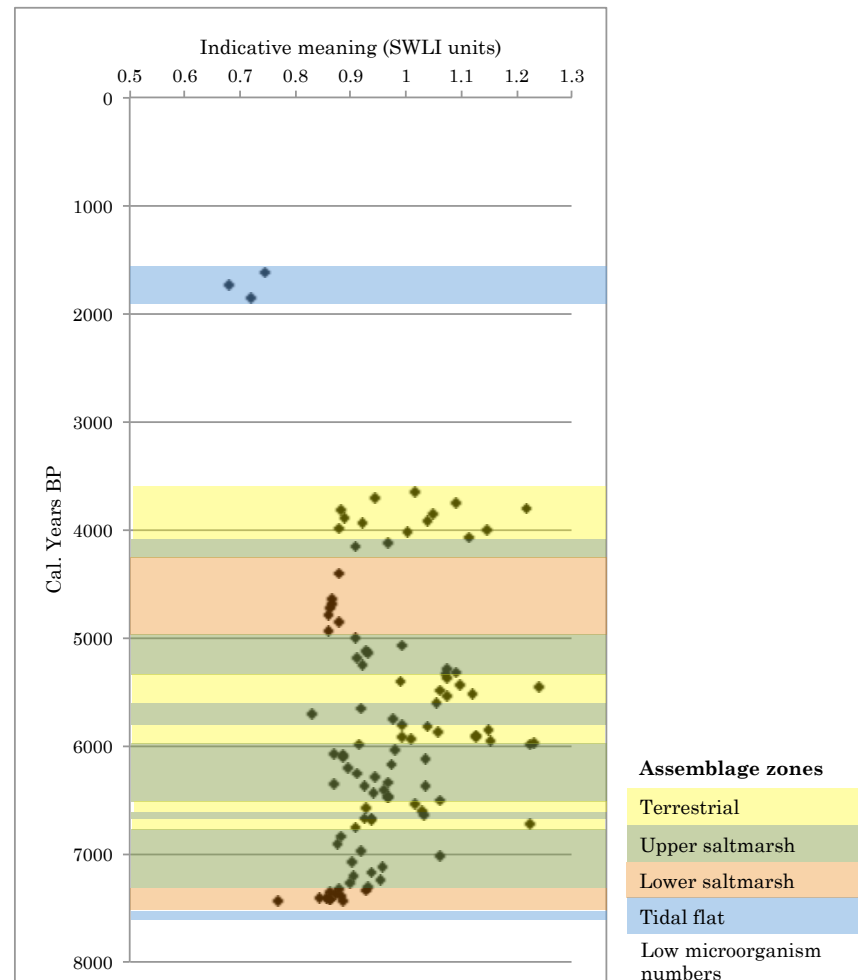
Figure 8.4: Indicative meanings throughout the Steart sequence as estimated by the multi-proxy WA-PLS transfer function B.

In using fossil assemblages with poor modern analogues in the training set there is a risk of over-interpreting a result based on a seemingly precise transfer function (Woodroffe, 2009). The analogue matching exercise highlighted which fossil samples might given an unreliable palaeo-tidal-level estimate.

In particular, the diatom assemblages from the basal peat were interpreted by the transfer function to represent a tidal flat environment. This makes little ecological sense. The basal organic sediments together with the marine-brackish to freshwater-brackish diatom taxa suggested a brackish lagoon environment here. Many of the marine-brackish to freshwater-brackish taxa identified in the basal peat, such as *Cocconeis placentula, Cosmioneis pusilla*

and *Tryblionella navicularis*, were not well-represented in the modern training set, meaning that the transfer function did not have adequate elevation data for much of the assemblage (see Figure 7.15), resulting in a prediction of a low, tidal flat environment based mainly on the marine species *Paralia sulcata*. The tranfer function prediction for the basal unit was therefore disregarded.

For the sediments immediately above the basal peat the transfer function prediction was assumed to be more reliable because modern analogues for samples from -7m to -4m OD were good or fair. However, because the transfer function predicted a shift from tidal flat to lower saltmarsh, the fall in sea-level necessarily implied was disregarded. The minerogenic sediments and diatoms common to marine and marine-brackish habitats deposited above the basal peat signified an increase in marine influence, and a fall in MTL is not conceivable given that there is no realistic mechanism for such a fall on this timescale. A more broad interpretation was made that MTL was -10m to -12m OD 7,480-7,330 cal. years BP, with marine influence increasing and MTL rising, though it was not possible to estimate a rate of rise given the data scatter.

The transfer function prediction for the remainder of the sequence made sense ecologically, with periods of higher predicted SWLI coinciding with the deposition of organic sediments as marine influence decreased periodically. However, such periods cannot be interpreted as absolute MTL changes within the margins of error present.

8.6   Integrated interpretation

Table 8.2 summarises the Holocene palaeoenvironments at the Steart Peninsula coring site as estimated by the stratigraphy, diatom and foraminifera assemblages and the multi-proxy transfer function. Diatom and foraminifera assemblages are those that were established in the cluster analysis (Section 6.1 and Figures 5.8, 5.9 and 5.10) and the inferred environments associated with those zones are based on the preferred environments of the key species in those zones. The indicative meanings and the palaeoenvironments are based on the SWLI values returned by the transfer function in relation to the modern environment. Palaeo-sea-level and sea-level tendency were calculated from transfer function predictions of reference water level and the present altitude (m OD) of the core samples to which the transfer function was applied.

Beginning at the base of the sequence, there appeared to be a discrepancy between the stratigraphy, the diatom assemblages and the transfer function-derived palaeoenvironment, as referred to in the previous section (8.5). DZ1 is composed of species that range from

Table 8.2: Summary of palaeoenvironmental change at the Steart Peninsula site, as estimated by the stratigraphy, diatom and foraminifera assemblages and multi-proxy transfer function B. M=marine, B=brackish, F=freshwater.

Altitude (m OD)	Age (Cal. Years BP)	Stratigraphy	Diatom assemblages	Foraminifera assemblages	Indicative meaning	Palaeo-environment	Palaeo-sea-level	Sea-level tendency
3.65 to 3.78	1,860-1,620	Silty clay	N/A	FZ8 (M)	MSL-below MHWST	Tidal flat	0.7 to 0.6	negative
2.33 to 3.65	3,660-1,860	Silty clay	N/A	N/A	N/A	N/A	-3.7 to 0.7	positive
1.65 to 2.33	4,410-3,660	Silty clay, peaty silt, peat	DZ7 (M-MB), DZ8 (M-FB)	FZ4 (B)	MHWST-above HAT	Terrestrial and upper saltmarsh	-3.0 to -3.8	negative
1.01 to 1.65	5,000-4,410	Silty clay with plant remains	DZ7 (M-MB)	FZ4 (B)	below MHWST	Lower saltmarsh	-3.9 to -3.0	positive
0.66 to 1.01	5,290-5,000	Silty clay with plant remains	DZ7 (M-MB)	FZ4 (B)	below MHWST	Upper saltmarsh	-6.1 to -3.9	positive
-0.11 to 0.66	5,805-5,290	Peaty silty clay, silty clay with plant remains	DZ6 (M-B)	FZ3 (B)	MHWST-HAT	Terrestrial	-6.0 to -6.1	negative
-0.13 to -0.11	5,820-5,805	Silty clay	DZ6 (M-B)	FZ3 (B)	MHWST	Upper saltmarsh	-6.5 to -6.0	positive
-0.24 to -0.13	5,980-5,820	Silty clay	DZ5 (B-FB)	FZ3 (B), FZ2 (B)	MHWST-above HAT	Terrestrial	-5.4 to -6.5	negative
-1.47 to -0.24	6,510-5,980	Silty clay, peat, clayey silt	DZ4 (M-B)	FZ2 (B)	below MHWST	Upper saltmarsh	-8.1 to -5.4	positive
-1.87 to -1.47	6,670-6,510	Silty clay	DZ4 (M-B)	FZ2 (B)	MHWST-HAT	Terrestrial	-7.1 to -8.1	negative
-4.99 to -1.87	7,325-6,670	Silty clay with plant remains	DZ2 (M-B), DZ3 (M-MB), DZ4 (M-B)	FZ2 (B)	below MHWST	Upper saltmarsh	-9.6 to -7.1	positive
-7.15 to -4.99	7,435-7,325	Silty clay with plant remains	DZ2 (M-B)	N/A, FZ1 (B), FZ2 (B)	below MHWST	Lower saltmarsh	-10.7 to -9.6	positive
-7.30 to -7.15	7,440-7,435	Peat, silty clay	DZ1 (MB-FB)	N/A	below MHWST	Tidal flat	-10.3 to -12.3	negative

marine to freshwater-brackish in terms of their preferred environment and, while the sediment stratigraphy might suggest an organic upper saltmarsh environment, the transfer function predicts a tidal flat environment. The marine component of the diatom assemblage in DZ1 was almost entirely due to the abundance of *Paralia sulcata* which is a highly mobile marine species that has been noted in every one of the modern diatom samples analysed. Pollen analysis of the same basal organic unit (Walter, 2013) (see Section 8.7 for more detail) implies a coastal reed swamp environment, and the very poor modern analogue situation for the two basal samples (Figure 7.15) suggests that the transfer function has incorrectly predicted a tidal flat environment based on the high proportion of *P. sulcata* and a lack of modern-fossil correspondence in the other species. This highlights one of the risks of relying on one source of palaeoenvironmental evidence in isolation.

An alternative interpretation for this basal unit is one in which the sediments experience little marine influence, but where planktonic, mobile species *P. sulcata* has been transported to the site in some way. The site may have been situated behind a barrier that was occasionally breached, resulting in the deposition of some marine and marine-brackish species.

The palaeoenvironment of the silty clay unit above the basal peat was more consistently predicted by the various proxies. Plant rootlets preserved in the sediment suggests that the water was shallow enough at this time to support vascular plants and the marine-brackish to brackish diatom and brackish foraminifera assemblages point to a lower saltmarsh environment. Lower saltmarsh was initially implied by the transfer function, followed by a period of upper saltmarsh development.

A terrestrial environment was predicted by the transfer function for the brief period 6,670-6,510 cal. years BP. This could not be directly interpreted as a fall in sea-level as the vertical scatter in the modelled data points was greater than 4m here (see Figure 8.2). However, an increase in silty-clays delivered to the site may have caused an increase in sedimentation in relation to the rate of sea-level rise.

Two fluctuations in marine influence were implied by the transfer function between 6,510 and 5,000 cal. years BP. The stratigraphy was uniformly composed of silty-clays throughout this period until the first intercalated peat deposition began at 6,270-6,000 cal. years BP. Following this organic unit minerogenic sedimentation returned. Data point scatter was still significant at this stage, even beyond the large error bars (see Figure 8.3). This is a common finding in Holocene sea-level studies and Long *et al.* (2006) attribute such data scatter to the complex compression processes that affect unconsolidated Holocene sediments. One model for the sedimentation seen above this peat unit is the action of compression

creating accommodation space in which infilling could occur.

A terrestrial environment was implied between 5,805 and 5,290 cal. years BP, coinciding with the middle intercalated peat. The data scatter is still too large to make an informed interpretation about absolute sea-level change here. MTL appears broadly to be rising throughout the mid-Holocene period, and changes in sediment supply and barrier development and decay might explain the apparent variations in marine influence, combined with the likely effect of autocompaction, particularly of organic sediments.

Data scatter reduced significantly between 5,000 and 4,200 cal. years BP, where samples generally had good or fair modern analogues. A clear positive sea-level tendency was implied here as the palaeoenvironment progressed from upper to lower saltmarsh. Further vertical scatter in the data points occurred around the uppermost peat unit where a negative tendency and terrestrial habitat is prediced by the transfer function, but as with the other two peat units, an absolute fall in sea-level cannot be inferred due to the vertical error present. Instead, a decrease in marine influence due to some other factor is estimated.

Above the final peat layer a further increase in marine influence was implied by the deposition of silty-clays, however, there was no micropalaeontological evidence to support this. The presence of marine foraminifera deposited around 1,860 cal. years BP implied a further increase in marine influence. Due to the lack of precise data for this period it is not possible to infer whether the site was undergoing a genuine rise in sea-level or some other process such as a barrier breach or increased sedimentation. Further work might seek to reconstruct the evolution of the shingle ridges at the Steart Peninsula during the late Holocene and their effect on the development of the intertidal environment.

This interpretation indicates that with the exception of the basal unit, which may have had a negligible relationship with sea-level at the time of deposition, strong correspondence between the stratigraphy, the salinity groups of the microfossils and the transfer function-derived sea-level and palaeoenvironmental estimates. Fuller discussion of the results in relation to previous research in Bridgwater Bay and the wider Severn Estuary region is given later in Sections 8.8 and 8.9.

8.7 Evaluating the quantitative sea-level reconstruction

The success of ecological transfer functions and their subsequent reconstruction is often based solely on the prediction statistics associated with the initial regression models (Gehrels, 2000; Horton and Edwards, 2000; Massey *et al.*, 2006a; Charman *et al.*, 2010), but as has already been discussed in terms of modern analogues and the meaning of prediction statistics, the r^2

and RMSEP are only indicators of a model's *potential* ability to reconstruct former sea-levels at a given site. Much of the success of the actual application of these models to fossil data depends on the nature of the fossil sediments and decisions made by the researcher(s) about coring sites, sampling strategies and the choice of proxies and regression models (Barlow *et al.*, 2013).

Watcham *et al.* (2013) advise that the performance of sea-level reconstructions based on ecological transfer functions should be reviewed using three main criteria. These are:

(a) The number of fossil samples with poor or no modern analogues.

(b) That the reconstructions are reasonable when compared with independent measurements.

(c) That the reconstructions make ecological and environmental sense.

(a) Modern analogues

This issue has already been discussed in detail in the previous Chapter(Section 7.3), with the conclusion that the single proxy foraminifera-based transfer function may not be appropriate due poor modern analogues, but that elements of the diatom and multi-proxy transfer functions may be more reliable for application to the Steart fossil sequence; particularly the multi-proxy transfer function (version B) that was ultimately used for the transfer function-based reconstruction.

(b) Independent verification

In this study there is no observational record of sea-level changes over the timescale being reconstructed, as there often may be for studies seeking to reconstruct 19th to 20th century sea-level, where tide gauge records are available and useful comparisons can be made. However, Barlow *et al.* (2013) advises that those reconstructions without independent measurements can be evaluated using the sediment lithology. Later, in Section 8.9 the transfer function-based reconstruction is also considered in the context of, among other work, the other transfer function-derived sea-level history from the region, based on work at Gordano (Hill *et al.*, 2007).

The sediment lithology does not indicate as much variability in the palaeoenvironment as the transfer function-based reconstruction. The transfer function-based reconstruction has already been discussed in the context of the sediment stratigraphy (and micropalaeontology) in the previous section (8.6). However, a more explicit comparison of the transfer function results and stratigraphy is given briefly here.

From the basal organic unit upwards the transfer function initially disagrees with the stratigraphy, estimating a tidal flat palaeoenvironment where the stratigraphy indicated a brackish lagoon environment, as discussed previously (Section 8.6). Above the basal peat unit the transfer function estimated a lower saltmarsh environment for 110 years, corroborated by the silty-clays containing plant remains. The following section, from 7,350 to 5,980 cal. years BP was upper saltmarsh according to the transfer function, whereas based solely on the silty-clay sediment stratigraphy, an upper tidal flat to lower saltmarsh environment was indicated. A fluctuation between 5,980 and 5,820 cal. years BP, to and from a terrestrial environment, occurred around the lowest intercalated peat unit. A further oscillation to a terrestrial environment and back to upper saltmarsh occurred between 5,290 and 5,805 cal. years BP, coinciding with a peaty-silty-clay stratigraphic unit; both suggested a negative sea-level tendency. The 880-year long period of positive sea-level tendency between 5,290 and 4,410 cal. years BP was supported by the silty-clay deposition. A further fluctuation in marine influence was predicted by the transfer function between 4,410 and 3,660 cal. years BP was inferred by the final peat unit in the sequence. The tidal flat environment predicted by the transfer function between 1,820 and 1,620 cal. years BP was not necessarily distinguishable by the stratigraphy alone due to its similarity to the silty-clays of the lower saltmarsh deposition, but was supported by the calcareous foraminifera species indicative of a tidal flat environment identified in this upper part of the sequence.

It would appear that the sediment lithology and multi-proxy transfer function indicate broadly similar palaeoenvironmental histories, but that there were some fluctuations and changes in the transfer-function derived indicative meanings that were not apparent in the interpretation based on the sediment lithology alone.

(c) Ecological and environmental sense

Pollen analysis has been carried out on parts of the Steart sequence by an undergraduate student at the University of the West of England (Walter, 2013). While the full Holocene sequence was not covered by this analysis, and the level of methodological rigour means that only 100 pollen grains were identified per sample, rather than the suggested 200 to 300 (Allen and Dark, 2008), the data collected broadly supports the transfer function-based palaeoenvironmental reconstruction.

Walter (2013) examined the pollen content of the second, third and fourth deepest organic units and the transitions to and from the minerogenic units either side. He found that typical native English woodland species *Quercus* (oak), *Pinus* (pine), *Taxodiaceae* (coniferous trees) and *Alnus* (alder) occurred throughout those sections reflecting the regional woodland

throughout the Holocene.

Beginning from the basal organic unit and working upwards, the base of the core was characterised by sedges, aquatic plants, ferns, mosses, plantain and bullrush species, indicating an open, wet environment (Pigott *et al.*, 2000). *Typha latifolia* occurred at the very base of the sequence and is a common wetland pioneer on silty/muddy substrates, and sometimes on saltmarshes (Pigott *et al.*, 1995). Freshwater pools were implied by the presence of *Potamogeton*-type pollen (Spencer *et al.*, 1998). Walter (2013) identified this as a coastal reed swamp environment. The pollen analysis coupled with the lack of correspondence between the diatom assemblage and the transfer function-derived palaeoenvironment (Section 8.6), as well as the absence of foraminifera, imply that the transfer function-derived palaeoenvironment is not accurate for his basal organic unit, as already discussed in Sections 8.5 and 8.6. Palaeo-sea-level may therefore be several metres lower than the transfer function predicted at this point.

The transition out of this basal organic unit saw an increase in *Plantago*, and the appearance of herbaceous species *Convolvulus arvensis*, *Galanthus*, *Reseda* and *Saxifraga*, and *Adiantum capillus-veneris* ferns. The accompanying decrease in aquatics suggests a transition from reed swamp to sedge fen.

The development of a saltmarsh environment was implied by the pollen content of the third deepest peat unit with the abundance of *Gramineae* and *Cyperaceae*-type pollen, and the presence of *Epilobium hirsutum* and *Chenopodiaceae* pollen at the upper boundary of this unit suggested that conditions were wet.

The pollen found in the second peat unit was indicative of reed swamp moving upwards into saltmarsh with *Caryophyllaceae*, *Equisetum* and *Ericaceae* giving way to *Cyperaceae*, *Polypodiaceae* and *Typha latifolia* towards to upper end of this unit.

With the exception of the basal peat, the pollen data were broadly in line with the palaeoenvironmental reconstruction based on the sea-level transfer functions. However, the data were limited and further pollen work, with larger samples sizes and greater chronological coverage would be beneficial.

8.8 Sea-level change in Bridgwater Bay

Broadly, Holocene sea-level at the Steart Peninsula site, as evidenced by the research carried out in this study, rose from about -12m OD 7,440 cal. years BP to 0.7m OD 2,000 cal. years BP. The initial rate of rise, and of sedimentation, was rapid, and began levelling off around 6,800 cal. years BP.

Three main periods occurred in which the marine influence decreased, which may be due to a difference in the direction of relative sea-level change, or to changes in relative biogenic vs minerogenic sedimentation rates, or to the evolution of shingle ridges, allowing higher marsh conditions to develop at the Steart site around 6,670-6,980, 5,805-5,290 and 4,410-3,660 cal. years BP. Throughout these periods mobile, marine planktonic diatoms continued to be deposited regardless of the nature of the intertidal environment, and despite the possibility of some of the Holocene sequence developing behind a shingle ridge, this suggests that the site continued to have some open access to the water throughout the mid-Holocene.

At Burnham-on-Sea Druce (1998) identified a similarly rapid period of sea-level rise slightly later in the Holocene sequence than seen in this study, perhaps reflecting the location of Burnham-on-Sea further into the estuary, or the possibility a more localised factor such as a breach of a shingle ridge at Steart giving a record of marine influence earlier in the sequence presented in this study. Silt deposition 2.7m thick was recorded by Druce (1998), between 6,455 and 6,130 cal. years BP. An average rate of deposition of 9mm per year at Burnham-on-Sea during this period is broadly similar but somewhat quicker than the rate of 7mm interpreted from the stratigraphy and age-depth modelling at Steart during the same period. This may be due to differing volumes of sediment available or to the growth of a shingle ridge at Steart reducing the influence of the open estuary at this time.

Figure 8.5 shows the four SLIPs established by Druce (1998), plotted with the sea-level reconstruction from this study. Druce (1998) used foraminifera, pollen and plant macrofossils to establish the indicative meanings of the SLIPs. The four SLIPs appear to indicate two periods of little or no sea-level change, between the oldest two SLIPs (7,210 and 6,450 cal. years BP) and between the younger two (6,130 and 5,525 cal. years BP). The reconstructions presented in this thesis suggest a gradual rise over this period, while Druce (1998) interprets the SLIPs as indicating a period of stable sea-level followed by rapid rise. The period between the oldest two SLIPs of Druce (1998) is not covered by samples with good or fair analogues from this study, meaning that it is not possible to state whether either scenario is the more likely. If the points with fair analogues around 6,400 to 6,300 are deemed reliable, the second oldest SLIP of Druce (1998) would imply an almost instantaneous sea-level rise of about 2.3m around 6,455 cal. years BP, which seems unlikely. This variation could be explained by the presence of barrier protection at Steart that was abruptly breached, increasing marine influence over a short time period.

There is greater agreement between Druce (1998) and this study between 6,130 and 3,525 cal. years BP, though the transfer function-based reconstruction suggests some fluctuation
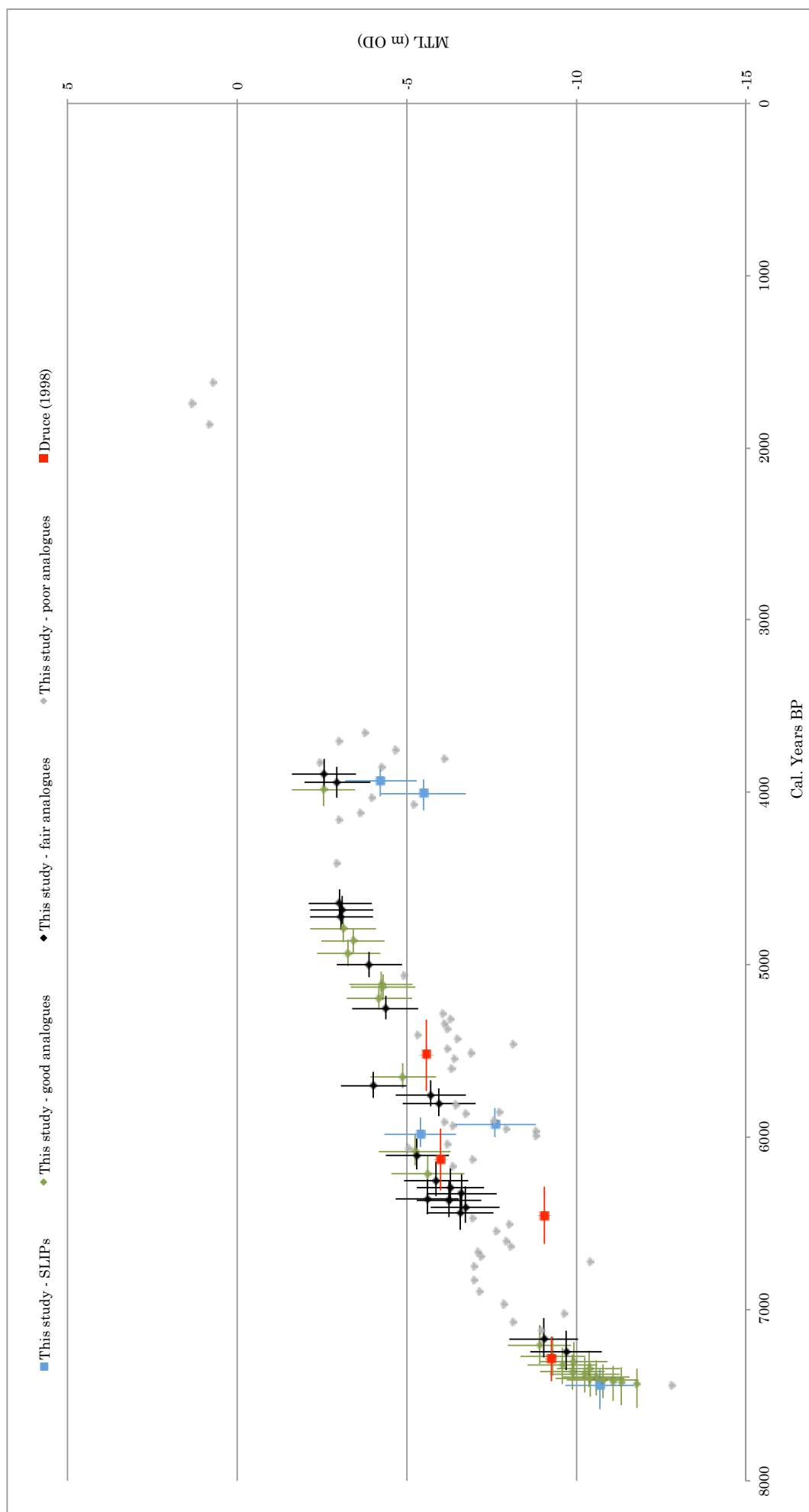
Figure 8.5: The transfer function-based reconstruction plotted with the four SLIPs established by Druce (1998) at Burnham-on-Sea. Estimates of vertical error are not available for the Druce (1998) data points, but are envisaged to be at least of the magnitude of those estimated in this study. Error bars for the poor analogue points in this study have been left off to avoid cluttering the plot

here, highlighting the increased level of detail that can be gained by using sea-level transfer functions to derive precise indicative meanings for many more data points.

Druce (1998) concludes that sea-level tendencies are the most reliable pieces of information available for sites such as Bridgwater Bay, where huge tidal ranges result in difficulties for sea-level reconstructions. This thesis shows that while there *are* certainly several significant issues that do make sea-level reconstruction in the Severn Estuary challenging, estimates of former sea-level can also be made, and that there is value in research in the macrotidal enviornment that works towards a clearer picture of Holocene environmental change in macrotidal regions such as the Severn Estuary.

Eleven data points from the Bridgwater Bay region published by Heyworth and Kidson (1982) were compared with the transfer function-based reconstruction (Figure 8.6). They are not referred to as SLIPs here because indicative meanings have not been assigned, so their relationships with sea-level are uncertain. The oldest data points, dated between about 8,170 and 7,730 cal. years BP form a continuation of the oldest points in the Steart Peninsula sequence, but suggest a less rapid phase of sea-level rise than is indicated by the intial 200 years of the reconstruction presented in this thesis.

Two index points around 7,150 cal. years BP suggest an almost instantaneous sea-level rise of over three metres. This highlights the disadvantage of having very few data points, because if the Heyworth and Kidson (1982) points are taken as a stand-alone data set, there are no other points around this period to help interpret what the pattern and magnitude of change was. Apparent jumps of two to three metres can be seen within the cluster of poor analogue samples immediately after the 7,150 cal. years BP points of Heyworth and Kidson (1982), but the overall trend in the data points from this study suggests a less abrupt sea-level rise during this period. Being able to distinguish between samples with good, fair and poor analogues is useful here, because the somewhat smoother course of sea-level change either side of the cluster of poor analogue samples suggests that large, instantaneous changes in sea-level in this section are unlikely, unless driven by a barrier breach.

There is general agreement with Heyworth and Kidson (1982) around 6,000 cal. years BP, followed by a data point with very large horizontal error bars (5,883 to 5,078 cal. years BP) that does not contribute much to our understanding of sea-level change in this period.

Around 4,000 cal. years BP the reconstruction is difficult to interpret. The SLIPs defined in the present study sit 1 to 2.5m below the other transfer function-based points, and the index point of Heyworth and Kidson (1982) is another 1.8m below again. Based only on the dated points, a steep fall in sea-level is implied, but the older of the two SLIPs from
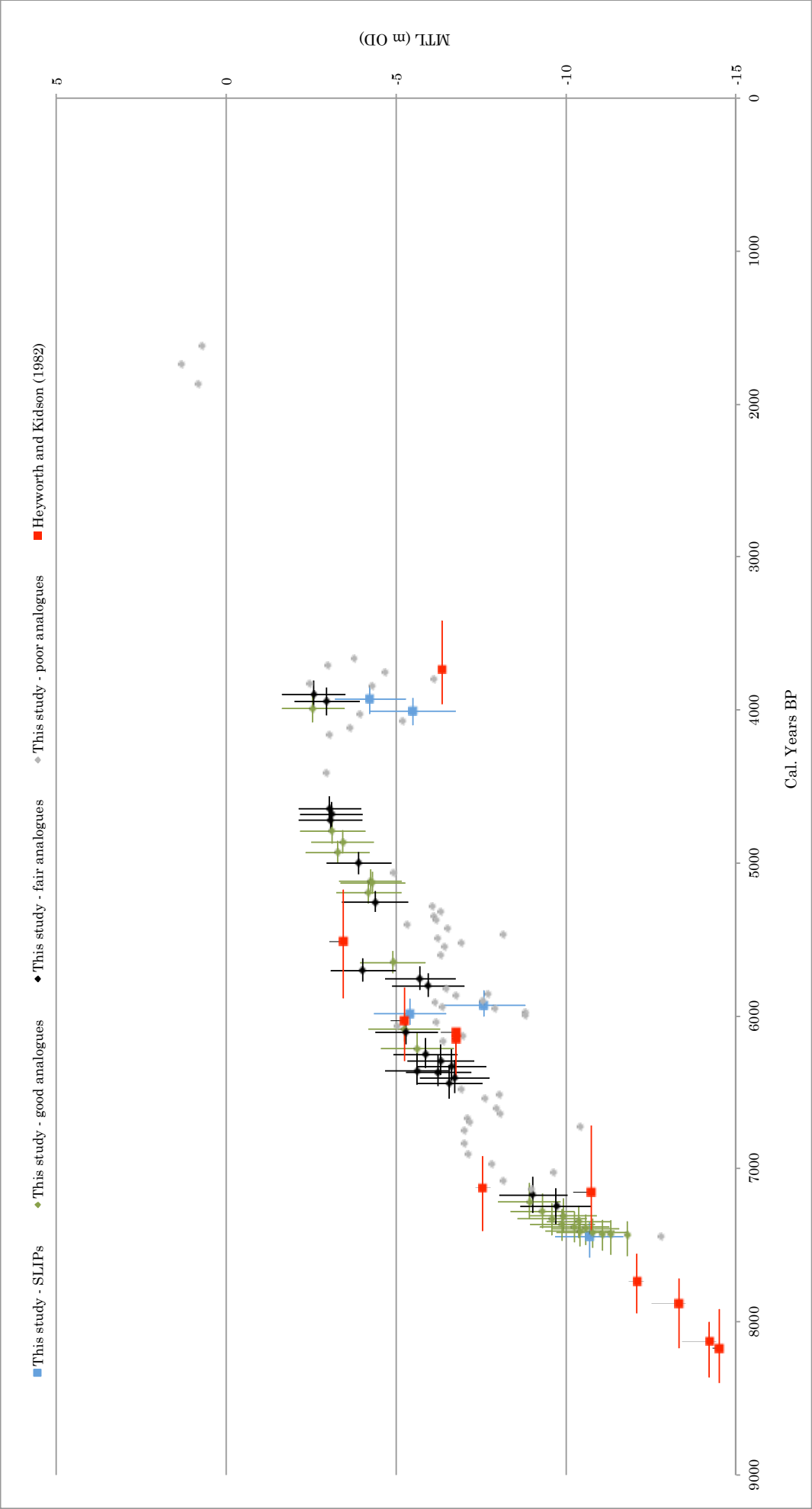
Figure 8.6: The transfer function-based reconstruction plotted with the ten sea-level data points established by Heyworth and Kidson (1982) in Bridgwater Bay. Estimates of vertical error are not available for the Heyworth and Kidson (1982) data points, but are envisaged to be at least of the magnitude of those estimated in this study. Error bars for the poor analogue points in this study have been left off to avoid cluttering the plot.

this study did not have good analogues in the modern microfaunal data, and the Heyworth and Kidson (1982) data point has not had its relationship with sea-level established using any biostratigraphy. Based only on the undated samples with good analogues, sea-level apparently rose slightly between 4,645 and 3,900 cal. years BP. No other studies provide sea-level data for Bridgwater Bay during this time, so verification from an independent source is not yet available. A tentative suggestion that sea-level fell during this period is made, based on the brackish foraminifera species leading upwards to a barren zone, indicating decreasing salinity over time, as well as a change in the diatoms from marine to marine-brackish and freshwater-brackish to a barren zone over time, and the development of a peat in the sediment stratigraphy.

The sea-level reconstruction of the Steart Peninsula sequence has contributed to the current understanding of Holocene sea-level change in Bridgwater Bay by providing five additional SLIPs, plus a further 98 age-depth modelled data points. Some gaps in the Holocene sea-level chronology for Bridgwater Bay have been filled, based on quantitative estimates of former environments from multi-proxy microfaunal samples with good or fair analogues (terminology as established in the Methodology (Chapter 4) in the modern intertidal estuarine environment, where species-height relationships have been modelled statistically. There remains a gap in the record of sea-level change in Bridgwater Bay from 3,660 cal. years BP onwards. Foraminifera data suggested that MTL was between -0.95m OD and 3m OD around 1,800 cal. years BP, but the large error bars mean that it is not possible to constrain this further with this data.

The Steart Peninsula sea-level reconstruction is discussed in the context of wider Severn Estuary Holocene sea-level and environmental change below in Section 8.9.

8.9   The wider Severn Estuary region

The reconstruction of sea-level from the Steart Peninsula sequence is plotted alongside Holocene sea-level data from previous studies from the region (Druce, 1998; Haslett *et al.*, 1998; Heyworth and Kidson, 1982; Hill *et al.*, 2007; Smith and Morgan, 1989) in Figure 8.7. With the exception of the 4,000 to 3,200 cal. years BP period and some points around 5,400 cal. years BP the variation in the data points on the vertical axis occurs within a range about three metres wide. While there is much variation in the data, the general pattern is of an initial rapid rise -13m OD to -5m OD between 7,440 and 5,650 cal. years BP, followed by a period of more steady rise to -2.5m OD 3,300 cal. years BP.

While there are some small fluctuations in the data between 6,600 and 3,900 cal. years BP they are within the magnitude of vertical error and cannot be resolved with any confidence as oscillations in absolute sea-level.

Since the Heyworth and Kidson (1982) curve was published other authors have established, based on the presence of peat-silt cycles in the Holocene estuarine alluvium, the presence of fluctuations in relative sea-level from sites at Redwick in the Gwent Levels (Allen, 2000c) and at Gordano in the Avon Levels (Hill *et al.*, 2007), as well as in Burnham-on-Sea in Bridgwater Bay (Druce, 1998) as discussed in the previous section (Section 8.8).

The earliest peat formation recorded at Steart in this study ended 7,480-7,330 cal. years BP. MSL was then estimated to be -10.7m OD by the multi-proxy transfer function. Therefore the majority of the post-glacial transgression had taken place by this time.

At Redwick in the Gwent Levels (see back to Figure 3.1 for a map of the Severn Estuary levels), forming in the northern margin of the Severn Estuary, the deepest peat recorded by Allen and Haslett (2007) was sampled from about 1m above a pre-Holocene head deposit, at -2.44m OD, and dated to 5,623-5,374 cal. years BC (about 7,620-7,370 cal. years BP). This is in contrast to the deepest peat sampled in this study, which was deposited at a similar time (7,440 to 7,435 cal. years BP), but was basal, and was situated -7.3m OD. Foraminifera analysis implied an upper saltmarsh environment during this period of peat formation at Redwick, with 100% *Jadammina macrescens* recorded in the sample of this peat unit (Allen and Haslett, 2007).

At both the Steart and Redwick sites deposition of estuarine clays followed the deeper peat formation, implying an increased marine influence on a regional scale around 7,500 to 7,350 cal. years BP, occuring on both sides of the estuary. Both this study and Allen and Haslett (2007) noted very low numbers of foraminifera following the initial peat formation, and when tests were preserved they were indicative of mud flat to mid-marsh environments in both cases, with the simultaneous occurrence of both calcareous species typical of a tidal flat environment, and agglutinated, saltmarsh dwelling species.

At the Gordano Valley, to the north east of the Steart Peninsula and west of Bristol, Hill *et al.* (2007) recorded a later incidence of marine inundation which occurred as clay deposition replaced peat formation 6,820-6,670 cal. years BP. This suggests that the Gordano Valley may have been more sheltered that the Steart Peninsula from the direct influence of the estuary during the early- to mid- Holocene than the Steart Peninsula. The orientation of the Gordano Valley, stretching WSW to ENE, parallel to the estuary, and its present day position behind the coastal Carboniferous limestone rigdge (Bridle, 2012), differs to the aspect of the
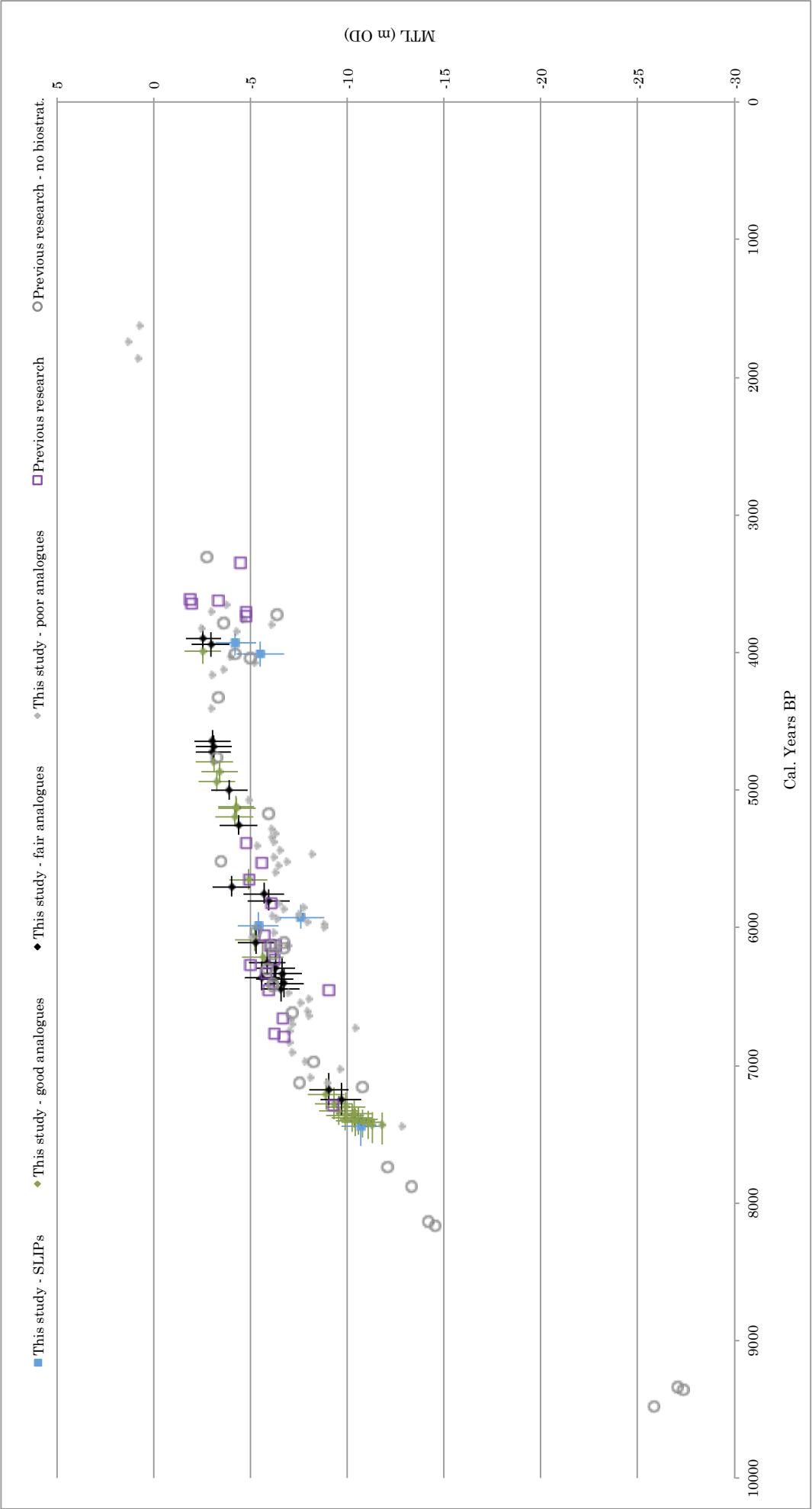
Figure 8.7: The transfer function-based sea-level reconstruction plotted alongside sea-level estimates for the Severn Estuary region from Druce (1998), Haslett *et al.* (1998), Heyworth and Kidson (1982), Hill *et al.* (2007) and Smith and Morgan (1989). To avoid cluttering the plot, error bars have been left off the poor analogue points and the points from other studies.

Steart Peninsula, where the low-lying spit openly faces the estuary with less protection at present.

Similar to the deepest peat found at Gordano, the deepest Holocene peat at Goldcliff in the Gwent Levels, to the west of the Redwick site on the Caldicot Level, is recorded between 6,650 and 6,350 cal. years BP (Smith and Morgan, 1989). At Redwick an additional three cycles of peat to clay overlapping occurred between 7,200 to 6,350 cal. years BP (Allen and Haslett, 2007). This is in contrast to the long periods of uninterrupted clay deposition that occurred from 7,480-7,330 to 6,270-6,000 cal. years BP at Steart and from 6,870-6,670 to 6,180-5,930 cal. years BP at Gordano. This suggests a more localised influence at Redwick, such as a greater degree of protection from the open estuary, allowing peat to develop, causing a frequently changing environment of deposition in the early- to mid-Holocene.

Allen and Haslett (2007) interpret this sequence as a combination of local and regional drivers superimposed onto the more general gradual rise in MTL. The deepest peat at Redwick is thought to be a result of an interval of very slow sea-level rise, while the second, third and fourth peats occurred due to rapid sedimentation in relation to sea-level rise, effecting periods of relative regression as the marine influence lessened during these periods, although the overall direction of sea-level change was positive or, at times, virtually static (Allen and Haslett, 2007).

The second-deepest peat recorded at Steart, deposited between 6,270-6,000 and 5,900-5,610 cal. years BP signifies a decline in marine influence and the micropalaeontology implies a marine-brackish to brackish environment of deposition at this time.

At Burnham-on-Sea Druce (1998) presents two thin (1-2cm thick) peat layers deposited at 6,270-6,410 cal. years BP and 5,520-5,660 cal. years BP. The lower of the two coincides with the lower boundary of the deepest intercalated peat unit at Steart (this study), while the upper is at the latest chronological extent of that Steart peat. Druce (1998) found some evidence of erosion at the upper boundary of this upper peat, implying that an unknown period of further peat deposition may have occurred beyond 5,520-5,660 cal. years BP.

The presence of organic silt between the two thin peats at Burnham-on-Sea is interpreted by Druce (1998) as evidence of a period of positive sea-level tendency and mid- to high-marsh conditions, based on the foraminifera and pollen content of that unit and the thin peats above and below. However, it is possible that a localised marine incursion took place, that did not occur at the Steart site, perhaps due to the former presence of a shingle ridge at Steart that provided some protection at this time (Haslett, 2010), or to the breaching of barrier protection at Burnham-on-Sea.

At Gordano an intercalated peat deposited between 6,180-5,930 and 5,710-5,590 cal. years BP is coincident with the deepest intercalated peat at Steart, which further supports the notion of a regional decrease in marine influence during this period due to the additional protection at Gordano by the coastal ridge.

At Goldcliff Smith and Morgan (1989) identify an uninterrupted peat unit deposited between 6,100 and 3,500 cal. years BP, commencing around the same time as the peat deposition at Steart, Burnham-on-Sea and Gordano, but without the resurgence of more marine conditions later, implying that Goldcliff had a greater degree of barrier protection than sites in Bridgwater Bay during this period. Based on the stratigraphy and pollen and plant macrofossil analysis Smith and Morgan (1989) interpret the long peat unit as a cessataion of marine inundation followed by a sequence from bottom to top of reedswamp, then *Cladium*-dominated fen, reedswamp, *Sphagnum* raised bog and finally further reedswamp development before the return to estuarine conditions at 3,500 cal. years BP.

At Redwick, following the aforementioned cycling of peat-clay deposition between 7,200 and 6,350 cal. years BP, a further peat unit is seen later, deposited between 5,900-5,550 and 3,850-3,500 cal. years BP (Allen and Haslett, 2007). This is in contrast to what was found at Steart, with peat deposition there ending (5,670-5,900 cal. years BP) just as it begins at Redwick (5,900-5,500 cal. years BP). This implies that localised factors contributing to the environment of coastal deposition were overriding within the region at this stage lending support for the continued study of Holocene sea-level at other sites in the region, in order to distinguish where local factors cause the sea-level record to diverge from the regional trend (Allen, 2000c).

The middle of the three intercalated peats at Steart does not have associated radiocarbon dates, therefore, it may only be inferred that this organic unit was deposited at some time between 5,670-5,900 and 4,010-4,240 cal. years BP. Dates derived from smoothing spline interpolation age-depth model (Section 7.2 of Chapter 7) estimate that this organic deposition occurred from 5,386-5,525 to 5,315-5,455 cal. years BP, however, this estimate does not account for the autocompaction processes likely to have affected this organic unit post-deposition. During this time peat deposition continued to occur at Redwick and Goldcliff in the Gwent Levels and at Gordano in the Avon Levels. The relatively thin organic layer at Steart in comparison to the other sites implies that a local marine incursion or barrier breach occurred here, either due to a change in sea-level, another, non-sea-level related event such as sustained high water during storm surge activity, or a change in the sediment supply to the spit.

Deposition of the uppermost organic layer recorded at Steart began 4,010-4,240 cal. years BP. The final marine incursion signified by the return to estuarine clay 3,720-3,900 cal. years BP is coincident with a marine incursions at Redwick 3,850-3,500 cal. years BP, Goldcliff ~3,500 cal. years BP, Gordano 3,840-3,640 cal. years BP and further inland at Nyland Hill (3,725-3,465 cal. years BP and Godney to Glastonbury (cal. 2,950-3,860 years BP), implying a period of regional sea-level rise at this time.

The presence of tidal flat foraminifera species resulted in low indicative meanings predicted by the transfer function between 1,860 and 1,620 cal. years BP. Where previously the minerogenic saltmarsh conditions have kept pace with the rate of sea-level rise, the presence of tidal flat deposits suggests a fast or sudden deposition event. Without knowledge of what took place before this point, it is difficult to place this event in any context.

Embankment and draining of the Somerset Levels began in the Roman period (43 to 410 AD) (Williams and Williams, 1992), which is around the time that the tidal flat species are recorded at Steart, just before the biostratigraphic sequence ends. It is thought that Roman activities did take place at the Steart Peninsula (Wessex Archaeology, 2012), though the archaeological research of the Roman period at Steart has not yet been formally published (Baker, 2012; Wessex Archaeology, 2012). Preliminary findings by Wessex Archaeology suggest that human land reclamation began at the Steart Peninsula before 1,100 AD (Baker, 2012).

8.10   Limitations

There are two important limitations in reconstructing former sea-levels from soft sedimentary deposits cited by Holocene sea-level researchers; autocompaction (Haslett *et al.*, 1998; Edwards, 2006) and Holocene tidal range changes (Gehrels *et al.*, 1995; Shennan and Horton, 2002). Both of these issues are relevant here, but neither is yet fully understood in the context of sea-level reconstruction.

8.10.1   Sediment autocompaction

Outlined in Section 2.7 as a potential source of error, autocompaction is a relevant but, as yet, unquantifiable limitation to the reconstruction of Holocene sea-level at the Steart Peninsula, potentially lowering SLIPs from their position at deposition and causing the long term rate of sea-level rise to be overestimated (Long *et al.*, 2006).

Massey *et al.* (2006b) applied geotechnical corrections to a Holocene back-barrier sequence in south Devon, UK, in an attempt to decompact the sequence. They concluded that organic-

rich sediments undergo the most post-depositional compaction, up to 2.2m for their 10-15m Holocene sequence, and that minergenic sediments situated above basal facies undergo little compaction. Vertical displacement of intercalated organic and minerogenic sediments tended to decrease with depth, related to the impact of sediment overburden. Massey *et al.* (2006b) concluded that most sea-level studies underestimate the effects of autocompaction, particularly where SLIPs are established from intercalated peat-clay boundaries.

For sites on Romney marsh in southeast England Long *et al.* (2006) present a model of differential peat compaction to explain the late Holocene landscape. They demonstrate that same aged SLIPs from the surface of a laterally persistent late Holocene peat varied in height by up to 3m, with the lowest surfaces found above compressible minerogenic sediments. Pollen, foraminifera and grain size analyses suggested that an increase in water depth, due to a barrier breach, resulted in the deposition of tidally laminated sediments, with accommodation space provided by the compression of the thick peat.

Based on the discussion above, vertical displacement of 2-3m should not be ruled out for the four intercalated SLIPs presented in this study, with the compaction of the intertidal peats creating accommodation space for the deposition of highly mobile estuarine silts and clays. The basal SLIP is unlikely to have been lowered post-deposition.

Researchers at Durham University are developing a framework for the decompaction of Holocene intertidal sediments (see Section 2.7) which might ultimately allow for the routine correction for autocompaction in sea-level studies, based on LOI and SWLI (Brain *et al.*, 2011, 2012). In the future the resulting framework might be applicable to the Holocene sequences of the Somerset Levels.

8.10.2   Holocene tidal range changes

While the reconstruction of indicative meanings and of SWLI are assumed to be fairly robust, taking into account the sources of error already discussed, such as dating errors, modern analogues, transfer function prediction error and so on, the actual values of palaeo-sea-level calculated from these indicative meanings and the present-day elevations of sampling points are based on the assumption that the local tidal range has not changed over the course of the Holocene (Gehrels, 1999).

Drainage and embankment of the Somerset Levels in the Roman period and more extensive reclamation of the coastal alluvial marshes from the Medieval period onwards would have had significant effects on the intertidal environment and the tidal prism (Rippon, 2006). Intertidal mudflats and saltmarshes were transformed into agricultural land by Roman-British

and Medieval communities who embanked previously unprotected coastal areas and the major tidal rivers and constructed drainage systems on the clay belt (Williams and Williams, 1992). Displacement of saltmarshes and tidal flats within the tidal prism due to land reclamation, decreasing water depth and salinity and shifting and squeezing the intertidal habitats seaward, would directly affect attempts to reconstruct MTL from the preserved sediments that represent those past palaeoenvironments. Therefore, caution was applied when interpreting the results for the late Holocene.

Attempting to estimate any possible tidal range changes over the Holocene is a difficult and lengthy process, and until a robust method of doing so is established, most authors tend to refer to this issue as a limiting factor but do not attempt to correct for it. Trying to estimate the magnitude of potential tidal ranges in the Severn Estuary over the Holocene would be a large undertaking, and is well beyond the scope of this particular study, but would be a useful subject for future research on Holocene sea-level in the region. In terms of this study and its place within the body of existing research in the region, by not attempting to correct for possible Holocene tidal range changes, consistency is maintained with those previous studies.

While there can be confidence in the palaeoenvironments estimated by the transfer function-based reconstruction of the Steart Peninsula, the actual magnitude of change may well be under- or over-estimated, depending on what changes in the tidal range have taken place in the Severn Estuary over the last ~7,440 years.

8.11   Future research possibilities

The research into the modern distribution of biological sea-level indicators in the intertidal zone, the development of single- and multi-proxy sea-level transfer functions and their application in a severely macrotidal environment, as well as the palaeoenvironmental results from the Steart sedimentary sequence have revealed some areas for further research. Some of those have been mentioned in the preceding chapters, but they are drawn together here prior to the final conclusions.

8.11.1   Regional training sets for the Severn Estuary

An extra-local approach (Wilson and Lamb, 2012) to contemporary data collection for the training sets was implemented in this study, in order to take in the full range of intertidal environments in the unique setting of the extremely macrotidal Severn Estuary.

While a fair to good analogue situation between fossil and modern assemblages was revealed in the diatom and multi-proxy data sets, each fossil sample did not have a perfect modern counterpart in the training sets. The fossil foraminifera data in particular suffered from poor analogy with the modern training set, which itself had a large gap in the middle of the gradient. While the same species of foraminifera were found in the modern and fossil assemblages, their relative proportions were very different.

Other researchers have found that where local or extra-local training sets do not provide a satisfactory level of analogy with fossil data, adding regional data to the training set can reduce the dissimilarity of the closest modern analogues to fossil assemblages (Horton and Edwards, 2005; Wilson and Lamb, 2012).

Sites at the Gwent Levels have revealed promising diatom (Hill *et al.*, 2007) and foraminifera (Allen and Haslett, 2002) zonation and an investigation into building up regional Severn Estuary training sets might improve on the analogue situation found in this study.

Wilson and Lamb (2012) warn of the sometimes site-specific nature of diatom species and assemblages, where local factors apparently exert greater control on diatom ecology than is apparent for foraminifera, as implied by the ordination (CCA) analysis in Chapter 5 of this study. An investigation into the modern intertidal diatom variation within the Severn Estuary region might precede a focus on regional diatom-based and multi-proxy transfer function development and application.

8.11.2 Recent sea-level reconstruction

One of the major research themes within the sea-level community is the reconstruction of recent (19th to 20th century) sea-level change in order to test transfer functions against tide gauge data and effectively extend back observational records to pre-industrial times and test the hypothesis that the rate of sea-level rise in many parts of the world has accelerated since the industrial revolution due to greenhouse warming and the associated effects of atmospheric warming on global and regional sea-level (Gehrels, 2000; Gehrels *et al.*, 2002, 2008, 2012; Kemp *et al.*, 2009c; Rossi *et al.*, 2011; Woodroffe and Long, 2010). This approach is also used to evaluate the accuracy of transfer functions.

While this approach has been particularly successful on micro- and mesotidal coasts, the errors associated with recent sea-level hindcasting in macrotidal estuaries may be larger than the magnitude of change on decadal timescales. However, Barlow *et al.* (2013) encourage the study of macrotidal estuaries in order to contribute to the spatial coverage required to investigate the drivers of recent sea-level change. The application of single and multi-proxy

transfer functions to short cores from the Rumney, Awre and Northwick marsh formations and the use of short term dating techniques such as ^{210}Pb radiometric dating, bomb spike and geochemical analyses might allow for tests of corroboration of transfer function reconstructions against tide gauge records to be made in the Severn Estuary, and potentially improve our understanding of more recent sea-level change.

The distribution of testate amoebae assemblages across the intertidal zone has not been investigated in the Severn Estuary, but has been shown elsewhere to display strong zonation in upper marsh environments (Charman *et al.*, 2002, 2010; Gehrels *et al.*, 2001, 2006a) and may provide an additional source of evidence for the reconstruction of recent sea-level change in the Severn Estuary region.

8.11.3   Late Holocene sea-level reconstruction

A gap in both the diatom and foraminifera record between ~3,660 and ~1,860 cal. years BP occurs where numbers of both proxies is extremely low. The mean average number of foraminifera tests per 2cm^3 in this section of the sequence is just 24 and diatom numbers are very low both in this section and above it, with an average count of 25 per microscope slide.

The diatoms that do occur in this section are mainly marine species *Paralia sulcata* and *Pseudopodosira westii*, but as seen in the modern training set, these two species are fairly ubiquitous throughout the intertidal zone, meaning that no particular palaeoenvironment can be inferred with confidence.

Diatoms are subjected to taphonomic procresses before, during and after their incorporation into sediments (Flower and Ryves, 2009), such as grazing by invertebrates, dissolution and pH and temperature changes. Recycling of biogenic silica is a key biogeochemical process that will occur after the death of diatoms where the surrounding water is below the satuation concentration of dissolved silica (Flower and Ryves, 2009; Loucaides *et al.*, 2012).

Bidle and Farooq (1999) have shown that rates of marine diatom dissolution by bacteria are dependent on diatom type and bacterial assemblage, while Flower and Ryves (2009) state that pH, sedimentation rate, salt concentration and the temperature of the surrounding environment are also important in saline lakes, and that poor preservation is linked with low diatom count. Ryves *et al.* (2001) demonstrate marked differences in species susceptibility to dissolution by bacteria, leading to biased assemblages of diatoms in lake sediments.

Smetacek (1999) identified the ability of bacteria to break down a diatom's protective organic outer layer as a key factor in whether its silica will be recycled into the system. Experiments by (Moriceau *et al.*, 2007) showed that aggregated diatoms sink more rapidly

through the water column and are dissolved at slower rates than freely suspended diatoms, and Loucaides *et al.* (2012) note that while in the open ocean there is plenty of time for bacteria to access the diatoms as they sink to the ocean floor, in shallow waters, such as tidal flats and saltmarshes, diatom frustules are more likely to reach sediments with the organic layer intact, reducing their likelihood of dissolution.

This study has revealed that differential diatom preservation may have occurred at three main places in the Steart Peninsula Holocene sequence and further research might attempt to quantify potential dissolution rates in the estuarine sediments.

The foraminifera in this particular section of the sequence are mainly calcareous *Elphidium williamsoni* and *Haynesina germanica*, with some higher marsh species *Jadammina macrescens* and *Trochammina inflata*, suggesting perhaps a transition environment between the higher marsh environment signified by the assemblages below the missing zone and the tidal flat environment implied by those above it.

The preservation of intertidal foraminifera is usually discussed in the context of the dissolution of calcareous forms in low pH, organic saltmarsh sediments (Edwards and Horton, 2000; Gehrels *et al.*, 2001; Kemp *et al.*, 2009a; Leorri *et al.*, 2010; Callard *et al.*, 2011). It is possible, then, that during this transition period from high marsh to tidal flat, rising sea-level brought tidal flat species upwards onto the more acidic saltmarsh surface, causing them to be poorly preserved in the fossil record, until tidal flat sediments were deposited that provided the right conditions for the preservation of calcareous tests.

A further investigation into this period might include the collection of additional core material so that larger samples of foraminifera might be analysed. Techniques using sodium polytungstate are available that concentrate diatom frustules together (Ruhland *et al.*, 1999; Lippiatt, 2005), and those could be implemented here, to potentially provide a fuller account of the nature of sea-level during this transition period.

8.11.4   Testing transfer functions at other modern sites

Many sea-level researchers rely only on the prediction statistics of their transfer functions to test their success. Others look to the level of similarity between fossil and modern assemblages, as in this study, to judge whether a model will calculate acceptable estimates of former sea-levels from fossil sediments, and evaluate results against existing knowledge of their site and chosen proxy or proxies.

There is only one example in the sea-level literature of an attempt to test a transfer function by using it to predict real, measureable SWLI/elevation at a separate modern site,

from its microorganism surface sediment ecology (Charman *et al.*, 2010). This was part of a study of testate amoebae, but has not been done with diatom or foraminifera data sets, but in doing so one could test a model on a full data set, rather than relying only on cross validation techniques that sub sample within the training set and attempt to predict values from samples that cannot necessarily be shown to be statistically independent of the rest of the training set (Birks *et al.*, 2010).

Many existing modern training sets have the potential to be tested against one another. Methodological differences between studies may occur, such as the live/dead/total foraminifera assemblages debate, and differing sample sizes, and the apparent site-specific nature of some diatom assemblages may cause some sites not to be directly comparable, but an investigation into this approach as a possibility would help to judge how much confidence we can have in the prediction powers of ecological sea-level transfer functions.

8.11.5   An improved Holocene chronology for the Steart Peninsula

There are certain limitations to the chronology established for the Steart Peninsula in this study. The situation and thinness of the organic units in the sequence means that the radiocarbon dated samples are very unevenly spaced, and the non-basal samples are paired closely together. A more complete chronology might be developed to reduce temporal error by the use of additional dating methods.

Firstly, there are two further radiometric techniques that may be suitable. Lead-210 dating is based on determining the ratio of ^{210}Pb to ^{206}Pb present in sediments (Lowe and Walker, 1997). The method is suitable for sediments deposited in the last 100 years so is at the very margins of the timescale considered in this study, but has been successful in many studies of late Holocene sea-level change (Charman *et al.*, 2010; Gehrels *et al.*, 2006b, 2012; Kemp *et al.*, 2009a).

Caesium-137 dating is also used in some studies of late-Holocene sea-level change (Cearreta *et al.*, 2008; Gehrels, 2000; Leorri *et al.*, 2008). ^{137}Cs has only occurred in significant quantities since 1945 when thermonuclear weapons testing began (Lowe and Walker, 1997) and dates of known discharges of ^{137}Cs can be used to date spikes in the radionuclide and constrain Lead-210 dates (Marshall *et al.*, 2007). There is some concern about the post-depositional migration of caesium (Harvey *et al.*, 2007), so the Caesium-137 dating method is normally using in conjunction with others.

A further possibility is the use of geochemical analysis to provide estimated dates of deposition for estuarine sediments, with markers such as the peak in lead prior to the legislation

around the use of leaded petrol in the 1970s in the UK and signals from historic mining (Pirrie *et al.*, 2002; Price *et al.*, 2005; Rollinson *et al.*, 2007) and other industrial and post-industrial processes (Allen and Rae, 1986; Grant and Middleton, 1990).

For older Holocene sediments that are lacking in organic matter or pure carbonates, and hence are not suitable for radiocarbon dating, luminescence dating might be appropriate (Oldfield, 2005). Electrons emitted during radioactive decay become trapped in dense minerals such as quartz and feldspar and the intensity of light emited by minerogenic material upon heating is an indication of the quantity of electrons trapped since the material was last exposed to light. An estimate can then be made of the time that has passed since deposition (Lowe and Walker, 1997). In a comprehensive review of studies into luminescence dating of marine and coastal sediments, Jacobs (2008) found very few that dated estuarine and tidal flat deposits compared to the number of studies of beach, foredune, aeolianite and tsunami deposits.

Plater and Poolton (1992) showed that photoluminescence and thermoluminescence dating can reveal important information about the depositional history of coastal sediments and associated sea-level tendency and storm surge activity. Combining luminescence dating with radiocarbon dating and diatom analysis they derived a sea-level history from a 1.7m estuarine silty-clay core from the Tees Estuary, UK. Later Bailiff and Tooley (2000) used infra-red-stimulated luminescence (IRSL) dating to produce ages broadly consistent with radiocarbon dates for a Holocene sequence from the Fenlands, UK. Jacobs (2008) concludes that while luminescence dating has previously lacked the precision of radiocarbon dating, recent progress now means that accuracy and precision are increasing, and recommends that large, systematic studies are required before luminescence dating of coastal and marine sediments can rival established methods.

Finally, it may be possible to obtain radiocarbon dates from the tests of calcareous foraminifera found in the minerogenic sediments. Radiocarbon dating laboratories generally require samples weighing 10-20mg (Beta Analytic, 2014). The preparation required for this is time-consuming and the collection of enough foraminifera for such a sample size may not always be possible, depending on test availability within the core sediments. Recent developments in the use of AMS systems fitted with gas ion sources (Wacker *et al.*, 2013; Ruff *et al.*, 2007) may eventually mean that radiocarbon dates can be produced from single foraminfera tests. Wacker *et al.* (2013) were able to date a single 560μg *Cibicides pseudoungerianus* test, suggesting that in future dating foraminifera tests may be a more accessible process.

Chapter 9

Conclusions and implications

This chapter summarises the key findings with respect to the original aims and objectives and makes recommendations for the field of quantitative sea-level reconstruction and for future Holocene environmental research in the Severn Estuary region.

The first aim was to develop single and multi-proxy sea-level transfer functions for the macrotidal Severn Estuary region. This was met via the first three objectives. Two single-proxy training sets were created from samples collected between MTL and HAT from two intertidal sites in the Severn Estuary; a diatom training set composed of 71 samples and a foraminifera training set composed of 23 samples. The foraminifera training set was smaller due to a low density of tests between SWLI 0.671 and 0.873 (2.3m and 4.5m OD) and above SWLI 0.954 (5.8m OD). Cluster analysis revealed four distinct diatom zones and two foraminifera zones.

Multivariate analysis showed elevation within the tidal frame to be a significant factor in the composition of the assemblages of both microorganism groups, but of more importance to the intertidal variation in foraminifera. This finding was borne out in the prediction statistics of the resulting single-proxy transfer functions produced from the data, with r^2_{boot} and RMSEP values from the foraminifera data consistently better in all of the different models analysed.

Three groups of multi-proxy transfer functions were produced from the combined data, differing in the way that the two datasets were merged together. The best prediction statistics were for model A which used only the 23 samples which had acceptable counts of both proxies. However, this transfer function was not satisfactory given the substantial gaps between SWLI 0.671 and 0.873 and above SWLI 0.954. Prediction statistics for models B and C were very similar but model C was ultimately discarded because it relied on low numbers of foraminifera for many samples. It is recommended that in future studies where two proxy training sets are merged, method B should be used, where samples with sufficient counts in at least one proxy

are used, but low counts in the other proxy are not. In the case of this study this meant the diatom data were fully maximised while low counts of foraminifera in some samples were excluded.

The chosen model, using WA-PLS with two components, gave an r^2_{boot} value of 0.76 and RMSEP of 0.08 SWLI units (0.98m). Error values of this magnitude are not unexpected in the extremely macrotidal environment of the Severn Estuary (Hill *et al.*, 2007).

To fulfill the second research aim the selected multi-proxy transfer function was applied to samples from an 11.22m core from the Steart Peninsula. The core's stratigraphy was typical of many Holocene coastal sequences in the British Isles, with a thin basal peat overlain by over 11m of estuarine silty clays, intercalated by three thin organic units.

Analogue matching analysis revealed that the fossil diatom assemblages were better represented in the modern training set than the foraminifera. When the two proxies were combined the degree of analogy between the fossil and modern assemblages increased, indicating one of the benefits of analysing diatom and foraminifera data in combination. The lower 3m and upper 4m had more samples with closer modern analogues than the middle section. This was with the exception of the samples from the basal peat and the three uppermost samples, which were not well matched to any of the training set samples. In particular the transfer function prediction of a tidal flat environment for the basal peat did not make ecological sense and was rejected, with an alternative interpretation of a brackish lagoon environment made from the stratigraphy and diatom assemblages.

A methodological issue was raised during the analogue matching. The method applied required species abundance data to be converted to proportions. It would not have made sense to add the counts for all species of both proxies together and take proportions of the totals because the diatom data was more species-rich and sample sizes were generally larger. Instead, to preserve the distinct nature of the two microorganism groups proportions were taken for each proxy separately so that they summed to 2 instead of 1 overall. It is recommended that this approach is taken in future research where proportions are required for an analysis involving more than one multivariate dataset, rather than the more simplistic approach taken by (Kemp *et al.*, 2009a) that necessarily implies some unrealistic interdependence between proxy groups.

Data scatter and large vertical error bars prevented a detailed interpretation of Holocene sea-levl change to be made from the results of the transfer function. Broadly, an initial rise in MTL from -12m OD 7,582-7,345 cal. years BP to -5m OD 5,720-5,573 cal. years BP was followed by a period of more steady rise to -3m 4,034-3,852 cal. years BP. After this

date the only data available gave a MTL prediction of 0.9m±1.7m OD around 1,800 to 1,700 cal. years BP. Between 6,188-6,007 and 3,942-3,759 cal. years BP three main fluctuations in marine influence were implied by the transfer function and stratigraphy.

Vertical scatter in the data tended to be lower and error bars smaller where modern analogues were closer, but despite the better precision in some parts of the reconstruction, the apparent vertical fluctuations cannot be interpreted as anything more than changes in marine influence.

The new sea-level data provides broad information on the nature of the environment in the mid-Holocene at Bridgwater Bay, including data for the period 5,000 to 4,000 cal. years BP which was previously unavailable. In combination with research from other parts of the Severn Estuary the data imply that local factors influencing the intertidal environment were superimposed onto the regional drivers throughout the early to mid-Holocene.

In this instance the time spent analysing two tidal level proxies was beneficial because the high precision of the foraminifera and the good intertidal coverage of the diatoms combined to create a transfer function whose prediction statistics were at least as good as previous single-proxy studies, after taking the tidal rnage into account. Indeed, if the foraminifera training set could be improved in terms of modern analogues and density of tests, by sampling at other sites regionally or using a larger volume of material per sample , the need to use diatoms might be negated completely. The prediction statistics for the foraminifera transfer function in this study were better than the equivalent for the diatom and multi-proxy transfer functions, so it is recommended that future sea-level transfer function-based research in the Severn Estuary should concentrate on foraminifera in the first instance.

However, this study has shown that for the macrotidal Severn Estuary there are overriding sources of uncertainty that need to be reduced before a more precise sea-level history can be constrained. The most significant issues are the potentially powerful but currently unquantifiable effect of sediment autocompaction, possible Holocene tidal range changes and the lack of data, including dates, for the late Holocene. Recommendations for further research to address these issues were made in Section 8.11 of Chapter 8, and only after progress is made with those issues should research concentrate on finessing the multi-proxy transfer function for the Severn Estuary.

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