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Holocene sea-level changes in the Bristol Channel - Evidence from Porlock, Somerset, UK

Thomas Lawrence

Project Advisor: Roland Gehrels, School of Geography, Earth & Environmental Sciences, University of Plymouth, Drake Circus, Plymouth, PL4 8AA

Abstract

The surface distribution and elevation of contemporary intertidal foraminifera can be used as modern analogues to reconstruct former sea levels based on fossil foraminifera assemblages. A transfer function for southwest tide level is applied to fossil foraminiferal assemblages within a sediment core from Porlock Marsh, Somerset, U.K., in order to produce quantified altitudes of palaeo-sea level ('indicative meanings'). The indicative meanings of fossil foraminifera are compared to the altitudes of two previously published Holocene sea level index points from Porlock. The indicative meanings of fossil foraminifera are also used to provide a palaeo-environmental history of Porlock Marsh. The reconstruction is compared to a palaeo-environmental history previously provided by fossil diatom analysis. Results indicate that the palaeo-environmental history provided by foraminiferal indicative meanings correspond well to the previously published reconstruction provided by diatoms. When comparing the indicative meanings of foraminifera-based sea level index points with two sea level index points taken from intercalated peat layers, only one displays a clear match with regard to elevation. Biostratigraphic analysis has unveiled that the transgressive overlap of the highest intercalated peat bed within Porlock Marsh is eroded. Sea level index points previously taken from the upper transition of the intercalated organic layer should be discounted as 'limiting' before being verified by biostratigraphic analyses. The discovery of salt marsh foraminiferal assemblages in the transitions of the lower intercalated peat layer has shed light on the potential creation of two new sea level index points that are possibly early-Holocene in origin. The foraminifera sea level chronology indicates a relative sea level rise of 3.87m since 6383-6033 cal. yr BP. The successful utilisation of a foraminifera-based transfer function for tide level has demonstrated its regional relevance and applicability.

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1. Introduction

1.1 Sea level science

The measurement of sea-level change across various spatial and temporal scales has been a prime focus of scientists for over a century. Coastal change as a consequence of future sea-level rise is one of the major challenges facing policy makers and environmental managers (Edwards, 2006). A recent projection, detailed in the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC), predicts a rise in global absolute sea level of up to 88cm by 2100 (Church *et al*., 2001). This bears important implications for the world's coastal population, with up to 25% currently residing within 100km of the sea (Small and Nicholls, 2003). Additionally, a further increase in pressures placed upon the coast, associated with the projection of global population rise over the coming decades, will inevitably serve to intensify the impacts of future sea-level rise (SLR).

In compliance with the projections outlined by the IPCC TAR (2001) report, Church and White (2006) documented a global rise in mean sea level (MSL) from January 1870 to December 2004 at an annual rate of 1.7 ±0.3 mm yr^{-1} and observed a 20th Century acceleration in the rate of sea-level rise. However, these projections are of limited use on national scales as they fail to consider changes in regional sea level values which differ from the global average. These regional variations in sea-level change occur due to the complex interplays between isostatic, geoidal and oceanographic behaviours. Shennan and Horton (2002) determined the relative rates and directions of land movement for the UK and discovered spatial variability. It is therefore important to study the changes in relative sea level (RSL) that have occurred during the Holocene in order to determine the rate and direction of RSL change, specific to a given location. It is from the results of these detailed regional sea level reconstructions that future coastal management strategies can be implemented and tailored to a given location, not from global sea level estimates combined with information on land movements, changes in tidal range and storm surges (Gehrels and Long, 2008).

Sea level studies up until the late 20th Century have traditionally used tide-gauge measurements to reconstruct changes in RSL. However, the applications of tide-gauge records in RSL studies are spatially and temporally limited. The records also exhibit a strong bias towards the northern hemisphere whereby data readings become sparser as the records extend back in time (Nerem *et al*., 2006). These factors hold negative implications for the clarity of data that can be extrapolated, and tide-gauge data have since been popularly used as a way of assessing the validity of new approaches, by directly comparing the results with classical tide-gauge records (e.g. Engelhart *et al*., 2009; Gehrels, 2000; Gehrels *et al*., 2005; Gehrels *et al*., 2006).

An established methodology for reconstructing vertical changes in RSL is the utilisation of sea level index points (SLIPs). This approach uses radiocarbon (^{14}C) dated peat samples to fix the altitude of former RSL in time and space (Edwards, 2007; Shennan and Horton, 2002). The samples are derived from the regressive (clay-peat) and transgressive (peat-clay) contacts of stratigraphic sequences commonly found within coastal lowlands and salt marshes around the U.K. SLIPs can be categorised in accordance with their origin of formation in relation to former

sea level. They range from 'limiting', meaning they represent freshwater samples that have been formed above sea level, but it is unknown exactly how far above sea level. Of the same, lesser quality to sea level studies are points collected from within both minerogenic and organic sequences, known as 'intercalated' index points. These are prone to autocompaction, which can be defined as the compression of a sedimentary package under its own weight (Allen, 1990). The final type of index points is derived from basal peats that are underlain by a hard substrate. Basal index points are less prone to autocompaction and vertical displacement, and therefore exhibit a lesser error margin when calculating the formation of the index point with specific reference to the tidal frame (termed the 'indicative meaning').

Alongside autocompaction as a limitation in the usage of SLIPs in RSL studies, there are additional errors and uncertainties associated with the application of this method. For example, further vertical (altitudinal) error may be introduced when levelling a core and its associated subsample depths to a datum, while uncertainties may arise when establishing an indicative meaning (Edwards, 2008). Moreover, it is likely that age uncertainty will also be introduced where there are errors within the radiocarbon (^{14}C) dating and age calibration process of the SLIP, often caused by an element of contamination within a sediment sample. Although radiocarbon (^{14}C) dating is the standard method of assigning an age to organic remains, it is not entirely precise and results always involve calculated error margins.

Due to the potential for a SLIP to contain a relatively large degree of altitudinal and age uncertainty; combined with the spatial and temporal restrictions of tide gauge records, increased attention has been drawn to geological sea level indicators as proxies for changes in RSL. Initial palaeo-ecological investigations into biological indicators such as ostracodes (van Harten, 1986), foraminifera (Scott and Medioli 1986), testate amoebae (Charman *et al*., 1998) and diatoms (Devoy, 1979) have discovered a strong correlation between species diversity and tidal height. Consequently, they offer the potential for high-precision sea level investigations and many have been employed to successfully replicate former tide levels (e.g. Gehrels, 1994; 1999; Southall *et al.*, 2005; Massey *et al*., 2006, Hill *et al*., 2007, Charman *et al.*, 1998; and Woodroffe and Long, 2009). In earlier studies, the quantifiable potential of sea level indicators was not explored, and investigations involving the use of foraminifera, for example, traditionally provided qualitative estimates of RSL change (e.g. Gehrels, 1994). The reconstruction of sea level records using the quantitative approach is created by surveying the zones in which each species exist on a contemporary salt marsh surface. The knowledge of these relationships is then descriptively applied to a fossil core and sea level estimates can be provided based on the foraminiferal species distribution within stratigraphic horizons.

By means of increasing the precision of a sea level reconstruction, quantitative estimates of palaeo-sea level have been created using transfer functions. Transfer functions are produced by applying a range of multiple regression techniques to the indicative ranges of contemporary intertidal biological indicators. These relationships are often analogous to fossil species, and can therefore be transferred to fossil sequences extracted from the same region. This approach has been successfully employed using intertidal foraminifera on marshes in the North Atlantic (Gehrels *et al.,* 2006), Western Atlantic (Edwards *et al.,* 2003; Gehrels, 1999; Gehrels *et al*., 2005) and at numerous localities around the coast of the U.K. (e.g. Horton *et al*.,

1999a; Edwards and Horton, 2006; Massey *et al*., 2006). Despite such widespread application, it is important to consider the technique's reliability on the uniformitarianism principle; that the distribution of biological species assemblages have remained the same through time, and that the tidal frame has also remained unchanged. This thesis utilises such an approach, and presents sea level data for the Bristol Channel based on quantified indicative meanings of fossil foraminifera from Porlock Marsh, North Somerset.

1.2 Sea level data for the Bristol Channel

Kidson and Heyworth (1978) used geomorphological evidence to infer the southwest of England and the Bristol Channel region as being tectonically stable since the later Pleistocene until present. In comparison, Shennan (1989) calculated relative rates of land motion around the U.K., using the full database of SLIPs. It was determined that land on the North Somerset fringe of the Bristol Channel – Severn Estuary is currently experiencing a rate of relative land subsidence of ~0.24mm yr^{1}. This figure was later updated in a revision by Shennan and Horton (2002), who concluded that the Bristol Channel area appears to be subsiding at a relative rate of ~0.8mm yr^{1}. These figures are supported by recent studies involving the use of continuous global positioning systems (CGPS) (Bradley *et al.,* 2009; Teferle *et al.,* 2009) who maintain absolute land subsidence is occurring around North Somerset at a rate of ~0.8mm yr^{1}. Furthermore, Gehrels (2010) presents a revision of the Shennan and Horton (2002) map of crustal motion that takes into consideration the 20th Century sea-level rise and subsequent redistribution of ocean mass by the process of ocean siphoning. Results indicate a rate of relative land subsidence of 1mm yr^{1}. In comparison, sea level data recorded by the Newlyn tide gauge, Cornwall, are incongruous to the published results of Shennan (1989); Shennan and Horton, (2002); Bradley *et al.,* (2009); Teferle *et al.,* (2009) and Gehrels (2010). Readings over the past century show no indication of anomalous subsidence in southwest England, as the rate of rise (~1.6mm yr^{1}) shows insignificant differentiation from the global average. Although measurements at Newlyn are spatially limited to the extreme southwest of England, the same conclusion can be drawn for the case of the Bristol Channel, as Shennan and Horton's (2002) relative land motion calculation for the extreme southwest also differentiates between the rate provided by the Newlyn tide gauge.

Therefore, the figures surrounding the rate of relative land subsidence in the Bristol Channel area are questionable. On the basis of the published results, there is a general consensus that land levels around the Bristol Channel are subsiding, although at an intermediate rate compared to elsewhere in Britain (Fig. 1.2.1). Therefore, the deep Holocene alluvial deposits preserved in salt marshes fronting the Bristol Channel coast provide an invaluable resource when attempting to constrain sea level movements since the early Holocene.

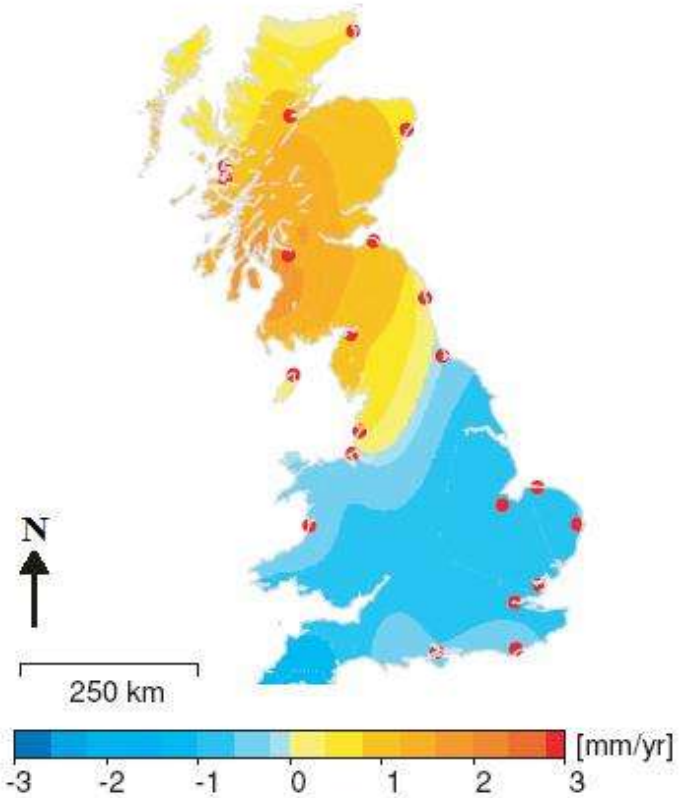


Fig 1.2.1 – Map of vertical crustal motions derived from Holocene relative sea level data from Shennan and Horton (2002). Extracted and modified from Teferle *et al.* (2009).

However, complications may arise due to the temporal and spatial variability of tidal elevation. This is compounded in the case of the Bristol Channel where tide levels exhibit severe spatial variability. For example, the height of high water of spring tides (HWST) above ordnance datum (OD) increases by more than 3m from the mouth of the channel to the head of the estuary (Kidson, 1986). Uehera *et al,* (2006) modelled palaeo-tidal evolution in the northwest European shelf seas since Pleistocene deglaciation. In the Bristol Channel, findings indicate that amplitudes in the tidal M_2 component may have increased since the onset of Holocene RSL in the region to the present day. However, no data is specified and the reader is referred to a low resolution image. Fig. 1.2.2 illustrates two enlarged sections of the Bristol Channel region from the original Uehera *et al*. (2006) graphical depiction of M_2 evolution. The image indicates some low order amplification of the M_2 tidal component since 8000 BP (before present); however, no quantified conclusion can be drawn. This is borne in mind when reconstructing palaeo-sea level from geological proxy data as any unquantified change in tidal range through time is likely to introduce error into RSL reconstructions (Edwards, 2007).

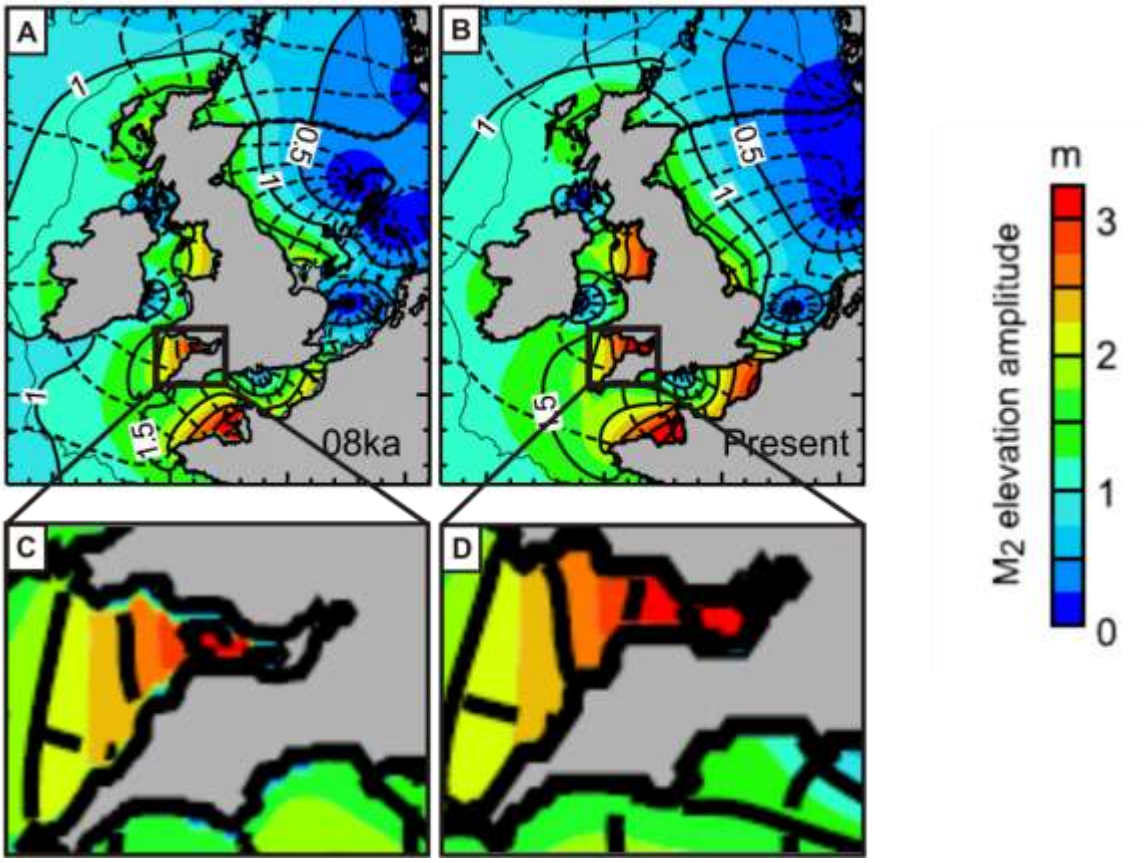


Fig. 1.2.2 – The M_2 component of tidal evolution in northwest European seas from (A) 8000 BP to (B) present. (C) and (D) are enlarged sections of (A) and (B), respectively. Extracted and modified from Uehera *et al.* (2006).

Most sea level curves for the Bristol Channel have been derived from plotting the broad database of radiocarbon (^{14}C) dated SLIPs for the region (Appendix 1) on age/altitude plots (e.g. Heyworth and Kidson, 1982; Kidson and Heyworth, 1973; Jennings *et al.,* 1998). At a glance, the results produced from many of these studies (e.g. Fig. 1.2.3) appear to be based on reliable evidence regarding the former position of RSL due to the relatively large database of SLIPs for the region from which these results are delineated. However, the database includes a number of SLIPs that were taken by Kidson and Heyworth (1973) and Heyworth and Kidson (1982) from the interior of extensive peat layers well beyond the coast (Haslett *et al.,* 1998). These in particular are limiting in the sense that the indicative meanings and ranges of these points are not known. Haslett *et al*. (1998) go on to suggest that the Kidson and Heyworth (1982) sea level curve for the Somerset Levels may solely represent peat accumulation, which may not be synonymous with sea level. Data uncertainties surrounding the indicative meanings and ranges of the peat-based SLIPs are also made difficult by the element of autocompaction. Many of the SLIPs sampled by Kidson and Heyworth (1982) were extracted from a broad area of Holocene infill in North Somerset, and in these areas, the pre-Holocene substrate is below >30m ordnance datum (OD) in places (Heyworth and Kidson, 1982). Compounding this is the likelihood that different types of peat may be found in small areas (Kidson and Heyworth, 1973) thus experiencing variable and individual rates of

autocompaction. These factors raise serious questions surrounding the precision and quality of sea level data that currently exist for the Bristol Channel region.

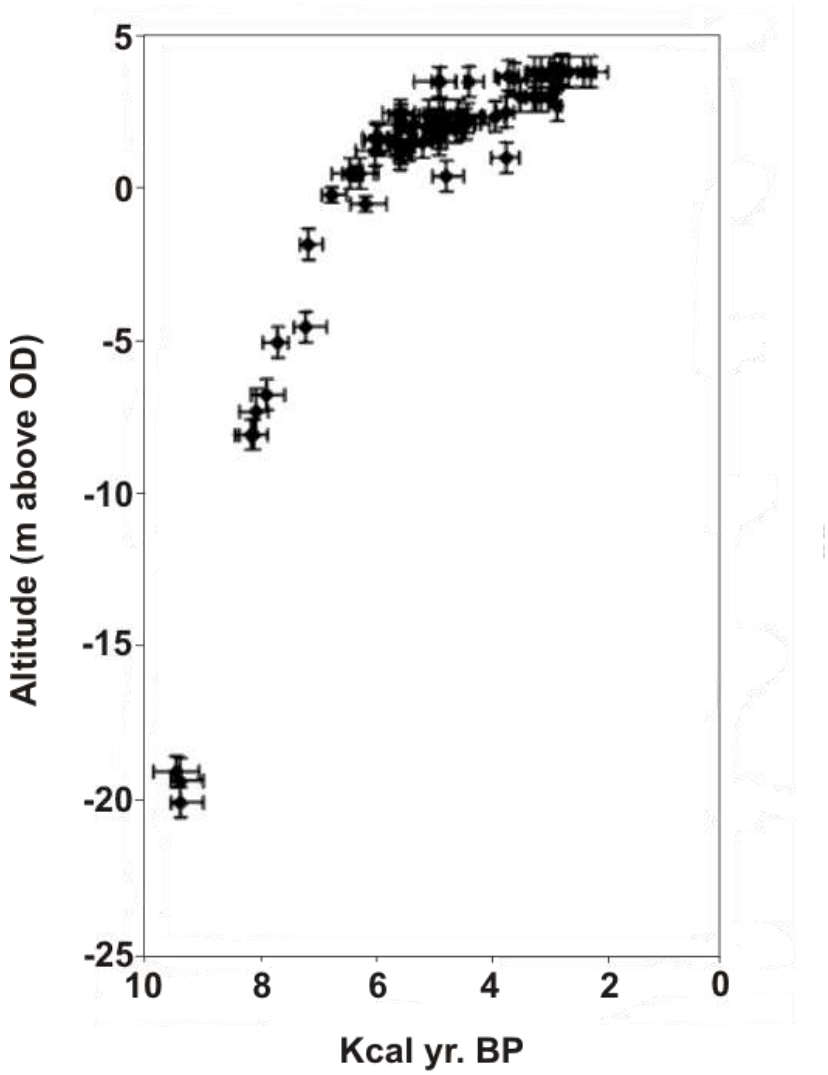


Fig. 1.2.3 – Age/altitude plot of Holocene RSL for the Somerset Levels. Extracted and modified from Heyworth and Kidson (1982)

Jennings *et al.* (1998) established a number of new sea level index points for the Bristol Channel. Most were sampled from an intercalated peat bed within the Holocene alluvial deposit at Porlock Marsh and from exposed tree stumps on the foreshore in Porlock Bay. When constructing the rates of RSL change for the area, they used the full database of SLIPs from the Bristol Channel region as a 'quality control' mechanism. This was to ensure that SLIPs occupying altitudes outside of the trend were excluded from the sea level reconstruction. Ultimately, Jennings *et al.* (1998) used SLIPs taken from tree stumps in their final reconstruction, with the exception of one that was sampled from Porlock Marsh. Two excluded sea level index points taken from the marsh (Table 1.2.1) have been re-plotted in Fig. 1.2.4. These are re-sampled in this study to check whether foraminiferal indicative meanings display similar altitudes.

Table 1.2.1 – Sea level index points taken from the highest organic layer within core EH2. Taken and adapted from Jennings *et al.* (1998)

Laboratory number	Sample thickness (cm)	Metres below MSL at sample top	Borehole	Radiocarbon (^{14}C) age (1σ) BP	Calibrated age range (2σ) BP
OxA-6399	1	-2.01	EH2	5120±55	5990-5730
OxA-6569	1	-2.16	EH2	5450±70	6410-5990

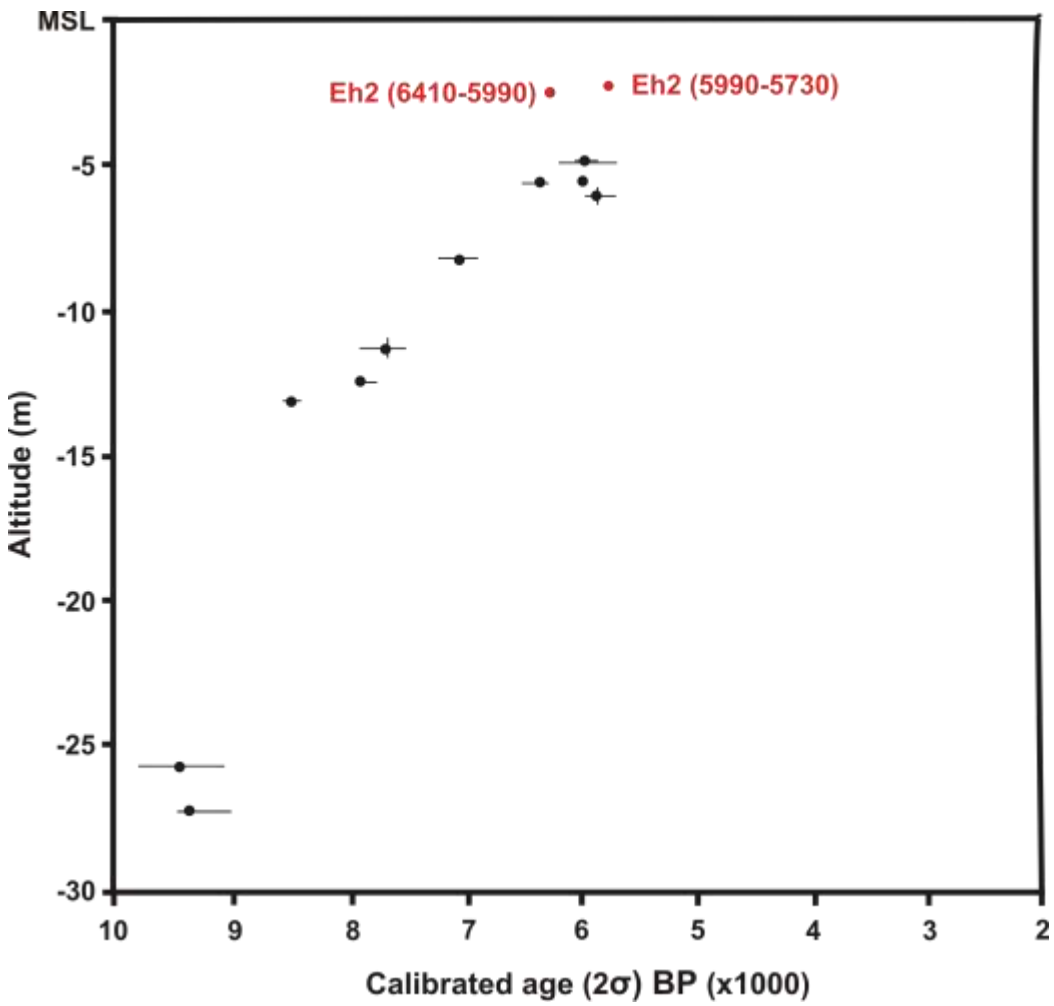


Fig 1.2.4 – Sea level index points used by Jennings *et al.* (1998). Red SLIPs were re-sampled in this study.

Furthermore, Jennings *et al.* (1998) reconstructed the palaeo-environmental history of Porlock Marsh using diatoms as a biological indicator and provided a qualitative

association to former RSL. Four local diatom assemblage (LDAZ) zones are recognised within a core extracted from Porlock Marsh (Fig. 1.2.5). Results show a gradual transition from a terrestrial freshwater environment at the base through to brackish environment, following a trend consisting of an incremental increase in the abundance of marine diatom taxa towards the top of the sequence. The very top of the core, representing the most recent sedimentary sequence, is dominated by freshwater diatom taxa. This, however, can be related to human-induced flooding of the marsh in recent times and is not considered to be linked to sea level (Canti *et al*., 1996). Therefore, it is clear that Jennings *et al.* (1998) provide a sea level reconstruction based on combined use of the database of SLIPs where the altitudes of some are uncertain, with a qualitative assessment of diatoms whereby weak linkages are made to the former position of RSL.

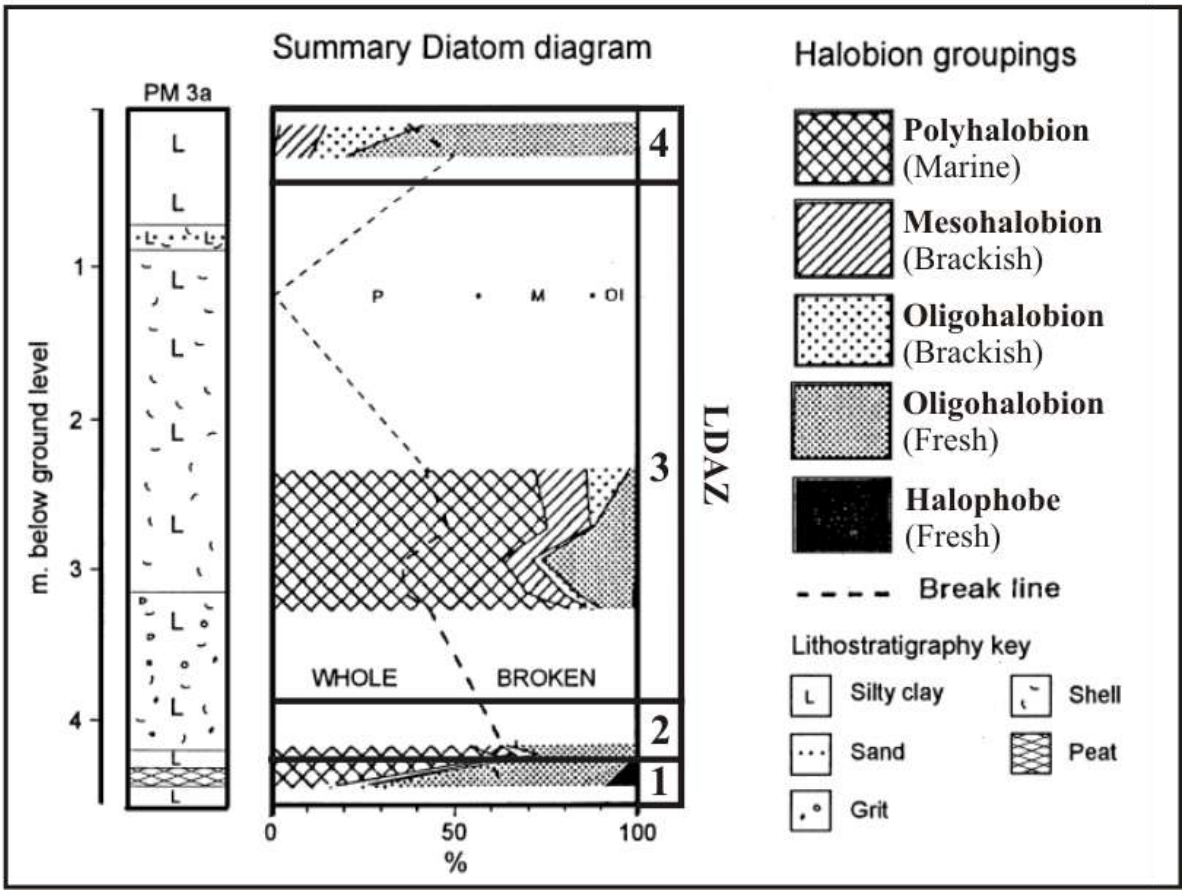


Fig. 1.2.5 – Diatom diagram for core PM3a. Four LDAZ zones are recognised (Refer to text for explanation). Extracted and modified from Jennings *et al*. (1998)

The application of biological indicators as proxies to changes in RSL has the potential to minimise the degree of vertical uncertainty attached to some of the previously published SLIPs, and they are often utilised as valuable alternatives as a means of assessing validity and precision. Studies involving transfer function reconstructions commonly use foraminifera and diatoms as sea level indicators. Hill *et al.* (2007) established a diatom-based transfer function to reconstruct sea-level changes in the Severn Estuary. Two transects containing data regarding the

contemporary diatom salt marsh surface distribution was merged in order to gain a full representation of the tidal frame, producing a vertical error prediction of ±0.876m. In comparison, foraminifera based transfer functions and their associated sea level reconstructions have been applied elsewhere in southwest Britain. Based on a training set of 85 samples, Massey *et al*. (2006) successfully combine two transects from separate marshes within estuaries from the south coast of Devon. Contemporary marsh surface foraminifera (Fig. 1.2.6) were used as modern analogues to provide an approximate vertical error of ±0.285m for indicative meanings of fossil samples (Table 1.2.1 and Fig. 1.2.7).

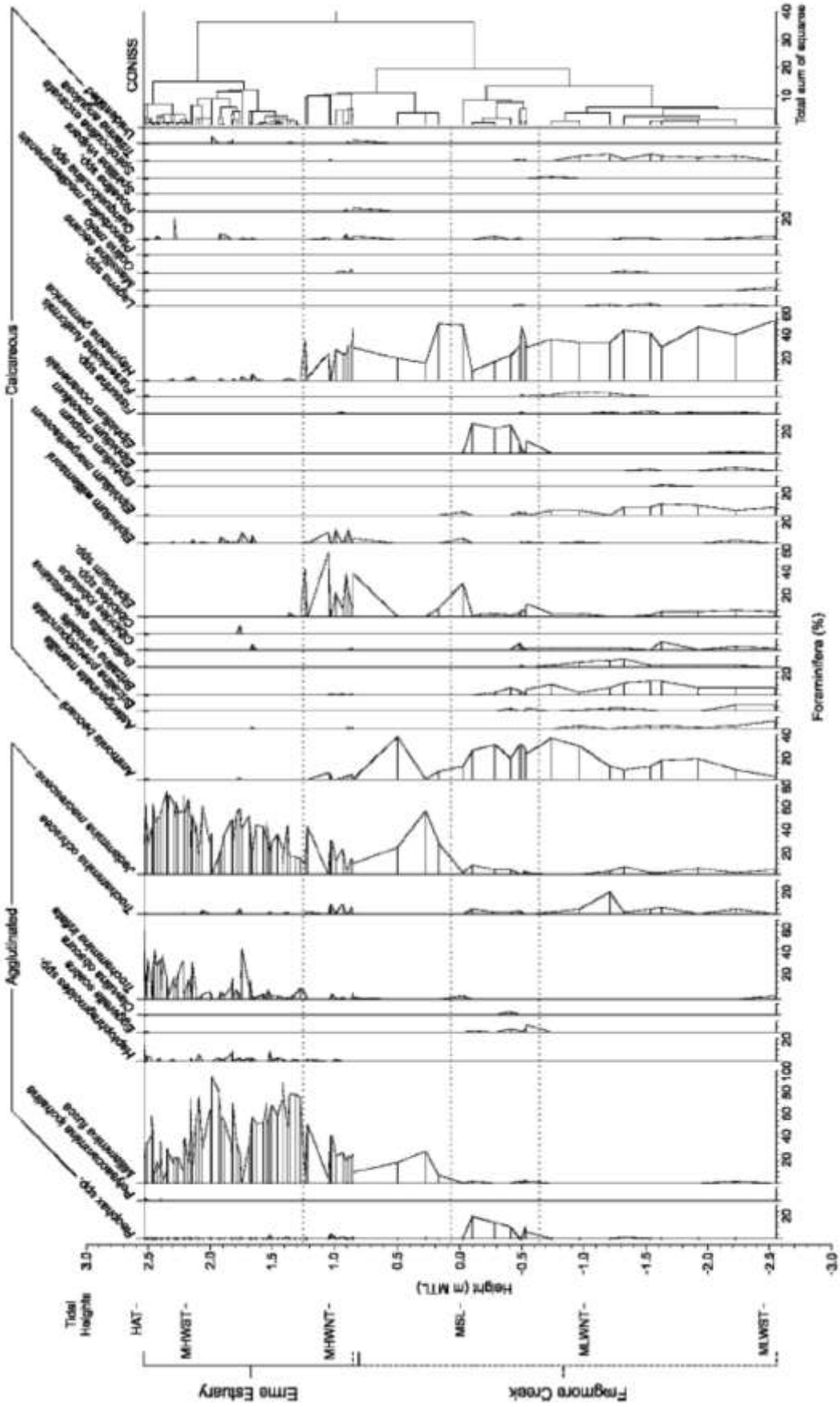


Fig. 1.2.6 – The contemporary distribution of intertidal foraminifera from the Erme estuary and Frogmore Creek in the Salcombe-Kingsbridge estuary, Devon, U.K (Massey *et al.*, 2006). Species-elevation relationships are quantified to produce indicative meanings with an estimated vertical error of ±0.285m (component 2 of the WA-PLS transfer function. Extracted from Massey et *al.*, 2006)

Table 1.2.2 – Performance of the regression models on the training set of dead foraminifera. The component used in this study is indicated in blue. Note the features indicated in red have to be multiplied to compensate for the greater tidal range in the Bristol Channel. Extracted and modified from Massey *et al.* (2006)

Model	1	2	3	4	5	6
Method	WA-PLS	WA-PLS	WA	WA-TOL	WA	WA-TOL
Component/Deshrinking	2	2	Inv	Inv	Inv	Inv
N	107	85	107	107	85	85
n	34	33	34	34	33	33
RMSE (m)	0.372	0.259	0.451	0.458	0.348	0.334
r^2	0.910	0.943	0.867	0.863	0.897	0.905
Max Bias (jack) (m)	0.760	0.384	1.361	1.504	0.683	0.796
RMSEP (m)	0.416	0.285	0.476	0.523	0.370	0.407
r^2 (jack)	0.887	0.931	0.852	0.823	0.883	0.862
Max Bias (jack) (m)	1.173	0.411	1.531	0.755	0.791	1.064

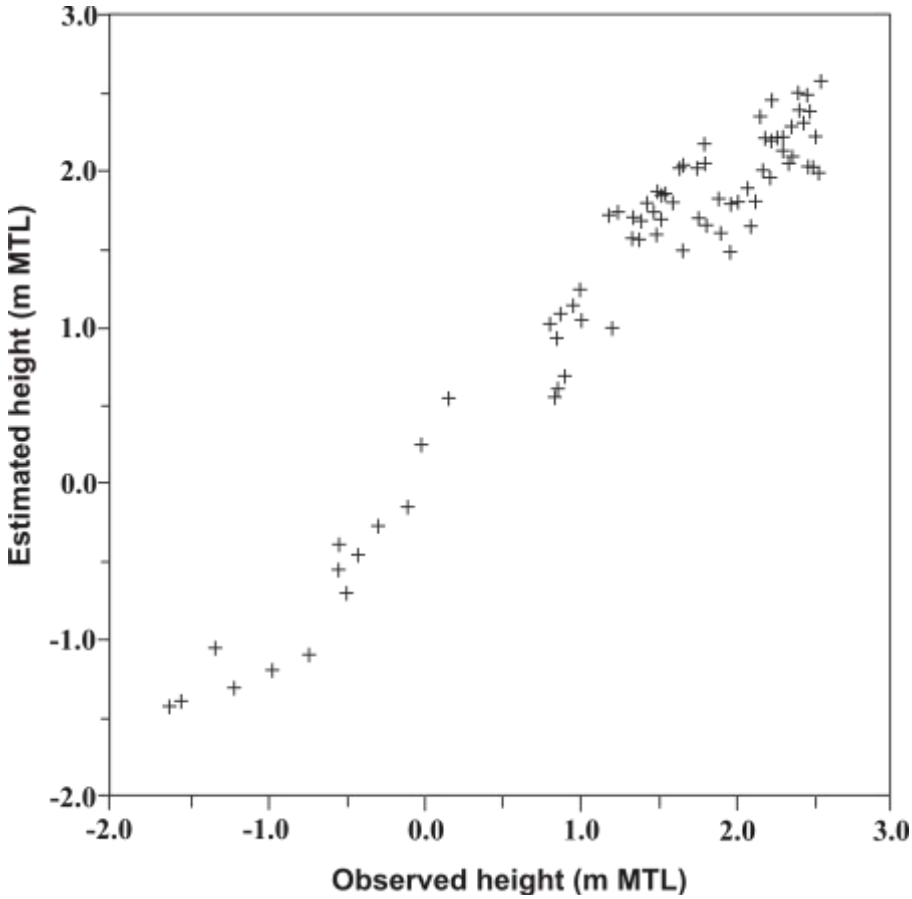


Fig. 1.2.7 – Observed and predicted values of indicative meaning (m MTL) for the component 2 WA-PLS transfer function (Massey *et al.*, 2006). Results produce the lowest (±0.285m) root mean square error prediction (RMSEP) of all components

In relation to southwest Britain, the results of Massey *et al*. (2006) indicate that foraminifera based RSL reconstructions have the potential to exhibit a greater degree of precision compared to diatoms. Moreover, Kemp *et al.* (2009) compared the performance of foraminifera and diatoms in North Carolina, U.S.A. and conclude that diatoms show high species diversity, making them imprecise compared to the foraminifera in reconstructing RSL. Although it is clear that the intertidal zonation of micro-organisms is site-specific (Gehrels *et al.,* 2001), the decision was made to use foraminifera as the proxy sea level indicator based on the lower vertical uncertainties illustrated by Massey *et al.* (2006). This study will therefore provide a quantitative RSL reconstruction for Porlock by applying the foraminifera based transfer function formulated by Massey *et al.* (2006). It considers the limitations of applying a transfer function created for a meso-tidal environment on a sediment sequence from a macro-tidal setting, throughout.

1.3 Aims and objectives

The Holocene sea level history of the Bristol Channel has to this date been presented by sea level curves based on a potentially unreliable database containing a number of limiting SLIPs from the region. With regard to Porlock, Somerset, there are some SLIPs that have been published by Jennings *et al*. (1998) yet are excluded from the sea level curve. This study re-samples two index points and checks whether indicative meanings of fossil foraminifera show similar results. The main aims and objectives of this study are as follows:

i) To compare the indicative meanings of fossil foraminifera quantified by the Massey *et al*. (2006) transfer function to the altitudes of two previously published Porlock sea level index points.

ii) To provide a palaeo-environmental reconstruction based on the indicative meanings of fossil foraminifera, and to assess whether they yield similar results to diatoms (Jennings *et al.,* 1998).

1.4 Study area

The salt marsh at Porlock, North Somerset, U.K. (Fig. 1.4.1), fronts low lying farmland and is being flooded daily by the tide through a breach in the adjacent barrier. An alternative name for the marsh used in the literature is Porlock Ridge (McDonnell, 2002; 2006; 2007). It is situated on the southern macro-tidal coast of the Bristol Channel (SS 87323 47841) on the north-eastern fringe of Exmoor National Park (ENP). The solid geology of Porlock Bay and marsh is Mercia mudstone, while the surrounding upland areas to the west, east and south are comprised of Devonian rocks (Evans and Thompson, 1979; Davies and Williams, 1991). The marsh and intertidal zone consists of Holocene alluvial deposits with intercalated peat beds (McDonnell, 2002), directly overlying Pleistocene solifluction (head) deposit (Figs. 2.1.2 and 2.1.3). Chart Datum (CD) in Porlock Bay lies at -5.2m OD (Admiralty, 2009) (Table 1.4.1) and spans 10.2m up until the mean high water spring tide (MHWST) mark at 5.0m OD. The majority of the marsh surface lies between 4-5m OD (Jennings *et al.,* 1998), and is dissected by tidal creeks that in places reach a depth of ~3m.

Table 1.4.1 – Tidal data for Porlock Bay. Extracted from McDonnell (2002)

Mean Heights	Chart Datum (CD) (m)	Ordnance Datum (OD) (m)
HAT	11.3	6.2
MHWST	10.2	5.0
MHWNT	7.6	2.4
MLWNT	3.7	-1.5
MLWST	0.9	-4.3
CD	0.0	-5.2

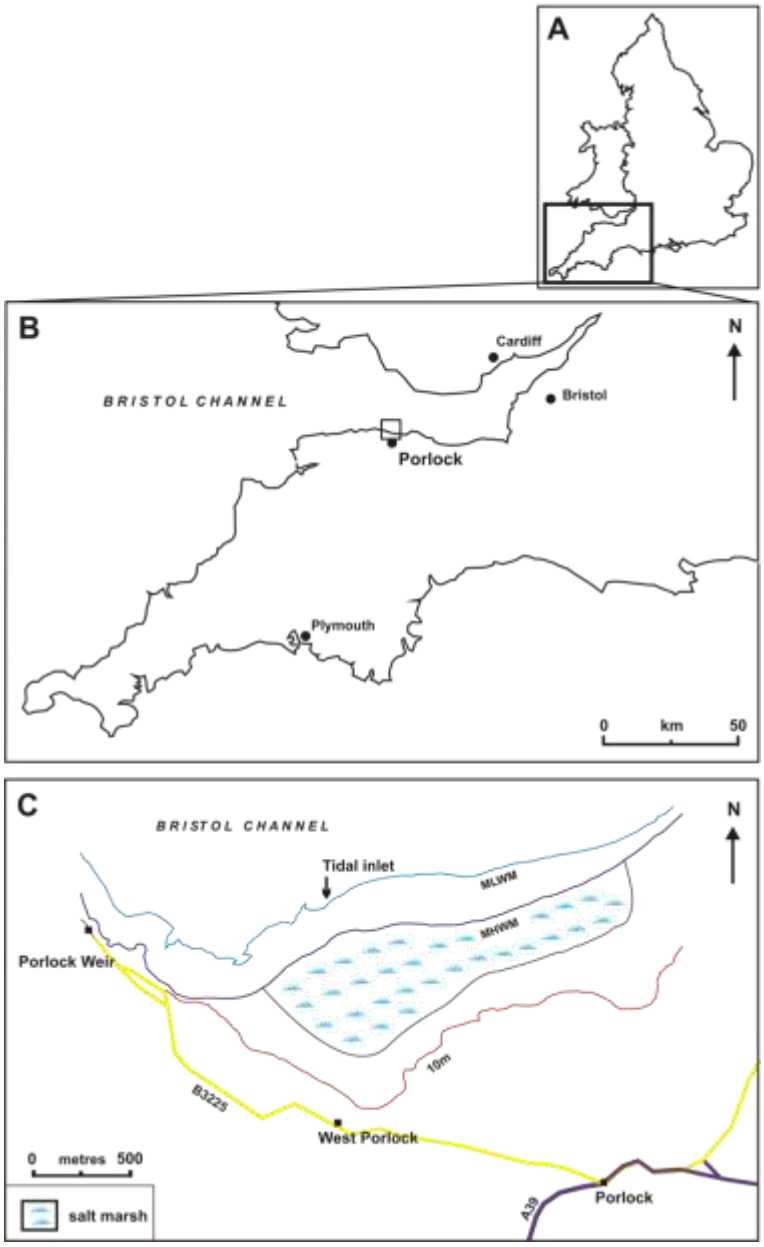


Fig. 1.4.1 – (A) Location map of the southwest of England in relation to the U.K. (B) Location map of Porlock in relation to the southwest (C) Local location map of Porlock Marsh

2. Methodology

2.1 Field methods

Fieldwork at Porlock was conducted in July 2009. The stratigraphy of the marsh is well established by Jennings *et al.* (1998) (Figs. 2.1.2 and 2.1.3) and this information was subsequently used to identify an appropriate site for re-sampling. Core EH3 was re-sampled (Fig. 2.1.1), and this was found by aid of the original location map from Jennings *et al*. (1998) overlain on an ordnance survey (OS) map detailing geographic coordinates, whereby the use of a global positioning system (GPS) receiver was used to locate the exact point for re-sampling. The decision was made to re-sample core EH3 based on depth of Holocene infill, as this location contains the deepest Holocene sequence at Porlock. The core was extracted with an Eijkelkamp gouge and levelled to the closest OS benchmark using a dumpy level and surveying staff. It was preferred to re-sample the section at EH2 in order to retrieve the exact two SLIPs published in Jennings *et al.* (1998). However, this section was inaccessible due to barrier overwash since the publication. The section at EH4 also contains a near-basal SLIP, although this section proved too difficult to sample due to the tough nature of the topsoil. Similar difficulties were experienced when attempting to sample the basal SLIP at EH39. However, section EH3 was re-sampled to a depth of -3.10m OD and spans a maximum length of 7.80m. The remaining 2.3m that underlays the sequence proved too difficult to extract with an Eijkelkamp hand gouge. Nonetheless, the sequence contains a peat layer where radiocarbon (^{14}C) dates have been calibrated to show similar ages across section EH2, EH4 and EH39 (Figs. 2.1.2 and 2.1.3). It is therefore considered that the intercalated bed was formed instantaneously and that the calibrated ages can be reliably transferred to EH3. In order to provide the most accurate age estimations, the ages of the upper and lower contacts of the intercalated peat beds are averaged using the weighted mean equation outlined in Froggatt and Lowe (1990) (Section 2.2). A total of two previously published 'traditional' SLIPs are re-sampled in this study and are analysed to assess whether foraminifera display similar indicative meanings. Details of the Jennings *et al*. (1998) original borehole locations are shown in Fig. 2.1.1.

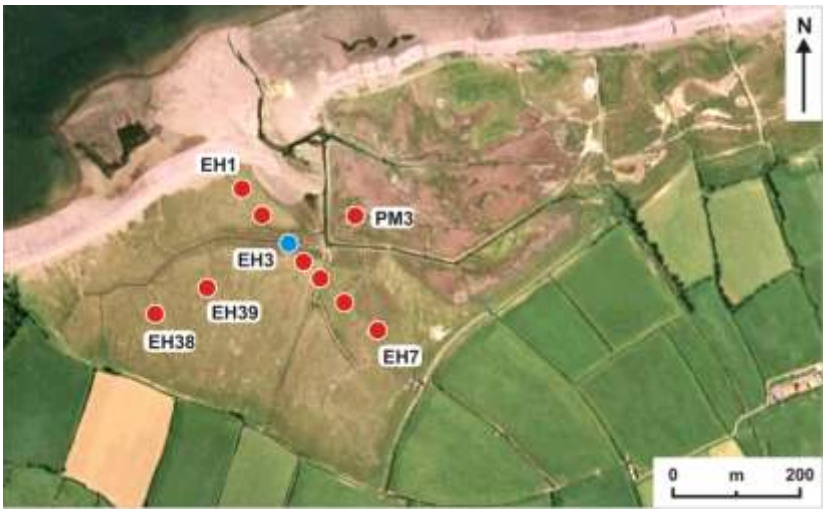


Fig. 2.1.1 – Satellite image of Porlock Marsh. Red markers indicate the original boreholes of Jennings *et al*. (1998). PM3 is the borehole sampled for diatoms. Re-sampled core is shown in blue. Source of satellite image: *http://www.maps.google.co.uk*

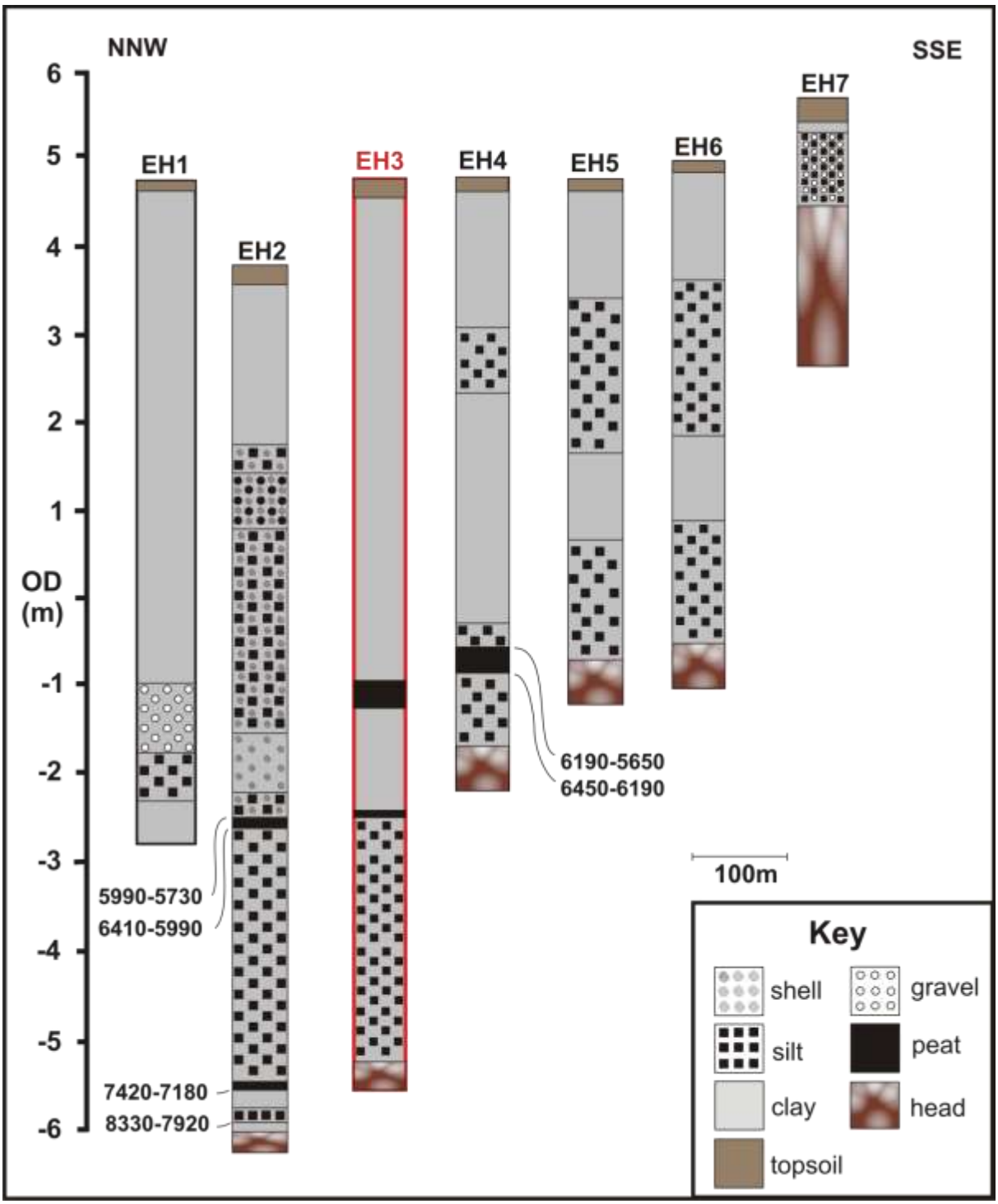


Fig 2.1.2 – Lithostratigraphy of Porlock Marsh transect boreholes (Refer to Fig 2.1.1. for locational information). Calibrated C^{14} ages BP (2σ) are annotated. Re-sampled core is shown in red. Extracted and modified from Jennings *et al.* (1998). Note that ages on the upper and lower contacts of the intercalated peat layer in EH2 and EH4 are almost identical. It is therefore assumed that similar ages apply to EH3 and these are calculated using the weighted mean equation (Froggatt and Lowe, 1990) outlined in Section 2.2

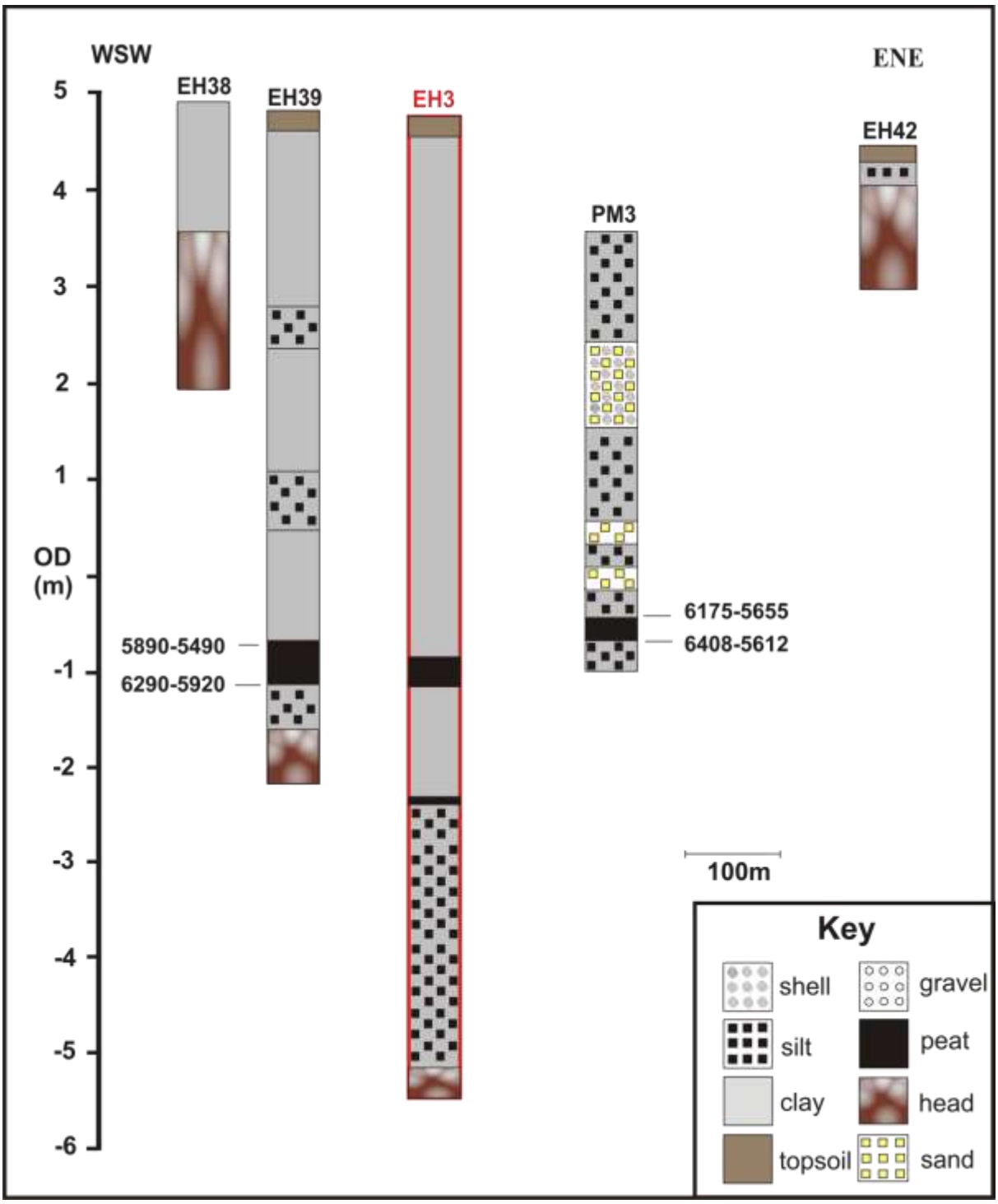


Fig 2.1.3– Lithostratigraphy of Porlock Marsh transect boreholes (Refer to Fig 2.1.1. for locational information). Calibrated C^{14} ages BP (2σ) are annotated. Re-sampled core is shown in red. Extracted and modified from Jennings *et al.* (1998). Note that ages on the upper and lower contacts of the intercalated peat layer in EH39 and PM3 are almost identical. It is therefore assumed that similar ages apply to EH3 are these are calculated using the weighted mean equation (Froggatt and Lowe, 1990) outlined in Section 2.2

2.2 Averaging radiocarbon (^{14}C) dates

It is necessary to provide an estimation of the upper and lower contacts of the highest organic layer within EH3 by averaging the radiocarbon (^{14}C) dated contacts of the same layer at EH2, EH4 and EH39, as Jennings *et al.* (1998) did not radiocarbon (^{14}C) date and provide calibrated age estimations for the peat layer at EH3. Known radiocarbon (^{14}C) ages are averaged using the weighted mean equation (Froggatt and Lowe, 1990):

$$A_p = \sum \left(A_i / se_i^{\ 2} \right) / \sum 1 / se_i^{\ 2}$$

$$se_{A_p} = \left(\sum 1 / se_i^{\ 2} \right)^{-1/2}$$

Where the individual ages (A_i) and their associated errors (se_i) are known, the weighted mean (A_p) can be calculated. The standard error of the mean ages (se_{Ap}) can also be calculated by averaging the associated errors of each age.

A_p Weighted mean

A_i Individual ages

se_{A_p} Standard error of the mean of the ages

se_i Associated errors

2.3 Laboratory methods

Upon extraction, the stratigraphy was analysed and recorded according to the Troels-Smith (1955) scheme of stratigraphic notation. This was to assess whether the stratigraphy remained uniform in comparison to the original core of Jennings *et al.* (1998) at EH3, and that the re-sampling site was the closest possible proximity to the original location. The core was divided into one metre sections and placed in perspex tubing sealed with polythene. On return to the laboratory, the core was stored below 4ºC in order to retard biological and chemical processes (Edwards, 2006). The core was sub-sampled for foraminifera analysis at a resolution of 0.5cm on the upper and lower contacts of unit transitions within the stratigraphy. Five samples were taken at across each contact. Further sub-samples were systematically taken at 0.5m intervals within each of the stratigraphic units. This sampling methodology was employed to 'maximise the foraminifera yield for analysis without compromising stratigraphic resolution' (Haslett *et al.,* 2001). Sub-samples were measured to 4cm^3 and washed through 500µm and 63µm mesh sieves, respectively. Sediment was diluted with distilled water and siphoned onto a Bergeroff tray where it was consecutively analysed under a low power binocular microscope. Foraminifera were hand 'picked' and placed onto glued slides where they were identified according to the taxonomy depicted in Horton *et al.* (1999b) and Horton and Edwards (2006). A transfer function for southwest tide level (Massey *et al*.,

2006) was applied to the dataset of dead foraminifera in order to provide indicative meanings for each sediment sample. SLIPs from the stratigraphy of Jennings *et al.* (1998) were used as chronostratigraphic age markers in the creation of a Holocene RSL reconstruction for Porlock.

2.4 Foraminifera as sea level indicators

Foraminifera are single celled protozoa that occupy the marine environment. They are either planktonic or benthonic and bear shells otherwise known as 'tests'. These unique coatings allow each foraminifer to be distinguished as individual specie. Typically, foraminifera display vertical zonation across a salt marsh with the upper zone consisting of agglutinated species, following a gradual transition to a greater calcareous abundance in the lower marsh (Table 2.4.1). With respect to sea level studies, the spatial distribution of foraminifera is thought to be related to the duration and frequency of tidal exposure (Horton, 1999). However, the subdivision of foraminifera is also caused by the tolerances of individual species with regard to water depth, turbulence, light, temperature, salinity, Ph, oxygen content and food supply (De Rijk, 1995). Vegetation also serves to protect foraminiferal populations from desiccation or tidal currents, thus promoting preservation on the surface of a salt marsh (Duchemin *et al.,* 2005). Foraminifera are therefore considered to be the preferred sea level indicator for utilisation in this study.

Table 2.4.1 – Typical foraminifera faunal zones and tidal data. Extracted and modified from Horton (1999).

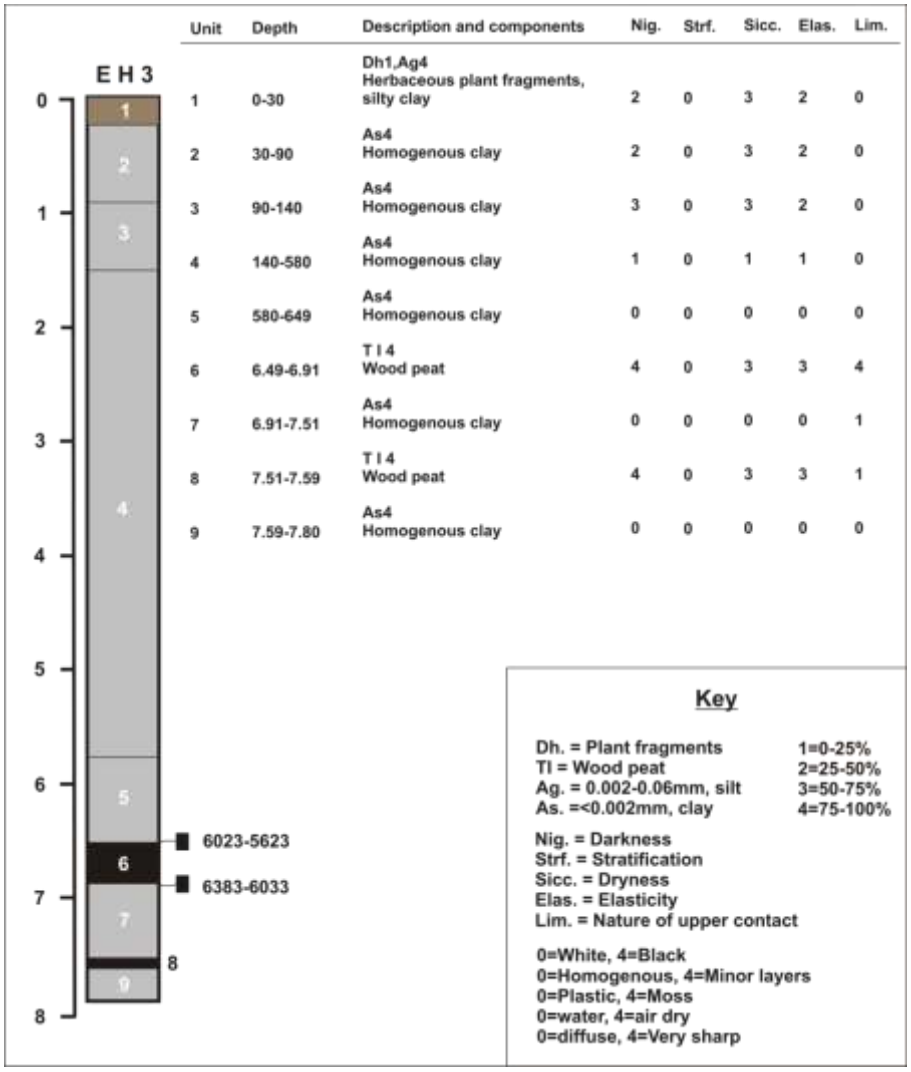
Altitude (m above OD)	Floral Zones	Foraminifera	Tidal Height
3.42	High marsh	Jadammina macrescens Trochammina inflata	HAT
2.47	Middle marsh	Jadammina macrescens Trochammina inflata Miliammina fusca	MHWST
1.99	Low marsh	Jadammina macrescens Miliammina fusca	MHWNT
0.32	Mud flat	Elphidium williamsoni Haynesina germanica *Quinqueloculina* spp	MTL

3. Results

3.1 Lithostratigraphy

The stratigraphy of Porlock Marsh at EH3 was logged using the Troels-Smith (1995) scheme of stratigraphic notation. An illustration of the nine stratigraphic units found within the core is provided in Fig. 3.1.1.

The bottom unit of EH3 extents for 21cm and is comprised of homogenous blue clay. A thin peat band displays diffuse upper and lower contacts at depths of 751cm and 759cm respectively. The sequence returns to homogenous blue clay for 60cm until the base of a second intercalated peat layer comprised of woody peat between 649-691cm. The lower contact of the organic unit displays a sharp transition and when applying the weighted mean equation (Section 2.2), has a calibrated age of 6383-6033 yr BP. The transgressive overlap also displays a sharp transition that has been calculated to contain an age of 6023-5623 cal. yr BP. The water content increases at this stage and the sediment becomes more saturated within blue homogenous clay between the depths of 580-649cm. The unit that follows has been identified as a light coloured homogenous clay and is the longest unit of the 7.80m section, ranging from 140-580cm. The clay remains homogenous and develops a darker colour at a depth of 90-140cm, followed by a diffuse transition to light brown homogenous clay at a depth of 30-90cm. The top 30cm of EH3 is topsoil comprised of minerogenic silts and herbaceous plant fragments.



Unit	Depth	Description and components	Nig.	Strf.	Sicc.	Elas.	Lim.
1	0-30	Dh1,Ag4 Herbaceous plant fragments, silty clay	2	0	3	2	0
2	30-90	As4 Homogenous clay	2	0	3	2	0
3	90-140	As4 Homogenous clay	3	0	3	2	0
4	140-580	As4 Homogenous clay	1	0	1	1	0
5	580-649	As4 Homogenous clay	0	0	0	0	0
6	6.49-6.91	T l 4 Wood peat	4	0	3	3	4
7	6.91-7.51	As4 Homogenous clay	0	0	0	0	1
8	7.51-7.59	T l 4 Wood peat	4	0	3	3	1
9	7.59-7.80	As4 Homogenous clay	0	0	0	0	0

Fig. 3.1.1 – Lithostratigraphy of EH3 according to Troels-Smith (1995). Core is divided into units for ease of analysis. Radiocarbon (^{14}C) dated sea level index points (Jennings *et al.*, 1998) from EH2, EH4 and EH39 are averaged using the weighted mean equation (Froggatt and Lowe, 1990) (Section 2.2) to provide calendar age estimations for EH3. Refer to text for explanation

3.2 Biostratigraphy

The biostratigraphy of EH3 is illustrated in Fig. 3.2.1. Foraminiferal data are expressed as percentage counts of the total number of tests counted (Appendix 2), and analyses indicate that EH3 consists predominantly of calcareous low marsh to estuarine species. Only six species are identified, and these include *Elphidium williamsoni, Haynesina germanica, Ammonia Beccarii, Trochammina inflata, Jadammina macrescens* and *Miliammina fusca* (Fig. 3.2.3). The latter three species

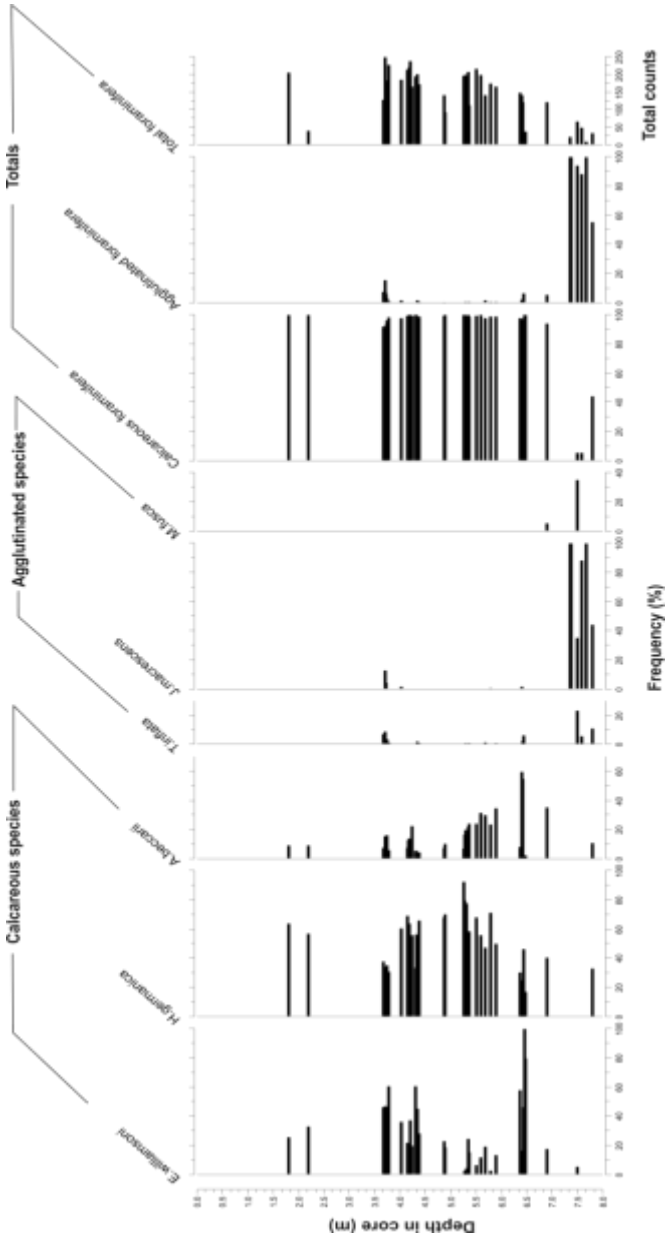


Fig. 3.2.1 – Percentage counts of fossil foraminifera in core EH3

are agglutinated and are known to occupy the low to high marsh, whereas the first three calcareous species indicate a mud-flat and estuarine environment (Horton, 1999). Raw counts of foraminifera are shown in Fig. 3.2.4. The complete dataset of raw counts is provided in Appendix 3.

At the bottom of the core, agglutinated species are prevalent in minor numbers. Calcareous species exhibit a gradual increase in representation with elevation containing numbers reaching between 40-50% the sum of the total. On the diffuse lower contact of the lowest intercalated peat bed, the section is dominated by *J. macrescens* with numbers reaching between 40-80% the sum of the total count. *J. macrescens* also dominate the diffuse upper contact with numbers reaching 80-100% the sum of the total count. A sample taken between the two intercalated peat beds are dominated by equal numbers of *H. germanica, A. beccarii* and *E. williamsoni*. Salt marsh foraminifera are present within the lower contact of the highest peat bed with *M.fusca* reaching numbers of ~5% of the total count. However, the sample is mostly dominated by equal numbers of *H. germanica* and *A. beccarii* at 40% of the total count, alongside a small representation of *E. williamsoni* with numbers reaching 15% the sum of the total. This is the only sample on the lower contact to contain foraminifera. On the upper contact, *E. williamsoni* represent the total number of tests counted. Salt marsh foraminifera show minor occurrences within samples taken from higher elevations on the upper contact. A graphical depiction of the foraminifera assemblages here are illustrated in Fig. 3.2.2. Following a 48cm section containing no foraminifera, the biostratigraphy shows an initial increase in *A. beccarii* which represent 60% the total count. Numbers of *T. inflata* and *J. macrescens* also increase and represent 5% and 2% of the total, respectively. From this point to 5.90m the total percentage counts show a reduction in the number of *E. williamsoni* from ~60% to ~15% of the total. In comparison, there is an increase in the prevalence of *H. germanica* from ~40% to ~70% the sum of the total. *A. beccarii* also show increasing numbers throughout this section ranging from ~20% in the upper region to ~35% in the lower region. The section also illustrates small numbers of agglutinated species, with *T. inflata* and *J. macrescens* occupying between ~2% and ~10% of the total count at certain intervals. The remainder of the core is largely dominated by consistent numbers of calcareous species representing 80-100% of the total count. Foraminifera are largely barren from 3.69m to the top, although calcareous species demonstrate a 100% representation in two samples between 1.5 and 2.2m. The lithostratigraphy of EH3 is therefore verified by the biostratigraphy.

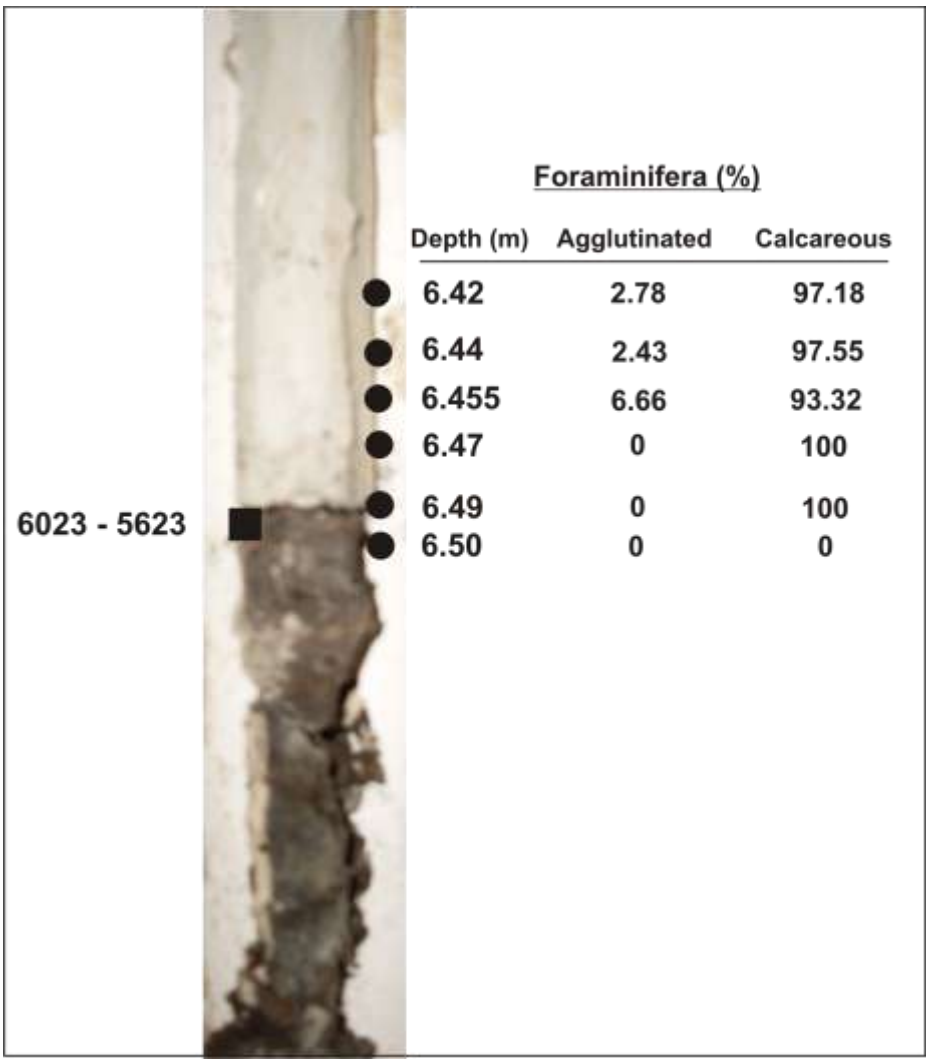


Fig. 3.2.2 – Biostratigraphy of the upper transition of the highest intercalated peat bed in EH3. Ages are in cal. yr BP. Salt marsh foraminifera are absent on the immediate upper contact although numbers emerge and gradually decline with elevation

Author: *T. Lawrence*

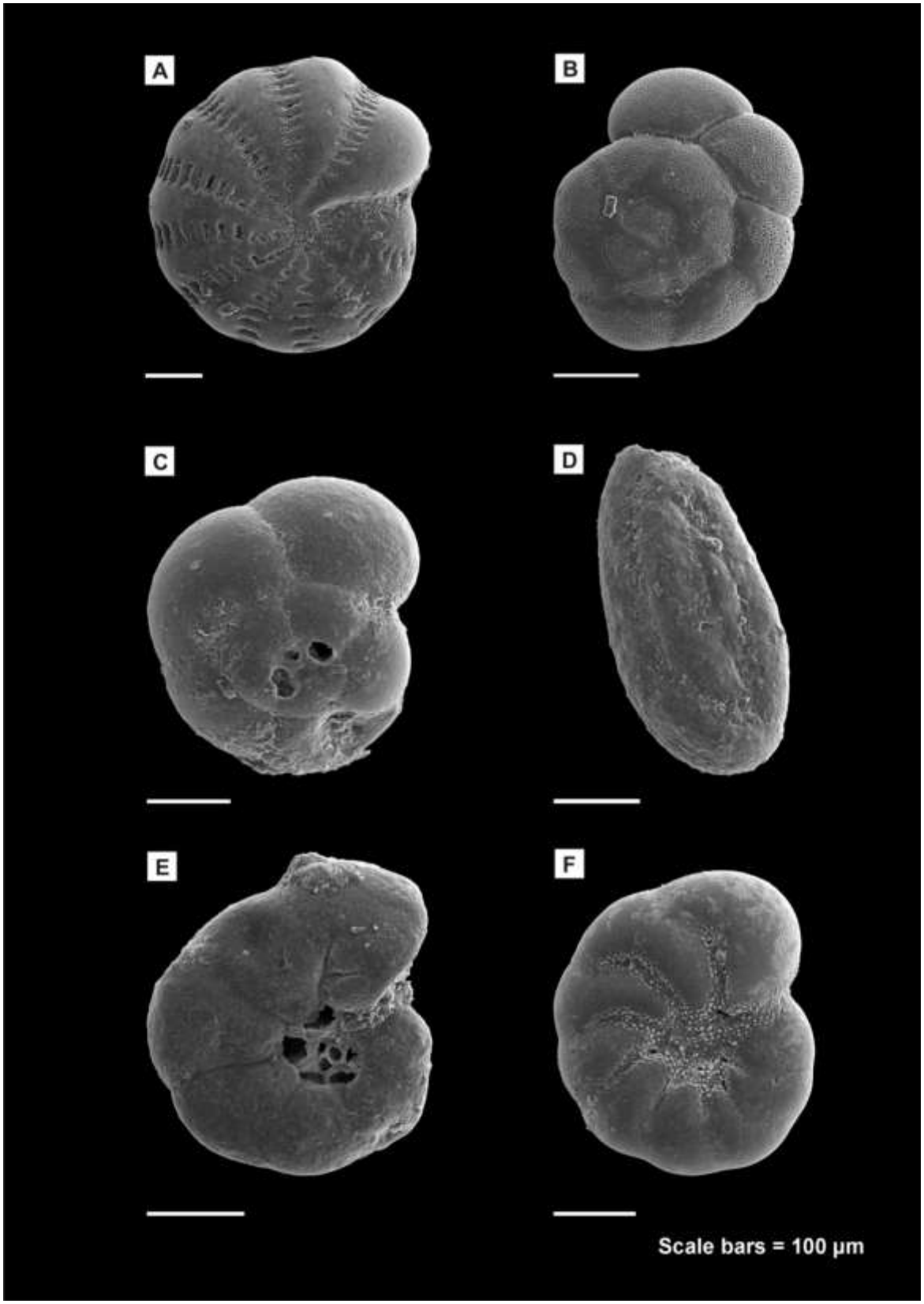


Fig. 3.2.3 – Scanning electron microscope (SEM) images of fossil foraminifera specimens found in this study. From top left (with depths found) (A) *E. williamsoni*, 1.81m (B) *A. beccarii*, 6.42m (C) *T. inflata*, 7.51m (D) *M .fusca*, 7.51m (E) *J. macrescens*, 7.59m (F) *H. germanica*, 5.32m

Author: *T. Lawrence*

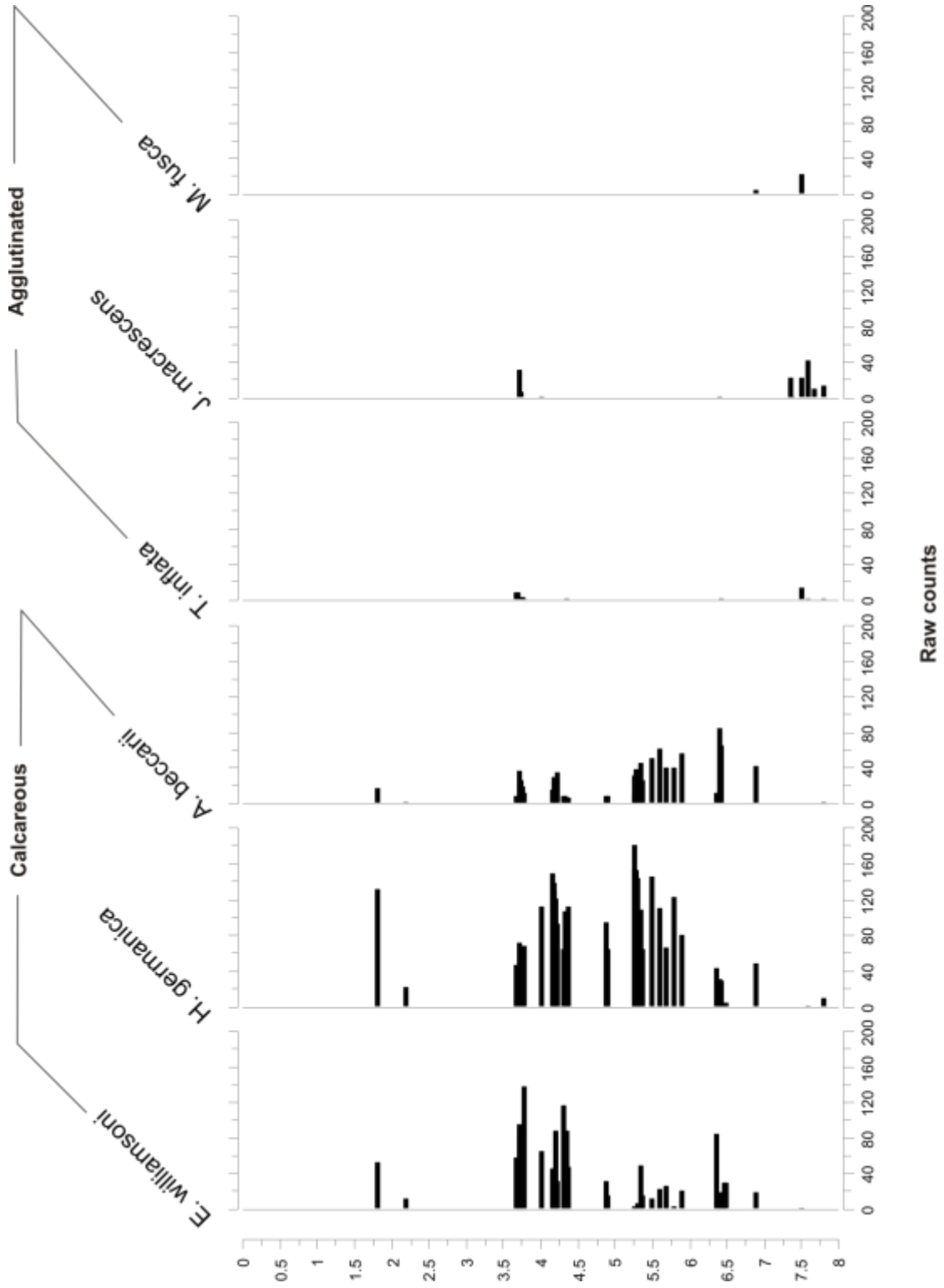


Fig. 3.2.4 – Raw counts of fossil foraminifera in core EH3. Note the dominance of calcareous over agglutinated tests in the majority of samples

With reference to raw numbers of individual species, results show variation with species and core depth. Fig. 3.2.4 illustrates that calcareous species are present in greater numbers than their agglutinated counterparts, often collectively reaching 200 within each sample. Alternatively, agglutinated species are in less abundance. In the middle section of the core where they are present in small intervals, counts rarely reach five in each sample. Despite this, there is a clear increase in the amount of agglutinated counts at the base of the core drawing particular attention to the transitions of the organic layers. Numbers here collectively reach a maximum of 64.

3.3 Quantifying indicative meanings

Using the computer program C2 (Juggins, 2009), the indicative meanings of fossil foraminifera assemblages are reconstructed using the weighted averaging partial least squares (WA-PLS) component 2 transfer function outlined in Massey *et al.* (2006) (Appendix 4). The indicative meanings have been plotted to produce a continuous curve of relative water change. Values are expressed in metres relative to mean tide level (MTL) (Fig. 3.3.1).

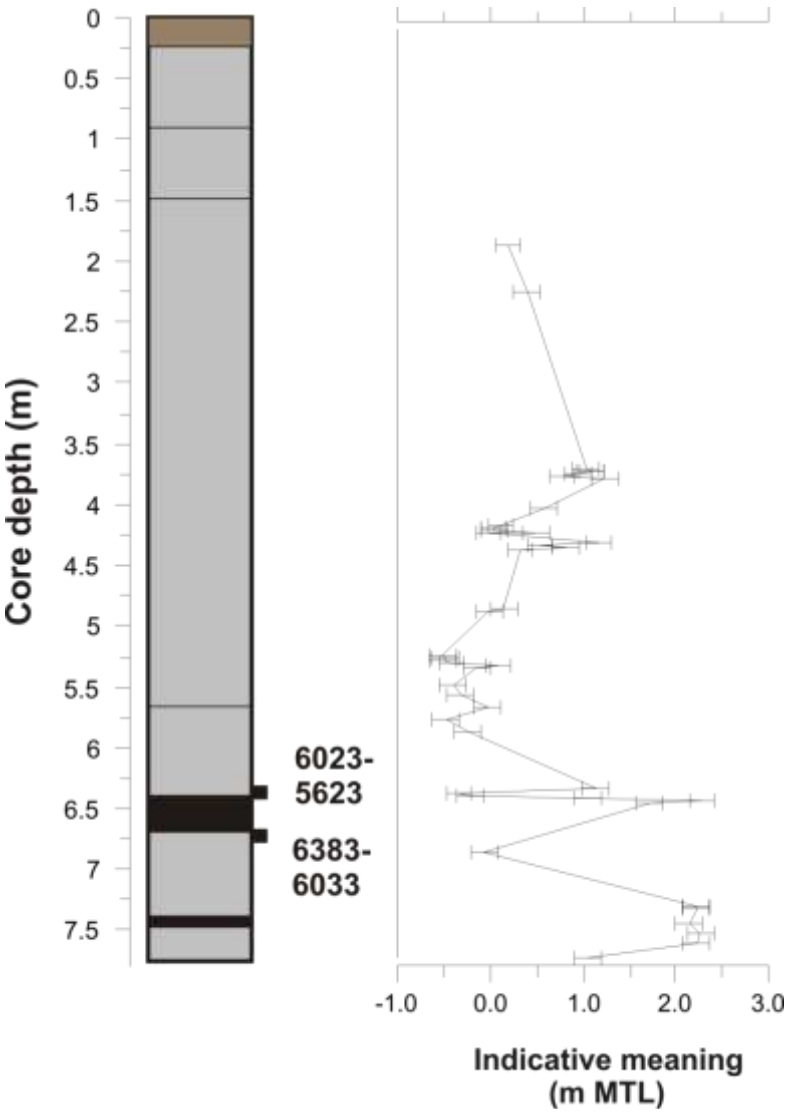


Fig. 3.3.1 – Quantified indicative meanings of fossil foraminifera from EH3 using the transfer function of Massey *et al.* (2006). Values are expressed in metres relative to MTL. Ages are provided in cal. yr BP

3.4 Adjusting indicative meanings for tide level

The indicative meanings of fossil foraminifera assemblages computed by the Massey *et al.* (2006) transfer function have to be adjusted to allow for differences in tidal range. The tidal range at Porlock (9.2m) is greater than in south Devon (4.65m). The indicative meanings have to be multiplied in order to account for the greater tidal regime at Porlock. In this instance, the results produced by the transfer function are multiplied by 1.98m to account for the macro-tidal regime in Porlock Bay as the tidal range at Porlock is 1.98m greater than on the south Devon coast. The root mean square error prediction (RMSEP) of the component 2 WA-PLS (±0.285) is also multiplied by 1.98m to produce an indicative meaning error of 0.564m. The adjusted dataset is provided in Appendix 5.

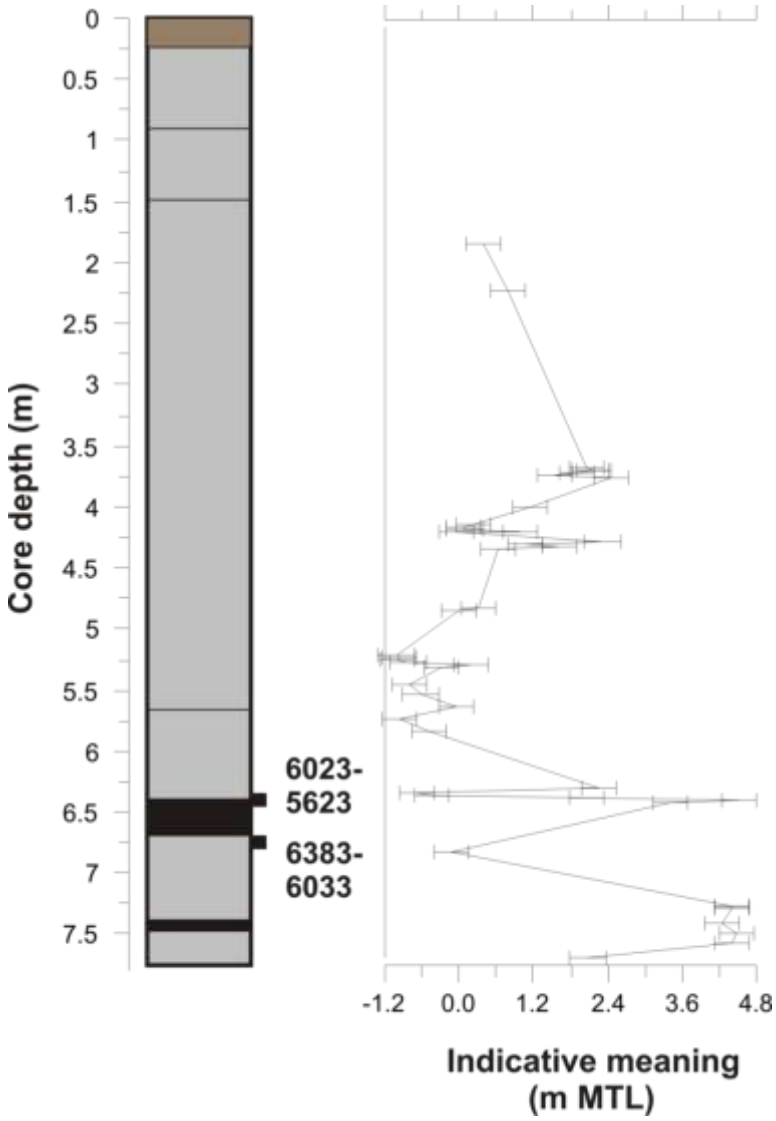


Fig 3.4.1 – Adjusted indicative meanings of fossil foraminifera from EH3 for the Porlock tidal regime. Values are expressed in metres relative to MTL. Ages are provided in cal. yr BP

By comparing Figs. 3.3.1 and 3.4.1 it is evident the adjustment has not affected the individual indicative meanings quantified by the Massey *et al.* (2006) transfer function. Instead, it has simply altered the dataset by increasing the overall scale to account for a macro-tidal regime. The altitudinal errors associated with each indicative meaning have also increased to account for greater foraminiferal indicative ranges.

3.5 Porlock sea level reconstruction

It is necessary to convert the indicative meanings of sampled fossil foraminifera assemblages to the height of palaeo-MSL in order to provide a continuous RSL curve for Porlock. This is achieved by applying the following equation.

$$S=H-I$$

Where *S* is palaeo-MSL, *H* is sample height relative to MSL and *I* is the indicative meaning. This equation is popularly used to convert the indicative meanings of fossil foraminifera assemblages into SLIPs (e.g. Gehrels *et al.,* 2006). However, it is noted that the reconstruction has no age control, and results solely represent altitudinal data with regard to MSL. The only sea level points of a known age are those sampled from the upper and lower contacts of the highest intercalated peat bed within EH3. Fig. 3.5.1 therefore illustrates the movement of palaeo-MSL at Porlock since between the minimum ages of 6383-6033 cal. yr BP. Values are expressed in metres relative to palaeo-MSL. The full dataset of foraminiferal sea level index points is provided in Appendix 6.

The results of the reconstruction infer that RSL at Porlock has exhibited directional variability since the mid-Holocene. RSL between the lowest and highest foraminiferal samples document a total rise of 10.32m. However, there are a number of fluctuations constrained within the sea level record. The most evident is the rapid RSL rise of 8.4m recorded at the base of the core. Following this is a sequence of rises and falls within the sea level record up until 6023-5623 cal. yr BP. It is noted that a pronounced sea-level rise of ~3m is delineated from samples taken from the upper contact of the highest intercalated peat bed. The record displays a further rise of ~4m although four 1m fluctuations are extrapolated between 5-6m core depths. The sea level record subsequently displays a falling trend of ~1.2m and a further four ~2m fluctuations are recorded. The end of the reconstruction documents a 2.88m gradual sea-level rise between the ~3.5 and ~1.75 metre core depth.

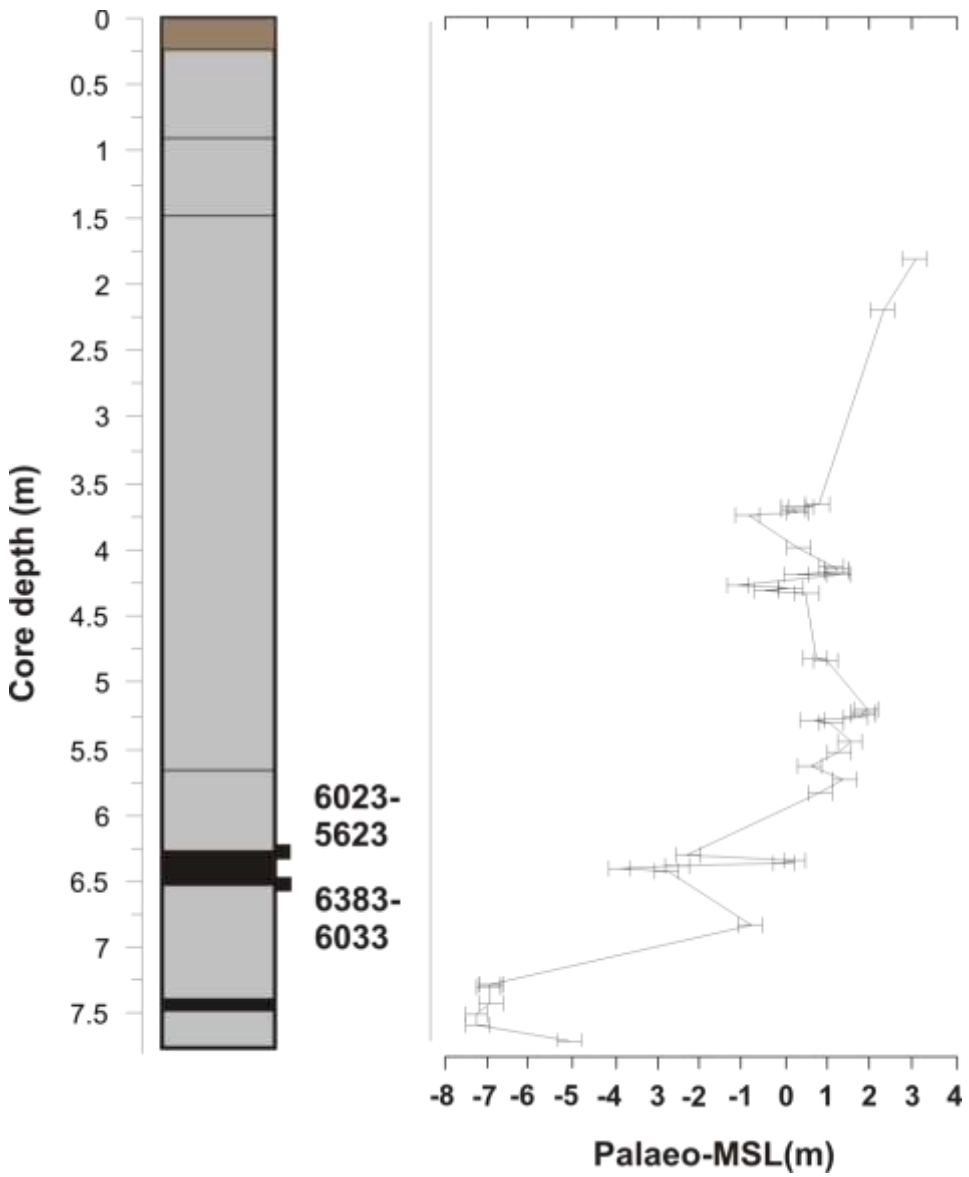


Fig. 3.5.1 – Relative sea level reconstruction for Porlock with associated lithostratigraphy and dated horizons. All ages are in cal. yr BP. Values are expressed in metres relative to MSL

3.6 Correcting for autocompaction

The sediment sequence at EH2 and EH3 has undergone different magnitudes of sediment compaction (Fig. 3.6.1). Assuming that each peat bed was formed instantaneously across Porlock Marsh, any differences in the elevations of the organic beds can be considered a result of autocompaction. The peat beds at EH2 and EH3 occupy a lower elevation compared to EH4 and are therefore considered to have been vertically displaced under their own weight.

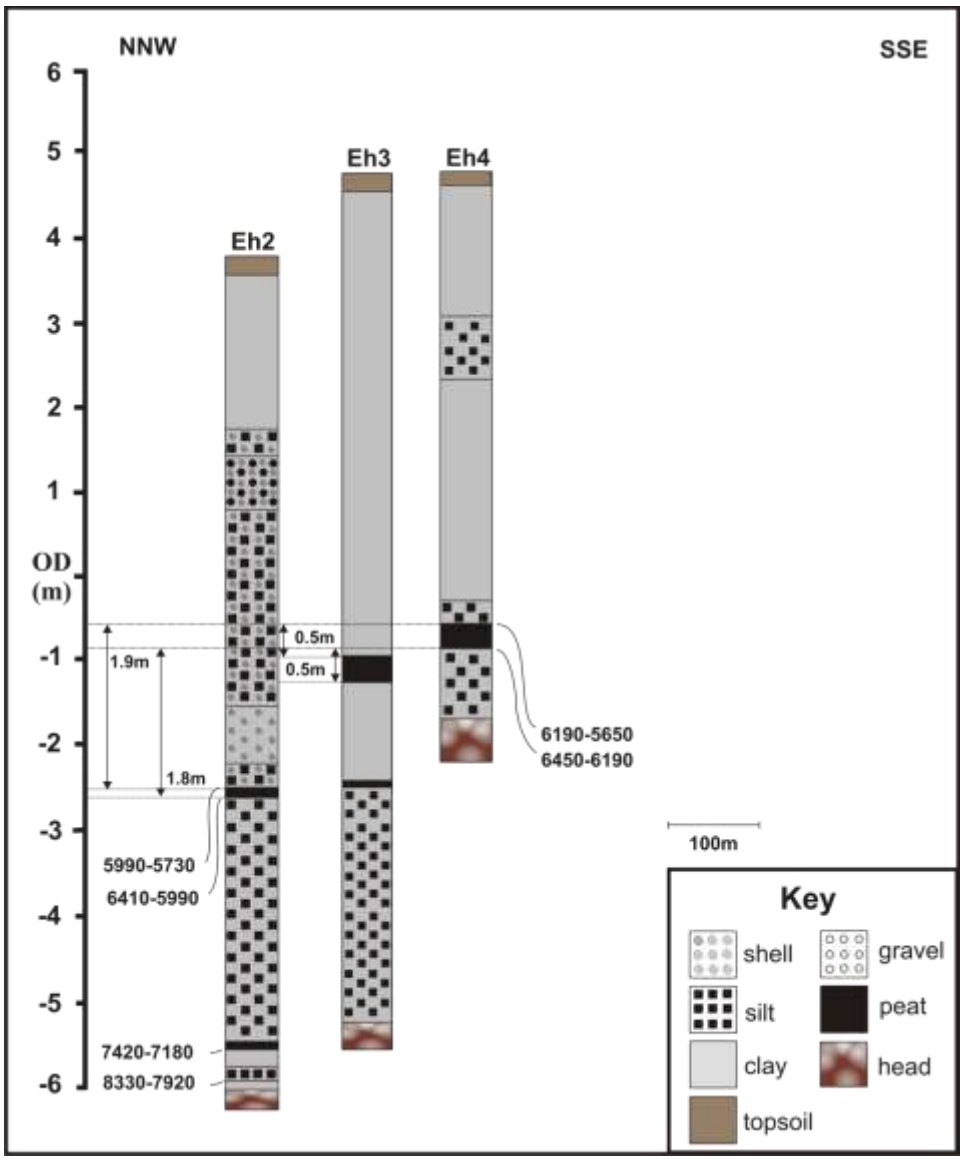


Fig. 3.6.1 – Lithostratigraphy of EH2, EH3 and EH4. All sections are likely to have experienced different orders of sediment autocompaction. All ages are in cal. yr BP

When removing the quantified element of compaction, the altitude of a SLIP with reference to its time of formation can be ascertained. In order to account for sediment autocompaction over time, the vertical displacement in cores EH2 and EH3 have been quantified relative to EH4. The intercalated peat layer in section EH4 occupies a position nearest to basement and is therefore considered to have experienced a minimal element of sediment depression compared to other sections. Despite this, uncertainties remain as the organic bed in EH4 is not an absolute basal layer, and some vertical displacement is likely to have occurred over time. The vertical displacement, if any, of the organic layer in EH4, is not taken into account in the following quantification of compaction.

The highest organic bed within EH2 has been quantified to be 1.8-1.9m lower than in EH4 (Fig. 3.6.1). When adding these figures to the initial elevations, the SLIPs taken

from EH2 are calculated to have been formed 0.11 and 0.36 metres below MSL. In EH3, the element of compaction has been quantified to be 0.5m on both the upper and lower contacts of the organic layer. All calculations are shown in Table 3.6.1. Results indicate that the radiocarbon (^{14}C) dated SLIP taken at the bottom contact displays a 0.007m difference in indicative meaning with reference to MSL (Fig. 3.6.2). The vertical position of the radiocarbon (^{14}C) dated SLIP is almost identical to the elevation of the foraminifera based SLIP generated in this study. These sea level points therefore display exact indicative meanings. Alternatively, the indicative meanings of the radiocarbon (^{14}C) dated SLIP and the foraminifera based SLIP, sampled from the upper transition of the intercalated peat bed, differentiate by 2.21m. After compaction, the traditional SLIP is calculated to occupy a position 0.11m below MSL. In comparison, the foraminifera based SLIP produced in this study indicates a position 2.32m below MSL. Refer to discussion for explanation (Section 4).

Table 3.6.1 – Altitudes of sea level index points from EH3 (this study) and EH2 (Jennings *et al*., 1998).

Borehole	Organic contact	Depth in core (m)	Depth to MSL (m) (before compaction correction)	Depth to MSL (m) (after compaction correction)	Radiocarbon (^{14}C) age (1**σ**) BP	Calibrated age range (2σ**)** BP
EH3	Upper	6.49	2.82	2.32	5049±37	6023-5623
EH3	Lower	6.91	0.87	0.367	5428±40	6383-6033
EH2	Upper	7.75	2.01	0.11	5120±55	5990-5730
EH2	Lower	8.00	2.16	0.36	5450±70	6410-5990

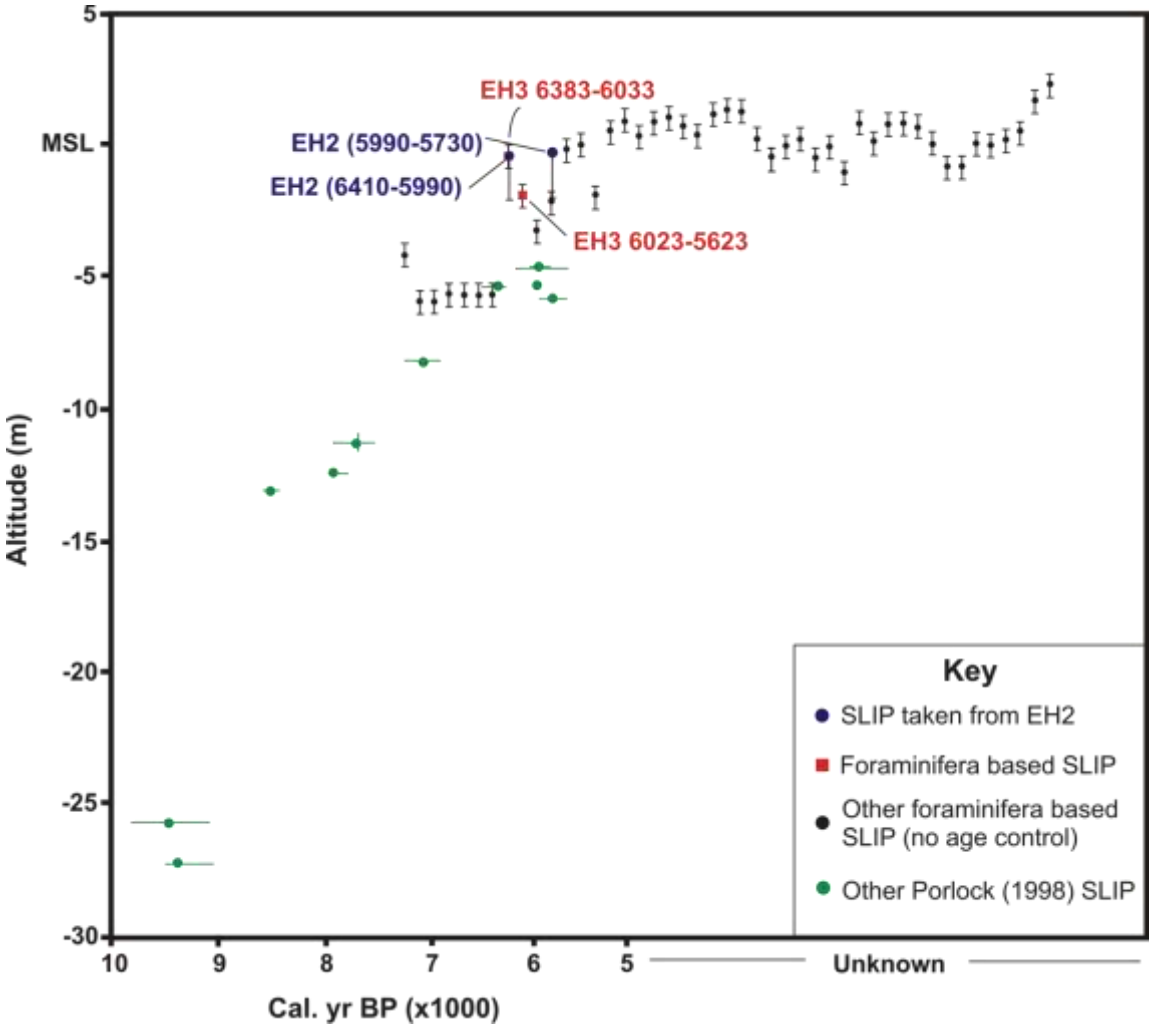


Fig. 3.6.2 – Relative sea level reconstruction for Porlock. SLIPs shown in blue (Jennings *et al.*, 1998) and red (this study) have been corrected for sediment autocompaction. Results show identical vertical correlation between SLIPs sampled from the lower contact although the upper contact SLIP is offset. Note that the remainder of the foraminifera based points (in black) have not been corrected for autocompaction and ages are unknown

3.7 Palaeo-environmental reconstruction

The indicative meanings of fossil foraminifera from EH3 are used as indicators in a palaeo-environmental reconstruction of Porlock Marsh. Results of the biostratigraphic analysis largely display similarities to the qualitative reconstruction provided by Jennings *et al.* (1998), although there are some discrepancies between the two datasets (Figs. 3.7.1). The base of EH3 corresponds well to the results produced by diatoms. The foraminifera count is dominated by the agglutinated species *J. macrescens*, *T .inflata* and *M. fusca* at 60-100% the sum of the total. The typically estuarine *H. germanica* and *A. beccarii* exist at ~40% the sum of the total. This is replicated in the diatom summary diagram provided by Jennings *et al.* (1998). However, where diatoms display a gradual transition to a marine environment, characterised by an increasing influence in the amount of brackish diatom valves

counted, the foraminifera record displays a rapid transition to a fully marine environment. Brackish salt marsh foraminifera are therefore absent from the dataset and estuarine species are found in numbers reaching 90-100% the sum of the total. The foraminifera biostratigraphy follows the same trend for the remainder of the core, and is dominated by increasing numbers of *E. williamsoni* and *H. germanica* to between ~40-70% the sum of the total, whilst displaying a reduction in the numbers of *A. beccarii* to ~15% the sum of the total. There is an occasional brackish signal as indicated by small interferences of agglutinated foraminifera within the record, with *T. inflata* reaching numbers between ~5-10% the sum of the total count. This is reflected in the diatom record where brackish diatoms are preserved in numbers up to ~30% the sum of the total. The final LDAZ is characterised by fully freshwater diatoms. This is in contrast to the foraminifera record where counts are barren in the upper section of EH3.

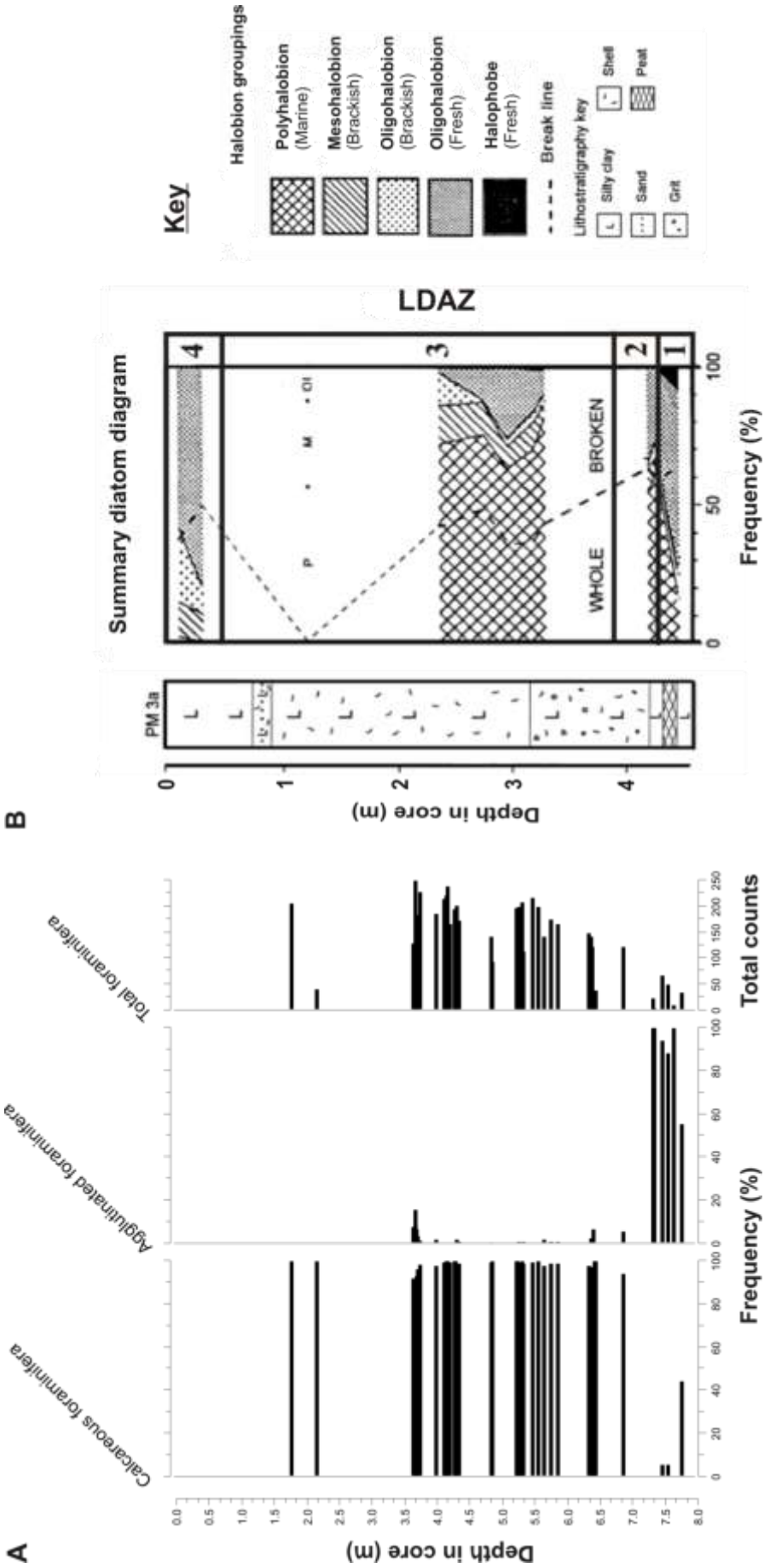


Fig. 3.7.1 – Comparison of foraminifera in EH3 (A) with diatoms in PM3 (B) (Jennings *et al.*, 1998). Results show foraminifera and diatoms correspond well as palaeo-environmental indicators. Refer to text for explanation

4. Discussion

4.1 Holocene palaeo-environmental change

The results of foraminifera as palaeo-environmental indicators show correspondence to the palaeo-environmental reconstruction using diatoms (Jennings *et al*., 1998). However, there is one discrepancy. The agglutinated assemblages at the base of EH3 indicate a gradual transition from a marine to brackish environment. This is followed by a transition to a freshwater environment as verified by the accumulation of terrestrial peat within the stratigraphy of EH3. The re-emergence of agglutinated foraminifera infers a return to an environment where the marine environment gained increasing influence. This is followed by an accumulation of clay within the stratigraphy, and the presence of lower-marsh estuarine foraminifera indicates increasing frequencies of marine inundation. Following this is a small representation of agglutinated salt marsh foraminifera within the sediment sequence, consecutively followed by a second accumulation of terrestrial peat. This transition indicates a gradual return to freshwater lagoonal conditions from an environment previously dominated by marine sedimentation. This phase represents the bottom sequence of the Jennings *et al.* (1998) diatom summary, and when contrasting the results of the two indicators, the first inconsistency is revealed. On the transgressive overlap of the terrestrial organic unit, diatoms display a gradual reduction in the amount of brackish frustules. This is in contrast to the foraminifera record where no agglutinated tests are present. On this basis, the top of the intercalated peat unit within EH3 is considered to be eroded. The foraminifera record at this point is discounted as it indicates rapid, instantaneous development from freshwater to marine conditions, whereas the diatoms indicate a gradually increasing phase of tidal submergence. The remainder of the foraminifera record indicates an environment typically dominated by marine influences and therefore corresponds to the diatom reconstruction. However, the uppermost LDAZ, as notified in the reconstruction, illustrates a full return to a terrestrial freshwater wetland. This stage in environmental change is absent from the foraminifera record as they are barren within the upper unit of EH3. The discrepancy across the two datasets is therefore considered to be not linked to sea level, but instead due to human management of a large proportion of the marsh for fish cultivation, as previously mentioned by Canti *et al.* (1996). If sea level was involved as a factor affecting the palaeo-environment of Porlock Marsh at this stage, agglutinated foraminifera are likely to have been found within the upper sediment sequence. Their absence indicates a palaeo-environment unaffected by sea level and is therefore beyond the scope of foraminifera as palaeo-environmental indicators, as they are limited by their marine exclusivity.

4.2 The Porlock sea level curve

The Porlock sea level curve and foraminifera-based SLIPs displays greater elevations compared to previously published SLIPs from radiocarbon (^{14}C) dated peat contacts (Fig. 3.6.2). When attempting to provide the most accurate age estimations for the upper and lower contacts of the intercalated peat bed in EH3 (Section 2.2) the result of averaging the previously radiocarbon (^{14}C) dated horizons at EH2, EH4 and EH39 still contains an element of uncertainty. The two averaged radiocarbon (^{14}C) dated contacts from EH3 provided in this study fail to fall in direct succession with the radiocarbon (^{14}C) dated SLIPs from EH2. Therefore, the Porlock sea level curve could not be positioned in relation to the previously published SLIPs on the basis of age alone. The foraminifera SLIP sampled from the lower contact of

the organic bed is considered to be the most reliable of the two in terms of elevation due to evidence contained within the litho and biostratigraphy of the associated upper transition. On the other hand, within the biostratigraphy of the transgressive overlap, the foraminifera record provides no indication of a gradual change from a terrestrial to marine environment due to the absence of agglutinated foraminifera. Despite this, they exist in the adjacent sample in low numbers, and continue to provide high indicative meanings. Likewise, the lithostratigraphy illustrates a sharp transition to the overlying clay. The contact is therefore considered to be eroded, and is not ideal to be used as a sea level index point. Usually, when a peat bed is ascertained to be unaffected by erosion there is a gradual transition to the overlying clay (Mook and Van de Plassche, 1986). It is therefore removed from the sea level reconstruction as a valid SLIP (Fig. 4.2.1). Refer to Fig. 3.2.2 for an image of the upper contact and its associated biostratigraphy.

Furthermore, it is uncertain as to whether the radiocarbon (^{14}C) dated upper contacts of the same intercalated peat bed from within other sections can be reliably transferred to EH3. The results of the diatom analysis provided by Jennings *et al*. (1998) indicate a gradual depletion of brackish valves with elevation. The diatom core (PM3) and the associated intercalated peat bed contained within it is therefore considered to be unaffected by erosion. These findings imply that the regressive contact of the entire intercalated peat bed within Porlock Marsh is not eroded. Instead, the surface erosion is likely to be spatially restricted to EH3. Nonetheless, it is essential that the transgressive overlap of the organic bed within other sections in Porlock Marsh should be verified by biostratigraphic analyses when creating new Holocene sea level index points from peat sequences within Porlock Marsh.

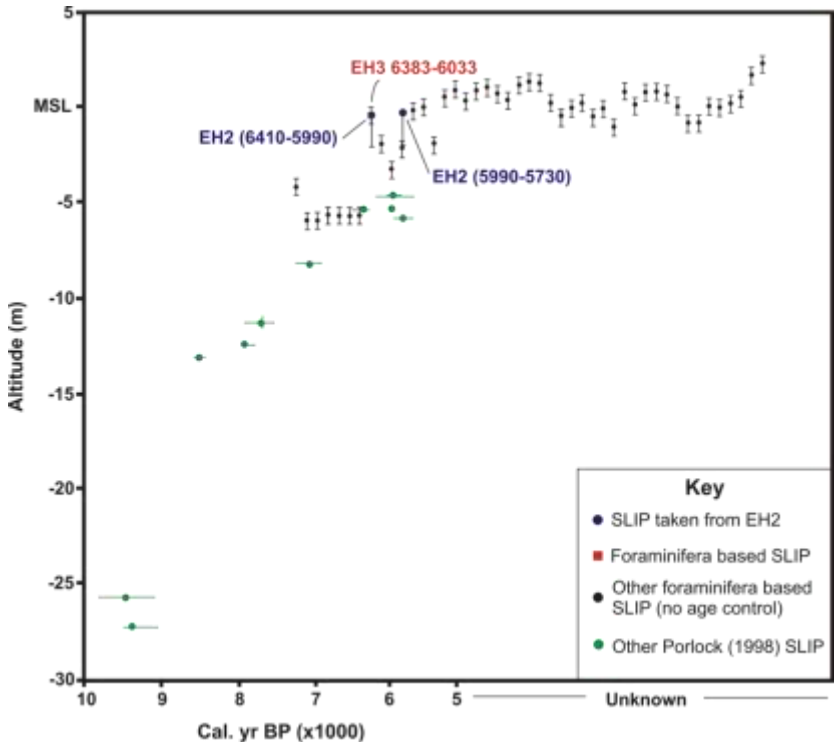


Fig. 4.2.1 – Relative sea-level changes at Porlock. Radiocarbon dated SLIPs have been corrected for autocompaction. The foraminifera based SLIP taken from the upper contact of the organic bed has been removed from the reconstruction as a valid SLIP (Refer to text for explanation)

4.3 Holocene relative sea-level change

The record from Porlock documents a 3.87m rise in RSL since 6383-6033 cal. yr BP. Due to the lack of information surrounding the ages of points within the sea level reconstruction, it is not possible to determine the rates of Holocene sea-level change. Despite the fluctuations, the record from Porlock is in general agreement with others presented for the Bristol Channel (Heyworth and Kidson, 1982). However, the foraminifera based reconstruction outlined in this study displays a 2.88m inflexion in RSL at the end of the sea level curve. Possibly, these sea level points may be outliers from the trend, as the indicative meanings from which they are produced are based on samples containing relatively low counts of foraminifera. However, the final sample, indicating the highest recorded sea level, is derived from a sample containing a large and statistically robust number of foraminifera. Overall, the samples that document the rise in RSL at the most recent end of the sea level curve are not based on exceptionally low counts, and their indication of a significant rise in RSL must be taken into consideration, despite the lack of age control over the sea level reconstruction.

Furthermore, some of the fluctuations constrained within the sea level record may be the result of an inadequate representation of foraminifera within the sample. For example, the sample taken at a depth of 4.90m contains a total count of 95 tests and demonstrates a sharp rise in indicative meaning. In such cases, foraminiferal assemblages are being poorly represented and are hindering the accuracy of the reconstruction when quantifying the elevation with regard to palaeo-sea level. Mostly, calcareous estuarine foraminifera are underestimated in the foraminiferal count. The calcium carbonate that forms the foraminifer's test means they are intolerant to prolonged episodes of subaerial exposure and, as a result, they dissolve (Green *et al*., 1992) and therefore contribute less significantly to fossil assemblages. Gehrels (2000) produced two sea level chronologies of a high marsh and middle marsh site in Maine, U.S.A. Findings indicate that small changes in the numbers of lower marsh and estuarine species considerably affect the indicative meanings of fossil foraminiferal assemblages, thus exaggerating fluctuations.

The location of core EH3 at Porlock Marsh has had an impact on the precision of the sea level curve presented. Scott and Medioli (1978) recognised that foraminifera assemblages occupying the high marsh between MSL and higher high water (HHW) are the most sensitive to changes in elevation. Localised sea level histories that can be derived from fossil sequences contain a greater degree of precision when higher marsh foraminifera are abundant. In core EH3, the foraminifera frequency counts are dominated by large numbers of calcareous forms, their presence being indicative of lower marsh marine deposition. Where foraminifera are discovered that are usually associated with upper marsh elevations, their narrow vertical ranges can be quantified with a greater degree of precision and are therefore of a greater use to sea level investigations (Gehrels and Van de Plassche, 1999). When they are found within a dataset predominantly comprised of calcareous forms, they have a tendency to offset the sea level curve and exaggerate fluctuations. This can be seen in the reconstruction illustrated in this study, as even where high marsh species are found in small quantities, they affect the overall indicative meanings produced by transfer functions significantly. Essentially, transfer functions assign greater 'weight' to high marsh species when producing indicative meanings. A sediment core sampled from a higher elevation at Porlock Marsh will allow for a reconstruction that is more

precise, supported by a reduction in fluctuations created by anomalous indicative meanings. It is therefore essential to pinpoint higher marsh species in order to constrain local sea level movements with greater precision. Although lower-marsh and estuarine foraminifera still have value in sea level reconstructions, their small tolerance to prolonged episodes of subaerial exposure, and low position on the flood duration gradient (Gehrels, 2000), means they are poorly preserved at certain elevations compared to their agglutinated counterparts.

It is clear when analysing the sea level curve (Fig. 4.2.1) that most of the fluctuations indicate a falling sea level. In this sense, the fluctuations within the sea level curve are not oscillating amplitudes, or 'true' fluctuations. Instead, they are caused by a sequence of rises in indicative meaning and are a product of samples where agglutinated higher marsh foraminifera are present in low numbers. The same is true for the substantially offset segment at the oldest end of the sea level curve. The total number of tests counted in these samples reaches as low as 12 in some instances. Therefore, it is irresponsible to assume these points are reliable indicators of palaeo-sea level, and are treated with caution. Moreover, the lack of age control over the entire Porlock sea level curve raises questions regarding its informative and scientific value. However, on the basis of other sea level curves presented for the Bristol Channel, and the comfortable placement of the record within the limits of the Jennings *et al*. (1998) curve of sea level index points, it can be considered a reasonably accurate record of sea-level change in the Porlock and broader Bristol Channel region, and sets a good foundation for further scientific study.

5. Conclusions and recommendations

The application of foraminifera as sea level indicators has proved to be extremely useful at Porlock. Findings indicate a relative sea-level rise of 3.87m since 6383-6033 cal. yr BP. The original palaeo-environmental reconstruction provided by Jennings *et al.* (1998) is verified by the reconstruction provided by foraminifera in this study. However, when checking the accuracy of two sea level index points published by Jennings *et al*. (1998) by comparing the indicative meanings of foraminifera, only one displays a clear match with respect to elevation. Biostratigraphic analysis of the transgressive contact of the highest intercalated peat bed in core EH3 has shown the section to be eroded. However, the brackish diatom assemblages present across the same contact in PM3 (Jennings *et al*., 1998) indicates a gradual transition from a salt marsh to marine environment, and is therefore not considered to be affected by previous erosive processes. Therefore, the erosion of the upper contact of the intercalated peat bed may be spatially exclusive to EH3, although uncertainty remains. It is recommended that sea level index points taken from the transgressive overlap of the highest organic layer from within Porlock Marsh are treated with caution, and should be verified by biostratigraphic analyses before being established as accurate indicators of former sea level. The previously published sea level index points taken from the upper contact within EH2 and EH4 (Jennings *et al*., 1998) should therefore be discounted and be considered 'limiting' sea level index points. Until they are verified by their biostratigraphy, their potential to be eroded raises doubts regarding their position of formation with reference to a former water level. The altitudes of these sea level index points are potentially inaccurate and must be re-examined.

Furthermore, biostratigraphic analysis of the lower intercalated peat bed within EH3 has unveiled that the associated transgressive and regressive contacts should be radiocarbon (^{14}C) dated. Across these contacts, agglutinated salt marsh foraminifera are present in the assemblage counts, and samples are barren of calcareous species. These intercalated clay-peat and peat-clay contacts will provide accurate ages of the precise position of former sea level if radiocarbon (^{14}C) dated. With respect to elevation, if the element of sediment autocompaction is accurately quantified, the transgressive and regressive overlaps of the secondary organic bed in EH3 will allow for the establishment of two new Bristol Channel sea level index points. Interestingly, when analysing the full stratigraphy of Porlock Marsh, the same organic bed may have been sampled by Jennings *et al.* (1998) in section EH2. Here, it occupies a location nearest to basement and has been dated to be early Holocene. The organic layer in EH3 may therefore provide two new sea level index points that are early Holocene in origin, and go further towards accurately constraining the earliest sea level movements in the Bristol Channel since the onset of Holocene sea-level rise.

Finally, this study has illustrated the usefulness of transfer functions in sea level reconstructions. The indicative meanings of fossil foraminifera from Porlock Marsh have been successfully computed by a transfer function developed for the intention of being applied elsewhere. Therefore, the Massey *et al*. (2006) transfer function has regional relevance and applicability and may be applied successfully to other sites in the region as long as the cross-site differences in tidal range are accounted for. The transfer function offers the opportunity for the indicative meanings of foraminifera from salt marshes in the southwest of England to be quantified quickly and effectively, and has proved to be an invaluable tool in the creation of a Holocene relative sea level chronology at Porlock.

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