



Holocene relative sea-level movements along the North Norfolk Coast, UK

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Abstract

Relative changes in Holocene sea level are reconstructed from foraminiferal assemblages in seven cores recovered from the intertidal zone of North Norfolk (Eastern England). A total of 33 radiocarbon and infra-red stimulated luminescence dates provide a detailed chronological framework for these changes. A transfer function approach, developed from modern UK foraminiferal datasets, establishes a series of 21 new sea-level index points for this coastline which are combined with 18 existing index points and a further number of limiting values. Errors associated with changing tidal ranges through the Holocene are reduced by adopting recently developed tidal models for this period. This new approach allows the use of foraminiferal assemblages to be extended from the upper saltmarsh environment (traditionally used for sea-level studies) to lower elevations in the tidal frame and include clastic detrital sediments.

The results confirm the previously observed trend of continuously rising sea-levels in this area during the last 10000 years which is consistent with a Glacial Isostatic Adjustment model. Relative sea-level (RSL) rises from an observed minimum of approximately -13.50 m OD at about 7500 cal. BP to approximately -4.0 m at about 5300 cal. BP, which equates to a mean rise of c. 4.3 mm yr⁻¹. Subsequently, RSL rose gradually to present levels, although there is evidence that a minor reverse in this trend occurred between 4000 and 2000 cal. BP when sea-level fell by about 1 m to c. -3.5 m. The rate of land subsidence for North Norfolk is 0.54 ± 0.03 mm yr⁻¹ (inverse of Late-Holocene sea-level rise).

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1. Introduction

The recognition of sea-level changes based upon the transition from organic to minerogenic sedimentation has formed the backbone of sea-level research in the UK (e.g., Shennan, 1986; Long, 1992; Zong and

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Tooley, 1996). Where microfossil indicators of sea-level change have been used, they have frequently been limited to confirming or refining the interpretations based on these switches in sedimentation. However, the accuracy of reconstructions remains limited by the lack of detailed knowledge of the relationship between relative sea level (RSL), environmental conditions, and the succession of microfossil assemblages. Many interpretations are based on models developed in the 19th century involving a simple classification of taxa into freshwater, brackish or marine forms, and provide only qualitative estimates of past conditions. Given this paucity of ecological information, palaeoecologists working in the coastal zone have recently adopted a transfer function approach to sea-level reconstruction (Horton et al., 1999, 2000; Zong and Horton, 1999; Edwards and Horton, 2000, in press; Gehrels, 2000; Gehrels et al., 2001, 2002; Horton and Edwards, 2001, 2003, 2005, in press; Edwards et al., 2004; Patterson et al., 2004; Sawai et al., 2004a,b).

Transfer functions were pioneered by Imbrie and Kipp (1971) and are routinely employed in a wide range of palaeoecological studies (e.g., Jones and Juggins, 1995; Gasse et al., 1997; Charman, 2001; Noon et al., 2001; Rosén et al., 2003). Birks (1995) outlines the general application of transfer functions to palaeoenvironmental reconstruction, and here we concentrate on their use to reconstruct regional scale Holocene sea levels from numerous cores. We evaluate the relative performance of the transfer function and present its potential implications to Holocene sea-level studies. Of greatest significance is the ability to produce sea-level index points from minerogenic sequences in addition to the transgressive and regressive contacts of intercalated and basal peats. In addition we combine the transfer function reconstructions with index points and limiting dates produced using established techniques, and the current geophysical model (ICE4G, Peltier et al., 2002). Finally, we apply palaeotidal corrections to all sea-level reconstructions and assess the impact of sediment consolidation.

2. Study area

During the last glacial period, it is believed that the southern-most ice margin in the East Anglian region

of Britain rested along a line that is now approximately coincident with the North Norfolk Coast, but that the area was probably ice-free by the last glacial maximum (Bowen et al., 2002). Following the retreat of the ice sheets and with the onset of rising sea levels in the North Sea, a series of sediments were deposited along this coastline that broadly record the balance between crustal readjustment, sediment supply and eustatic sea-level change over the last 10000 years (Andrews et al., 2000; Lambeck, 1995; Shennan et al., 2000a; Peltier et al., 2002; Shennan and Horton, 2002). Holocene sediments from the low-lying region of East Anglia have been studied by a number of authors, from Fenland in the west (e.g., Shennan, 1986) to the southern estuaries of Suffolk (e.g., Brew et al., 1992, 1996), Broadland in the east (e.g., Coles and Funnell, 1981; Boomer and Godwin, 1993; Horton et al., 2004) and North Norfolk (e.g., Funnell and Pearson, 1989; Andrews et al., 2000; Funnell et al., 2000; Horton and Edwards, 2005, in press). The Holocene sediments of the region are predominantly fine-grained detrital with peats intercalated at various levels. The sediments are generally rich in microfossils particularly benthic foraminifera but also contain ostracods, pollen, spores and diatoms. The relationship between the occurrence of foraminifera and depositional environments along this coastline has been detailed in Boomer (1998) and Horton and Edwards (2005).

The modern sedimentary environments of the North Norfolk coast comprise an intricate mosaic of depositional and erosional settings on a widely variable spatial scale. This coastline is characterised by westward-prograding sand and gravel barriers fronting extensive, fine-grained, vegetated saltmarshes. The dominant physical processes of the present-day include onshore wave action from the north-east and longshore wave action supplying sediment from the unconsolidated Pleistocene sediments to the east. These are superimposed upon a local relative sea-level rise of approximately 0.6 mm yr^{-1} (Shennan and Horton, 2002; Horton et al., 2004).

3. Material and methods

Twenty-nine cores along that coastline (Fig. 1) were successfully recovered using the shell and

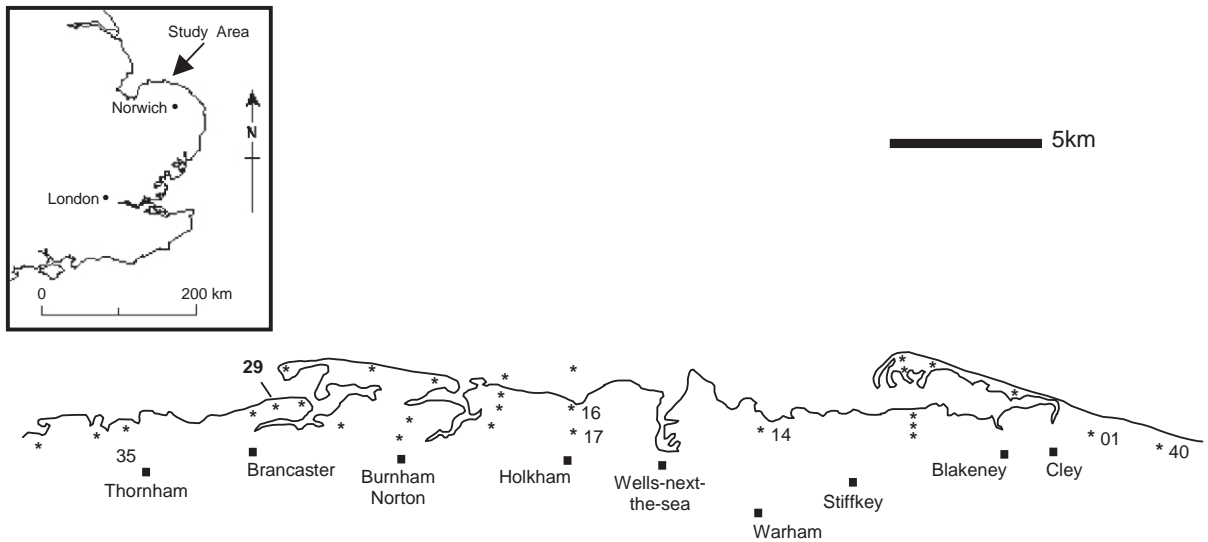


Fig. 1. Location map of core sites along the North Norfolk Coast. Asterisks mark all cores (see Andrews et al., 2000), numbered cores are referred to in this study.

auger method, with support from the British Geological Survey. Where possible, the cores penetrated to the base of the Holocene sequence, with glacial deposits recovered at a number of sites and fresh to weathered Chalk in others (Andrews et al., 2000). Although significant thicknesses of fine-grained back-barrier sediments occurred at some sites, many of the cores penetrating the seaward part of the inter-tidal zone to yield younger, unconformable, sequences of sands and occasional gravels deposited following erosional episodes and the passage of westward barrier progradation (e.g., Scolt Head Island, Blakeney Spit).

Seven cores were selected from the stratigraphic archives that record Holocene inter-tidal sedimentation under conditions of generally rising sea-levels with two distinct facies represented; fine-grained muds, silts and peats and coarser-grained sands and gravels (Fig. 2). Most cores encountered organic-rich basal and/or intercalated deposits (freshwater to marginal saltmarsh peats) within the Holocene. The environmental context of the cores has been determined through an integrated programme of biofacies analyses (Andrews et al., 2000) including the study of pollen, spores, diatoms, foraminifera and ostracods although not all groups were present in all samples. These organisms not only provide sensitive records of the palaeoenvironment but in some cases they also

provide accurate and precise reconstructions of tidal setting. The present study focuses on the application of benthic foraminifera in reconstructing past tidal levels. Although ostracods were also present in most samples their absence from the high-saltmarsh environment and their poor altitudinal control at lower elevations makes them unsuitable for such high-precision transfer function studies.

3.1. Sea-level reconstruction

A sea-level index point has four attributes: geographical position; an age, determined in this study by radiocarbon or infrared stimulated luminescence ages (IRSL) assays; a tendency of movement, either a positive or negative marine influence; and an elevation that can be related to a former sea level. To achieve the latter the indicative meaning of a sea-level indicator must be calculated. The indicative meaning describes the vertical relationship between the local environment in which a sea-level indicator accumulated and a contemporaneous reference tide level (Shennan, 1986; Van de Plassche, 1986; Horton et al., 2000). It is defined in terms of the modern vertical range occupied by the sea-level indicator (the indicative range) measured relative to a given tide level (the reference water level) such as mean high water spring tide (MHWST).

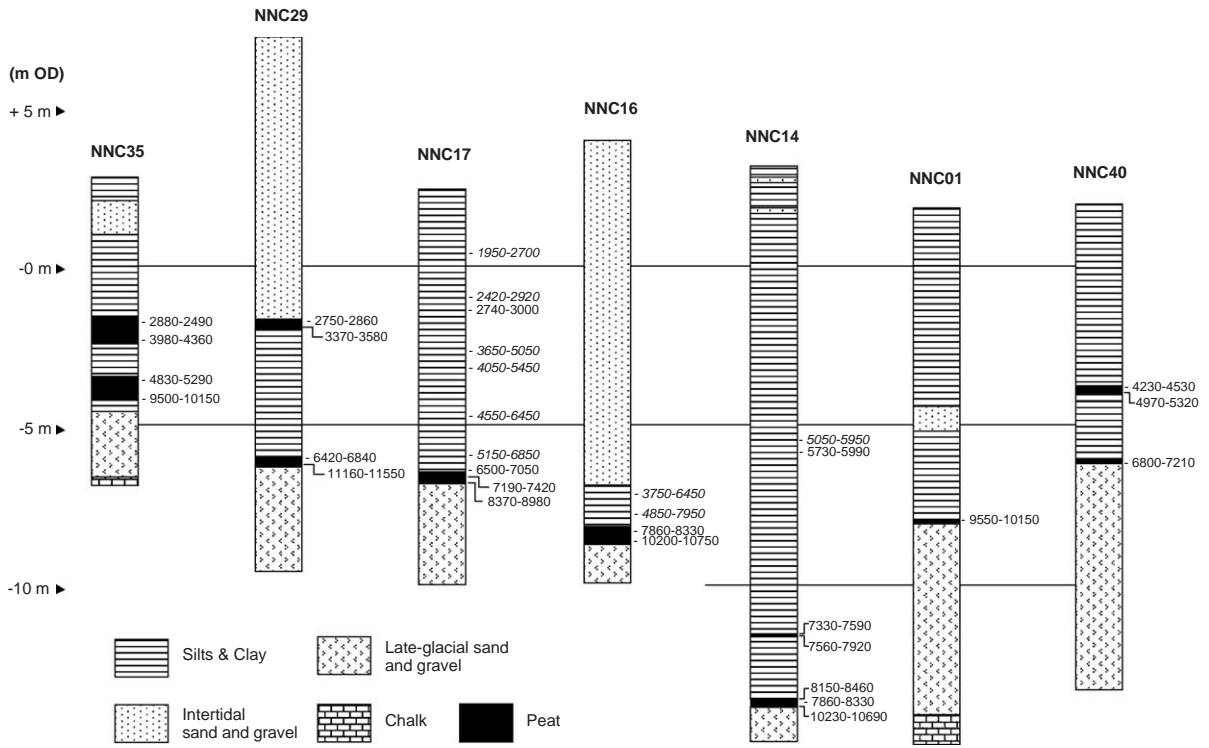


Fig. 2. Sedimentology, relative altitudinal and East to West relationship of cores referred to in text. Dates are calibrated ranges (all ^{14}C except IRSL dates in italics.).

The established approach to reconstruct former sea levels was developed during the International Global Correlation Programme (IGCP) Projects 61 and 200, and is described in *The Manual of Sea-level Research* (Van de Plassche, 1986) as well as a number of earlier papers (Preuss, 1979; Van de Plassche, 1982; Shennan, 1982; Tooley, 1982; Shennan et al., 1983). Shennan (1982) compiled data from a range of sources to permit quantification of the indicative meanings for lithostratigraphic and biostratigraphic contexts commonly used as sources of material for radiocarbon dating. The established approach assumes, where no hiatus is present, that intercalated sedimentary facies formed in environments that existed side by side in space. In this way, by quantifying the range of elevations across which the transition between one sub-environment and another occurs, it is possible to assign an indicative range to a lithostratigraphic or biostratigraphic contact.

Work by Horton et al. (1999) and Horton and Edwards (2005, in press) has recently developed

statistical-based methods to reconstruct indicative meanings based upon the relationship between foraminiferal assemblages and elevation with respect to the tidal frame for the UK. Foraminiferal and elevational data were collected from fifteen contemporary UK intertidal environments (Horton and Edwards, 2005, in press) and combined into a regional dataset. Horton and Edwards (2005) suggest that transfer functions developed from regional training sets are better suited to the analysis of fossil material than those derived from local data since they incorporate a greater range and variety of modern analogues. Local training sets, whilst giving a slight increase in precision, suffer from severely restricted predictive power due to the abundance of ‘no modern analogue’ situations. The elevational data from different marshes were expressed as a standardised water level index (SWLI) that takes account of differences in tidal range between sites, and defines elevation with respect to mean tide level. For example, SWLI=100 if the measured altitude equals MHWST. Conversely,

SWLI=0 if the measured altitude equals mean low water spring tide (MLWST).

Foraminiferal-based transfer functions have been developed using a unimodal-based technique known as weighted averaging partial least squares via the C2 program, version 1.3 (Juggins, 2003). Statistical measures suggest that precise reconstructions of indicative meanings are possible ($r^2=0.75$; root mean squared error of prediction (RMSEP)=6.86) together with sample-specific standard errors of prediction for individual fossil samples (Horton and Edwards, *in press*). Furthermore, Horton and Edwards (*in press*) investigated the issue of transport and mixing by comparing the results of repeat surface foraminiferal surveys from the salt-marshes at Brancaster and Thornham marshes, North Norfolk, and Welwick Marsh, Humber Estuary. Four surveys were taken at each site over the period of one year. These assemblages are calibrated via the 'national' transfer function to produce estimates of elevation that may be compared with the true (observed) elevation at which the sample was collected. These results suggest, for the surveyed salt-marshes at least, that foraminiferal assemblages from all environments of the intertidal zone retain a consistent elevation signature and may therefore be reliably used to reconstruct RSL changes (Horton and Edwards, *in press*).

In this paper we calibrate the foraminiferal-based transfer function of Horton and Edwards (2005, *in press*) to the Holocene sequences from the North Norfolk coastline to produce new sea-level index points. The calibration process assigns a SWLI to each fossil sample, and this is then back-transformed, to express the former elevation of each sample in metres with respect to mean sea level. In the following sections we apply the transfer function approach to seven cores from the Norfolk intertidal zone.

3.2. Age model

The chronological framework for the core is provided primarily by radiocarbon determinations and additionally by IRSL. A number of peats and other organic remains (wood, mollusc shell) were radiocarbon-dated (Andrews *et al.*, 2000). Samples for luminescence dating were taken from opaque core liners under subdued red light and sealed in black plastic containers to preserve water content. Andrews *et al.*

(2000) obtained the ages via the age equation in its simplest form:

$$\text{Luminescence age} = \frac{\text{palaeodose}}{\text{annual dose}}. \quad [1]$$

Evaluation of palaeodose and annual dose was determined via analytical techniques of Bailiff and Tooley (2000). We calibrated the radiocarbon data using the Intcal98 calibration curve (Stuiver *et al.*, 1998) and combined with the IRSL ages and associated stratigraphic information using OxCal (ver. 3.5: Bronk Ramsey, 1995; 1998). The resulting sequence of ages was interpolated to produce the general accumulation history that takes into account the variability in sedimentation. The age model is used to temporally constrain the variations in mean sea level identified from the foraminiferal data. All dates are reported as calibrated BP.

4. Core details

4.1. Core NNC40

Core NNC40 was the easternmost core taken during this study and was located by the main coast road, west of Salthouse. The core penetrated 15 m of sediments. The lowest 7 m were probably late-glacial in origin. This was overlain by a thin basal peat succeeded by approximately 8 m of fine-grained intertidal sediments (Fig. 3). A mid-section peat was recorded 2 m above the basal peat. A single radiocarbon date from the basal peat gave an age of 7210–6800 cal. BP while the mid-section peat was radiocarbon dated as 5320–4970 cal. BP and 4530–4230 cal. BP for the regressive and transgressive contacts, respectively.

The basal peat is barren of foraminifera, however the assemblages of the lower clastic unit and the intercalated peat are dominated by agglutinated foraminifera (*Jadammina macrescens* and *Trochammina inflata*), which are indicative of a saltmarsh environment. The calcareous species *Haynesina germanica* occurs in the assemblage of the upper clastic unit and indicates an increase in marine influence but still a saltmarsh environment. The reconstructed SWLIs are between 100 and 102 (i.e., MHWST to 0.12 m above local MHWST).

Code	Altitude m OD	Foraminiferal abundance (%)					SWLI	Error
		<i>Jadammina macrescens</i>	<i>Miliammina fusca</i>	<i>Trochammina inflata</i>	<i>Trochammina inflata</i>	<i>Haynesina germanica</i>		
NNC40_220	-0.30	73	0	25	0	2	98.42	8.92
NNC40_260	-0.70	78	0	19	0	3	97.86	8.93
NNC40_420	-2.30	79	0	12	0	9	94.77	8.93
NNC40_554	-3.64	63	2	31	4	0	98.91	8.93
NNC40_575	3.85	45	0	55	0	0	99.54	8.93
NNC40_590	-4.00	40	0	60	0	0	99.78	8.96
NNC40_680	-4.90	67	0	33	0	0	101.15	8.92
NNC40_760	-5.70	58	0	42	0	0	100.67	8.92

Altitude (m OD)	Method	Age cal. BP		
		Max	Mid	Min
-3.64	¹⁴ C	4530	4380	4230
-3.85	¹⁴ C	5320	5145	4970
-5.92	¹⁴ C	7210	7005	6800

Fig. 3. Core NNC40 Salthouse, Foraminiferal diagram. Foraminiferal abundance is calculated as a percentage of total foraminiferal tests. Stratigraphy and assays (expressed in calibrated years BP) and reconstructed standardized water level indices (SWLIs) are shown (MHWST=100; MLWST=0).

4.2. Core NNC01

Core NNC01 was situated at the eastern end of Blakeney Spit on the Cley Marshes Nature Reserve. Almost 17 m of material was recovered with chalk encountered at the base. The Holocene sequence consists of 10 m of entirely fine-grained intertidal sediments. A small peat was recorded at the base of the silts which was dated to 10150–9550 cal. BP (Fig. 4). From the peat and overlying silts and a small sandy cut at about 4.60–5.30 m OD a total of 22 microfossil samples were prepared and the foraminifera recorded. The samples from the peat proved to be barren, however, the next sample from the overlying clastic unit is dominated by the agglutinated foraminifera *Jadammina macrescens* and *Trochammina inflata*, which are indicative of saltmarsh conditions. In the succeeding clastic sequence the agglutinated foraminifera are replaced by a high diversity calcareous assemblage dominated by *Haynesina germanica*, which suggests a switch from saltmarsh to estuarine or tidal flat conditions. This pattern is reversed in the upper 2–3 m with saltmarsh taxa dominating before the final disappearance of the foraminifera in the top metre of sediment. The changes in the environment of Core

NNC01 indicated by the litho- and biostratigraphy are reflected in the transfer function. The upper and lower portions of the core, dominated by agglutinated foraminifera, have relative high SWLIs (greater than 99, i.e., at or above MHWST) whereas the calcareous foraminifera cause the SWLIs to decrease to less than 85 (c. 1 m below MHWST).

4.3. Core NNC14

Core NNC14 was taken on the extensive Warham Salt Marshes (Warden Marsh). The core at this site penetrated the greatest thickness of sediments in the study reaching almost 19 m at the base. Fine-grained sediments constituted most of the sequence reaching a depth of almost 17.50 m (c. 14.5 m OD) and resting on a 0.30 m thick peat (Fig. 5). The basal peat was dated to 10230–10690 cal. BP at its base and 8150–8460 cal. BP at the transgressive contact. A mid-peat sample returned a date of 8150–8540 cal. BP. A second, smaller peat 2 m above the basal peat returned dates of 7920–7560 and 7590–7330 cal. BP for the regressive and transgressive contacts, respectively. An additional suite of three IRSL (10750–7650; 5950–5050; 5850–4450 cal. BP) dates and an AMS assay (5990–5730 cal. BP) on an in situ *Scrobicularia* shell were also obtained from this core.

Twenty microfossil samples were investigated from this core. The basal peat and the overlying organic-rich silty sediments were barren but the sequence soon yielded saltmarsh (e.g., *Jadammina macrescens* and *Trochammina inflata*) and estuarine or tidal flat (*Ammonia* spp., *Elphidium williamsoni* and *Haynesina germanica*) assemblages. At a depth of about –7.00 m OD the saltmarsh assemblage became established and persisted throughout much of the succeeding sequence, although the uppermost three samples were either barren or contained very few foraminifera. The transfer function parallels the foraminiferal changes; SWLI increases up-core from a minimum of 66 (2.25 m below MHWST) at –12.10 m OD to 0.13 m above local MHWST (102) at –5.10 m OD.

4.4. Core NNC16

Core NNC16 was drilled just in front of the dunes at Holkham Gap and produced about 13 m of post-glacial sediments, however, the majority of the sedi-

Code	Altitude m OD	Haplophragmoides spp.	Jadammina macrescens	Miliammina fusca	Trochammina inflata	Ammonia spp	Elphidium excavatum	Elphidium magellanicum	Elphidium williamsoni	Haynesina germanica	Quinqueloculina spp.	Sub-tidal	SWLI	Error
NNC01_110	0.75	0	40	0	60	0	0	0	0	0	0	0	99.78	8.96
NNC01_150	0.35	0	89	0	11	0	0	0	0	0	0	0	102.27	8.94
NNC01_225	-0.40	0	90	0	5	0	0	0	0	5	0	0	101.74	8.95
NNC01_285	-1.00	0	51	0	49	0	0	0	0	0	0	0	100.35	8.93
NNC01_323	-1.38	0	50	0	50	0	0	0	0	0	0	0	100.28	8.93
NNC01_368	-1.83	0	28	0	4	2	0	0	6	60	0	0	90.59	8.95
NNC01_426	-2.41	0	4	0	5	5	0	0	2	83	0	0	86.95	9.00
NNC01_489	-3.04	0	1	0	2	4	1	0	2	89	0	0	86.34	9.03
NNC01_525	-3.40	0	1	0	2	3	1	0	4	88	1	0	85.99	9.03
NNC01_590	-4.05	0	17	0	7	4	0	0	4	68	0	0	89.22	8.96
NNC01_635	-4.50	0	1	0	12	9	2	0	6	70	0	0	85.54	8.97
NNC01_677	-4.92	0	12	0	39	3	1	0	12	32	0	0	90.65	8.93
NNC01_710	-5.25	0	8	0	31	0	0	0	8	54	0	0	90.45	8.95
NNC01_730	-5.45	0	2	0	0	3	0	0	2	89	1	2	85.91	9.03
NNC01_785	-6.00	0	3	0	0	5	1	0	0	89	0	0	86.27	9.03
NNC01_835	-6.50	0	3	0	5	8	5	0	3	72	0	3	84.42	8.99
NNC01_890	-7.05	0	5	0	4	11	1	0	5	74	0	1	85.02	8.98
NNC01_940	-7.55	0	8	0	0	9	1	0	4	78	0	0	85.70	8.99
NNC01_987	-8.02	0	75	0	25	0	0	0	0	0	0	0	101.55	8.92

Altitude (m OD)	Method	Age cal. BP		
		Max	Mean	Min
-8.04	¹⁴ C	10150	9850	9550

Fig. 4. Core NNC01 Cley Marshes Nature Reserve, foraminiferal diagram. Foraminiferal abundance is calculated as a percentage of total foraminiferal tests. Stratigraphy and assays (expressed in calibrated BP) and reconstructed standardized water level indices (SWLIs) are shown (MHWST=100; MLWST=0).

ments were of relatively well-sorted sands and occasional pebble horizons (Fig. 6). The basal part of the sequence did yield a peat (0.55 m thick) which was dated to 10750–10200 cal. BP at the base and 8330–7860 cal. BP at the top. Overlying the peat is just over 1 m of silts which yielded dates using the IRSL technique of 7950–4850 and 6450–3750 cal. BP.

Eight foraminiferal samples were examined from the silts and peat. Foraminifera are absent from the peat samples, but the silty-clay shows a predominantly calcareous assemblage (*Ammonia* spp., *Elphidium williamsoni* and *Haynesina germanica*) which reverts to an agglutinated assemblage at the top, indicating a transition to saltmarsh conditions. The transfer function reflects this change showing a relatively constant SWLI (81 to 85; c. 1.1 m below MHWST) between –6.98 and –8.00 m OD before a rapid rise to above MHWST (102) at –6.78 m OD.

4.5. Core NNC17

Core NNC17 was drilled just a few hundred metres directly to the south (landward) of core NNC16. The total core depth was just over 12 m with a lower unit of approximately 4 m of late-glacial sediments overlain by a basal peat, recorded at an elevation of –6.70 to –6.34 m OD and radiocarbon dated to 8976–8374, 7424–7188 and 7050–6500 cal. BP from the bottom, middle and top of the peat, respectively (Fig. 7). The peat is in turn overlain by an olive-grey silt-clay, containing dispersed organic remains and numerous bivalve fragments. Six IRSL (6850–5150; 6450–4550; 5450–4050; 5050–3650; 2920–2420; 2700–1950 cal. BP) dates and an AMS assay (3000–2740 cal. BP) on a *Scrobicularia* shell in situ were obtained from this part of the core indicating deposition between approximately 6850–1950 cal. BP.

Code	Altitude (m OD)	<i>Haplophragmoides</i> spp.	<i>Jadammina macrescens</i>	<i>Miliammina fusca</i>	<i>Trochammina inflata</i>	<i>Ammonia</i> spp.	<i>Elphidium excavatum</i>	<i>Elphidium magellanicum</i>	<i>Elphidium williamsoni</i>	<i>Haynesina germanica</i>	<i>Quinqueloculina</i> spp.	Sub-tidal	SWLI	Error
NNC14_20	2.90	0	64	0	36	0	0	0	0	0	0	0	100.97	8.92
NNC14_390	-0.80	0	93	0	7	0	0	0	0	0	0	0	102.44	8.95
NNC14_515	-2.05	0	23	0	6	4	2	0	1	63	0	0	90.25	8.95
NNC14_590	-2.80	0	58	0	42	0	0	0	0	0	0	0	100.69	8.92
NNC14_690	-3.80	0	41	0	58	0	0	0	0	0	0	0	99.65	8.95
NNC14_820	-5.10	0	83	0	17	0	0	0	0	0	0	0	101.94	8.93
NNC14_896	-5.86	0	71	0	27	0	0	0	0	1	0	0	101.15	8.92
NNC14_970	-6.60	0	40	0	60	0	0	0	0	0	0	0	99.78	8.96
NNC14_1090	-7.80	0	1	0	0	31	1	0	20	47	0	1	77.17	9.09
NNC14_1190	-8.80	0	2	0	1	21	10	0	8	55	0	3	80.12	9.04
NNC14_1310	-10.00	0	0	0	0	64	1	0	6	29	0	0	72.09	9.79
NNC14_1370	-10.60	0	13	0	39	14	3	0	12	17	0	2	87.33	8.97
NNC14_1496	-11.86	0	1	0	0	15	3	0	1	80	0	0	83.77	9.02
NNC14_1520	-12.10	0	1	0	0	96	0	0	0	3	0	0	66.22	10.97
NNC14_1610	-13.00	0	0	0	0	100	0	0	0	0	0	0	65.19	11.15

Altitude (m OD)	Method	Age cal. BP		
		Max	Mid	Min
-3.20	IRSL	5850	5150	4450
-5.41	IRSL	5950	5500	5050
-5.50	¹⁴ C	5990	5860	5730
-12.41	¹⁴ C	7590	7460	7330
-12.47	¹⁴ C	7920	7740	7560
-13.23	IRSL	10750	9200	7650

Fig. 5. Core NNC14 Warham Marsh, foraminiferal diagram. Foraminiferal abundance is calculated as a percentage of total foraminiferal tests. Stratigraphy and assays (expressed in calibrated years BP) and reconstructed standardized water level indices (SWLIs) are shown (MHWST=100; MLWST=0).

Twenty-four foraminiferal samples were examined from the silts and peat. Foraminifera are absent in the lower portions of the basal peat, however, agglutinated species (e.g., *Jadammina macrescens* and *Trochammina inflata*) dominate the transgressive contact, indicating a saltmarsh environment. In the overlying silt–clay, percentage frequencies of agglutinated species fall, reflecting the increased abundance of calcareous taxa. The assemblage is dominated by *Ammonia* spp., *Haynesina germanica* and *Elphidium* species, and is indicative of estuarine or tidal flat environments. Towards the top of the core an increase in relative abundance of agglutinated taxa suggests a return to saltmarsh conditions. The maximum SWLI (102) occurs within the peat, 0.13 m above local MHWST, associated with the agglutinated saltmarsh

foraminifera. The SWLIs rapidly decline above the transgressive contact and within the silt–clay reaching a minimum of 73 (1.77 m below MHWST).

4.6. Core NNC29

Core NNC29 was taken on the seaward margin of Brancaster Golf Course and penetrated over 16 m of sediments. The lowest 3 m were considered to be of late-glacial in origin based on their sedimentology (poorly sorted sands and gravels) and correlation with pre-Holocene sediments elsewhere along the coast (Andrews et al., 2000). Above this layer there was a basal peat followed by 4 m of fine-grained clastic sediments capped by a second peat (Fig. 8). The basal peat was dated to 6841–6416 cal. BP at the

Code	Altitude m OD	Foraminiferal abundance (%)										SWLI	Error
		<i>Jadammina macrescens</i>	<i>Miliammina fusca</i>	<i>Trochammina inflata</i>	<i>Ammonia</i> spp.	<i>Elphidium excavatum</i>	<i>Elphidium williamsoni</i>	<i>Haynesina germanica</i>	<i>Quinqueloculina</i> spp.	Sub-tidal			
NNC16_1080	-6.78	85	0	15	0	0	0	0	0	0	0	102.07	8.94
NNC16_1100	-6.98	2	0	0	3	0	0	81	3	10		83.41	9.00
NNC16_1140	-7.38	3	0	2	25	1	2	54	12	2		81.51	9.02
NNC16_1192	-7.90	11	0	2	33	0	4	46	3	0		81.28	9.11
NNC16_1196	-7.94	11	0	1	9	0	13	67	0	0		85.09	8.96
NNC16_1200	-7.98	3	0	1	11	0	15	69	0	0		83.12	8.97
NNC16_1202	-8.00	13	0	8	9	0	28	32	1	6		81.66	8.92

Altitude (m OD)	Method	Age cal. BP		
		Max	Mid	Min
-7.09	IRSL	6450	5100	3750
-7.87	IRSL	7950	6400	4850
-8.04	¹⁴ C	8330	8095	7860
-8.57	¹⁴ C	10750	10475	10200

Fig. 6. Core NNC16 Holkham, foraminiferal diagram. Foraminiferal abundance is calculated as a percentage of total foraminiferal tests. Stratigraphy and assays (expressed in calibrated BP) and reconstructed standardized water level indices (SWLIs) are shown (MHWST=100; MLWST=0).

top and 11553–11164 cal. BP at the base while the intercalated peat was dated to 3577–3372 cal. BP at the regressive contact and 2862–2749 cal. BP at the transgressive contact. The intercalated peat is abruptly overlain by a fine to medium yellow brown sand with broken shell fragments.

The samples from the basal peat were barren of foraminifera. Foraminifera from the lower samples of the overlying silt are dominated by calcareous species such as *Ammonia* spp., *E. excavatum* and *Haynesina germanica*. This calcareous assemblage, indicative of estuarine conditions, is replaced by agglutinated species such as *Jadammina macrescens* and *Trochammina inflata*, suggesting a return to saltmarsh conditions, just below and within the intercalated peat. Foraminiferal data from the overlying sand shows a return to a calcareous assemblage. The reconstructed SWLI increases from 81 (1.26 m below MHWST) at –5.58 m OD at the base of the silt unit, above the basal peat, to 101 (0.07 m above MHWST) at –3.63 m OD below the regressive contact with the intercalated peat.

4.7. Core NNC35

Core NNC35 was the westernmost core taken during this project and was located on the seaward edge of

the modern saltmarsh at Thornham. The sequence yielded almost 7 m of Holocene sediments overlying about 2.5 m of late-glacial sand and pebbles. The sequence rested on a weathered chalk surface at about –6.5 m OD. The Holocene sequence contained two peats each of about 1 m thickness in the lower half of the Holocene section. The peats were set in grey, fine-grained intertidal sediments which continued through to the top of the core, apart from a 1.2 m interval of sand and gravels near the top of the core. The basal and upper intercalated peats are found at depths of –3.98 m (10150–9500 cal. BP) to –3.17 m OD (5290–4830 cal. BP) and –1.97 m OD (4360–3980 cal. BP) to –1.11 m OD (2880–2490 cal. BP), respectively. Foraminiferal tests are absent at the lower contacts of both peats (Fig. 9). However, the remaining samples are dominated by *Jadammina macrescens* and *Trochammina inflata*, which suggests a saltmarsh environment and thus, the reconstructed SWLIs are relatively similar (c.102 or c. 0.1 m above local MHWST).

5. Reconstructing Holocene sea-level change

The value of samples as indicators of former sea levels can only be assessed following a consideration

Code	Altitude m OD	<i>Jadammina macrescens</i>	<i>Miliammina fusca</i>	<i>Trochammina inflata</i>	<i>Tiphotocha comprimata</i>	<i>Ammonia</i> spp	<i>Elphidium excavatum</i>	<i>Elphidium williamsoni</i>	<i>Haynesina germanica</i>	<i>Quinqueloculina</i> spp.	Sub-tidal	SWLI	Error
NNC17_180	0.57	12	0	1	0	18	6	15	42	0	6	80.24	8.98
NNC17_225	0.12	8	0	1	0	41	8	3	31	0	8	75.90	9.29
NNC17_240	-0.03	14	0	4	0	11	0	4	54	0	14	82.20	8.94
NNC17_300	-0.63	13	0	3	0	24	6	10	36	0	8	79.77	9.02
NNC17_325	-0.88	22	0	2	0	9	2	11	44	0	10	83.60	8.92
NNC17_350	-1.13	0	0	0	0	13	6	16	52	0	12	77.48	8.97
NNC17_400	-1.63	3	0	2	0	22	7	15	43	1	8	77.71	9.02
NNC17_425	-1.88	1	0	0	0	16	0	0	69	7	6	82.00	8.98
NNC17_445	-2.08	5	0	1	0	59	14	6	12	3	1	72.81	9.82
NNC17_500	-2.63	2	0	0	0	23	4	2	69	0	0	81.80	9.05
NNC17_550	-3.03	0	0	0	0	15	2	2	75	2	4	82.14	8.99
NNC17_600	-3.63	3	0	2	0	9	1	3	82	1	0	85.26	9.00
NNC17_650	-4.13	12	0	1	0	5	3	3	74	2	0	87.40	8.98
NNC17_700	-4.23	1	0	1	0	5	1	1	91	0	0	86.07	9.03
NNC17_743	-5.06	1	0	10	0	6	1	4	77	1	0	86.33	8.99
NNC17_800	-5.63	0	0	1	0	3	1	1	95	0	0	86.45	9.05
NNC17_835	-5.98	51	0	21	0	0	0	0	17	11	0	97.51	8.90
NNC17_861	-6.24	72	1	26	1	0	0	0	0	0	0	101.51	8.92
NNC17_865	-6.28	84	0	16	0	0	0	0	0	0	0	101.98	8.93
NNC17_867	-6.30	85	0	15	0	0	0	0	0	0	0	102.02	8.93
NNC17_869	-6.32	86	0	14	0	0	0	0	0	0	0	102.14	8.94
NNC17_871	-6.34	62	0	38	0	0	0	0	0	0	0	100.89	8.92

Altitude (m OD)	Method	Age cal. BP		
		Max	Mid	Min
0.54	IRSL	2700	2325	1950
-1.44	IRSL	2920	2670	2420
-1.61	¹⁴ C	3000	2870	2740
-2.94	IRSL	5050	4350	3650
-3.00	IRSL	5450	4750	4050
-4.88	IRSL	6450	5500	4550
-6.10	IRSL	6850	6000	5150
-6.36	¹⁴ C	7050	6775	6500
-6.53	¹⁴ C	7424	7313	7188
-6.70	¹⁴ C	8976	8549	8374

Fig. 7. Core NNC17 Holkham, foraminiferal diagram. Foraminiferal abundance is calculated as a percentage of total foraminiferal tests. Stratigraphy and assays (expressed in calibrated BP) and reconstructed standardized water level indices (SWLIs) are shown (MHWST=100; MLWST=0).

of errors affecting the calculation of sea-level index points. Significant errors are possible in the estimation of the elevation and age of index points, such as tidal range change through time. It is important to state clearly the extent of such errors because they may equal or exceed the trends in RSL and, therefore, produce invalid interpretations. Many existing approaches assume that tidal range has remained constant through time, although it is acknowledged that

by making these assumptions the value of the indicative meaning is reduced (Shennan, 1986; Horton et al., 2000). Woodworth et al. (1991) indicated that there could be long-term changes in the tidal regime of the north-west European continental shelf as the result of changes in the deep ocean tides bordering the shelf. These may stem from long-term changes in the tidal potential arising from variations in the orbital elements of the Sun and Moon, from long-term changes

Code	Altitude m OD	<i>Jadammina macrescens</i>	<i>Trochammina inflata</i>	<i>Ammonia</i> spp	<i>Elphidium excavatum</i>	<i>Elphidium williamsoni</i>	<i>Haynesina germanica</i>	Sub-tidal	SWLI	Error
NNC29_740	-0.33	10	4	17	12	3	48	6	83.17	9.01
NNC29_815	-1.08	4	1	21	13	18	35	8	84.57	9.06
NNC29_876	-1.69	31	51	4	0	4	9	1	98.14	9.06
NNC29_917	-2.10	9	91	0	0	0	0	0	98.23	9.08
NNC29_1070	-3.63	80	15	1	0	0	4	0	101.08	8.93
NNC29_1170	-4.63	19	4	17	10	2	46	1	85.19	9.01
NNC29_1265	-5.58	15	1	24	10	4	39	7	80.57	9.06

Altitude (m OD)	Method	Age cal. BP		
		Max	Mid	Min
-1.68	¹⁴ C	2862	2776	2749
-1.94	¹⁴ C	3577	3467	3372
-5.87	¹⁴ C	6841	6670	6496
-6.49	¹⁴ C	11553	11267	11164

Fig. 8. Core NNC29 Brancaster, foraminiferal diagram. Foraminiferal abundance is calculated as a percentage of total foraminiferal tests. Stratigraphy and assays (expressed in calibrated BP) and reconstructed standardized water level indices (SWLIs) are shown (MHWST=100; MLWST=0).

in the shape or depth of the major ocean basins or from the rate of global tidal dissipation. Furthermore, various researchers have noted that tidal range is strongly influenced by shelf width and basin configuration (Redfield, 1958; Jardine, 1975; Cram, 1979; Woodworth et al., 1991). Coastlines which are fronted by a wide shallow shelf or by a semi-enclosed sea (such as at North Norfolk) are most susceptible to tidal range changes (Gehrels et al., 1995).

To reduce the error associated with tidal range change for sea-level reconstructions from the North Norfolk coast, we have used the Holocene tidal models developed by Shennan et al. (2000b, 2003). Their tidal modelling approach predicts tides for past bathymetries and coastline configurations to give predictions of tide levels for the east coast of England. Contemporaneous investigations for the coastal areas (Andrews et al., 2000; Brew et al., 2000; Horton et al., 2000; Metcalfe et al., 2000; Rees et al., 2000) provide the information to produce better palaeobathymetric and palaeogeographic reconstructions. The models predict an increase in tidal range for the western North Sea during the Holocene. For example, the model estimates the tidal range of the North Norfolk coast has increased 0.8 m during the last 7000 years.

Fig. 10a shows an age–elevation plot of all validated index points, including the data from this study, for North Norfolk. It comprises 21 sea-level index points reconstructed using foraminiferal-based transfer function, and a further 18 index points from cores in this study and others (e.g., Shennan and Horton, 2002) using established techniques (e.g., Shennan, 1986; Long, 1992; Zong and Tooley, 1996) where foraminifera are either absent or in low numbers. For example, foraminiferal tests are absent at the lower contact of the intercalated peat from Core NNC 35, however, diatom assemblages are dominated by polyhalobous (e.g., *Opephora pacifica* and *Paralia sulcata*) and mesohalobous (e.g., *Achnanthes delicatula* and *Navicula peregrina*) taxa, respectively, which indicates that the peat must have been deposited under saltmarsh conditions (Horton, 1997). In addition to the 39 index points, a further 20 dated samples from freshwater peats along this coastline do not show a direct relationship to the contemporaneous tide levels. They could have formed at approximately the level of MHWST or an unknown height above that level. Therefore they act as limiting dates, in that RSL must have been at or below the level at which they are found (Table 1).

Code	Altitude m OD	<i>Haplophragmoides</i> spp.	<i>Jadammina macrescens</i>	<i>Miliammina fusca</i>	<i>Trochammina inflata</i>	<i>Ammonia</i> spp	<i>Elphidium excavatum</i>	<i>Haynesina germanica</i>	<i>Quinqueloculina</i> spp.	SWLI	Error
NNC35_20	2.55	0	90	0	3	0	0	2	4	101.46	8.94
NNC35_270	0.05	0	36	0	64	0	0	0	0	99.58	8.97
NNC35_386	-1.11	0	100	0	0	0	0	0	0	102.80	8.97
NNC35_520	-2.45	0	12	0	88	0	0	0	0	98.35	9.07
NNC35_592	-3.17	6	53	14	27	0	0	0	0	101.89	8.90
NNC35_672	-3.97	0	33	0	67	0	0	0	0	99.44	8.98

Altitude (m OD)	Method	Age cal. BP		
		Max	Mid	Min
-1.11	¹⁴ C	2880	2685	2490
-1.97	¹⁴ C	4360	4170	3980
-3.17	¹⁴ C	5290	5060	4830
-3.37	¹⁴ C	5590	5450	5310
-3.98	¹⁴ C	10150	9825	9500

Fig. 9. Core NNC35 Brancaster, foraminiferal diagram. Foraminiferal abundance is calculated as a percentage of total foraminiferal tests. Stratigraphy and assays (expressed in calibrated BP) and reconstructed standardized water level indices (SWLIs) are shown (MHWST=100; MLWST=0).

Fig. 10a shows relative sea-level rising from an observed minimum of -13.48 ± 0.20 m at 7628–7397 cal. BP to approximately -4.09 ± 0.22 m at 5560–5083 cal. BP, which equates to a rise of c. 4 mm yr⁻¹. This includes an increase of c. 5 m around 7000 cal. BP (Fig. 10a). Thereafter, relative sea-level gradually rises to present levels except for a possible 1 m oscillation in sea-level between 4000 and 2000 cal. BP when sea-level falls to c. -3.5 m. This oscillation in relative sea-level has been observed elsewhere on the North Norfolk coastline (Horton and Edwards, 2005, in press; Edwards and Horton, in press) and Humber Estuary (Parnell, unpublished data).

The plot of all index points from North Norfolk confirms the upward trend of Holocene RSL to present. This is typical of an area at or beyond the margins of the last British ice sheet, rapid in the Early Holocene then at a much reduced rate in the Mid- and Late-Holocene (e.g., Shennan et al., 2000a; Shennan and Horton, 2002). Shennan et al. (2000a) identified local scale and regional scale factors to explain spatial and temporal variations in the altitude of Holocene sea-level index points from the east coast of England. The isostatic effect of the glacial rebound

process, including both the ice (glacio-isostatic) and water (hydro-isostatic) load contributions, explains regional-scale differences along the east coast of England: c. 20m range at 8 ka cal BP and by 4 ka cal BP relative sea level in Northumberland was above present, whereas in areas to the south, including North Norfolk, relative sea level has been below present throughout the Holocene.

The Glacial Isostatic Adjustment (GIA) model ICE-4G of Peltier et al. (2002), with lithospheric thickness=90 km, gives good RSL fits globally as well as for much of the Holocene for the North Norfolk data. Peltier et al. (2002) revised the ice model for Great Britain to fit with published observations on ice limits and heights, and more significantly incorporated a different chronology for the partial deglaciation of Antarctica. Nevertheless, there are still disagreements between the model predictions and observations in the Early Holocene (c. 2 m at c. 7500 cal. yr BP). Shennan et al. (2002) suggest that a finer temporal resolution GIA model may be needed to resolve misfits between model predictions and RSL observations. For North Norfolk an offset of only 500 yr later, half the time step of the ICE4G model, would

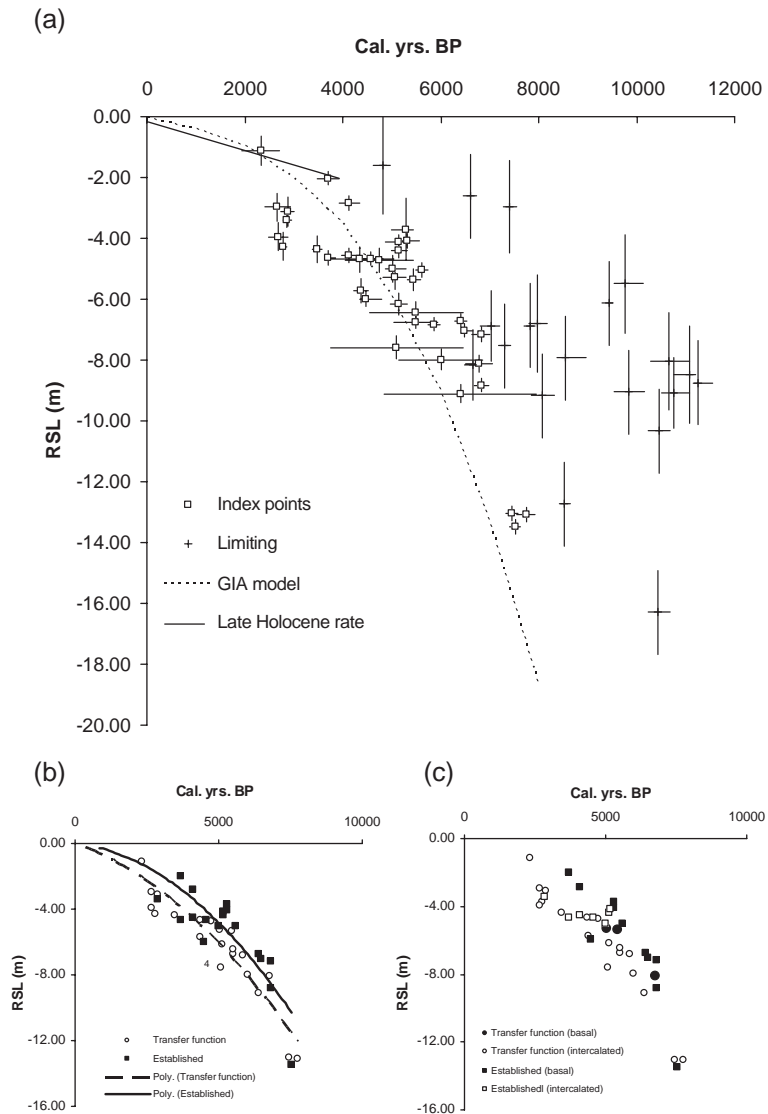


Fig. 10. (a) Reconstruction of Holocene sea level for North Norfolk. Glacial Isostatic Adjustment (GIA) model ICE4G (Peltier et al., 2002) and calculated rate of Late Holocene land uplift/subsidence are also shown. (b) Reconstruction of Holocene sea level for North Norfolk showing foraminifera-based transfer function and established methods including best-fit polynomials. (c) Reconstruction of Holocene sea level for North Norfolk showing basal and intercalated index points.

virtually eliminate the misfits. Conversely, it should be noted that the variability in sediment accumulation rates may influence the age model of each core.

The data from North Norfolk provide further important information regarding Late-Holocene rates of relative uplift or subsidence (Fig. 10a). We calculated these rates by inserting best-fit linear-trend using an intercept free model. In order to provide a compa-

parison of a similar analysis with the Great Britain dataset (Shennan and Horton, 2002) we estimate the rate for each area using all index points younger than 4000 cal yr BP., which equates to 0.89 ± 0.08 mm yr^{-1} . However, due to the broad scatter of index points, all of which are unconsolidated intertidal sediment, we place the line towards the top of the scatter to make an allowance for sediment consolidation

(following Shennan and Horton, 2002). Thus the ‘best estimate’ of land subsidence for North Norfolk is $0.54 \pm 0.03 \text{ mm yr}^{-1}$ (inverse of Late-Holocene sea-level rise), which is slightly lower than previous estimates for North Norfolk (0.6 mm yr^{-1}) but still consistent with other data on the east coast of England; from the Humber to Kent all the estimates fall in the range 0.6 to 0.9 mm yr^{-1} (Shennan and Horton, 2002). The dated index points, thus, provide Late-Holocene trends in relative sea-level change for North Norfolk prior to any possible acceleration during the twentieth century (e.g., Houghton, 2001).

The Lowestoft tidal station estimates the twentieth century mean sea-level trend to be $+1.81 \text{ mm yr}^{-1}$ (see Woodworth et al., 1999 for details of data quality and analysis). This implies an additional rate of mean sea-level change during the twentieth century of the order of 1 mm yr^{-1} , which agrees with the consensus of opinion that global sea levels have increased between 10 and 20 cm over the past century. It is assumed that thermal expansion of sea water and the melting of mid-latitude glaciers have been the major contributors to this. However, it must be noted that the main deficiencies in determining secular trends from historical data are the unequal distribution of measurements and the considerable amount of inter-annual (typically decadal) variability present in all tide-gauge records (Shennan and Horton, 2002; Horton et al., 2004).

Fig. 10b compares the sea-level reconstructions using the transfer function and established methods. The polynomial trend lines illustrate that the reconstructions of the former method are lower than the latter. Horton et al. (2000) noted that difference between methods is dependent on the type of stratigraphic contact; the reference water levels estimated by transfer function are slightly lower (relative sea-level is higher) in regressive contexts and significantly higher (relative sea-level is lower) in transgressive ones. In this study only three of the eighteen index points were reconstructed from regressive contacts. The tide levels for transgressive dates using the transfer function may occur at higher elevations because of properties of the fossil data. It is generally acknowledged within fossil deposits that there is a lag between a movement of sea level and the response of a salt-marsh to this change (Allen, 1993, 1995, 2003; French, 1993; French et al., 1995). Furthermore, it is

acknowledged that biological indicators such as foraminifera may respond more rapidly to these changes (Long, 1992; Allen, 1995; Reed, 1995; Horton et al., 2000; Horton and Edwards, in press).

The results of this study appear to demonstrate the more rapid response time of foraminiferal assemblages relative to lithostratigraphic indicators because the transfer function estimates the tide level for a foraminiferal assemblage at one point in time and space and not for a change in assemblage from one environment to another. In this way during a transgressive event the foraminifera are capable of recording its early stages and, therefore, yield higher reference water level estimates and thus a lower relative sea-level than those from the lithostratigraphic response to a change in depositional environment.

Table 1 also shows that the indicative ranges of the transfer function (average = 0.34 ± 0.09) are greater and more variable than the established methods (average = 0.21 ± 0.04). The cause of these observed differences in estimates of indicative range becomes apparent when the details of each method are examined (Horton et al., 2000). The data used to develop the established technique was originally developed with the objective of reconstructing Holocene sea-level changes in the Fenland (Shennan, 1982, 1986). The indicative range is selected from a variety of constants depending upon the stratigraphic context of a sample. The use of constant values is equivocal when applied to areas outside the Fenland since, naturally, the vertical range of an indicator will be greater in areas with larger tidal ranges and moreover, will alter as tidal ranges change through time. In contrast, the data used to compile the transfer function are derived from fifteen sites that vary from micro-tidal to macro-tidal in nature (Horton and Edwards, 2005, in press). Furthermore, estimates of indicative range are expressed in terms of a SWLI interval that contains within it an inherent consideration of tidal characteristics and thus palaeotidal changes can be incorporated into the error estimate. For this reason, the vertical interval of the indicative range estimated by transfer function is greater and more variable.

Fig. 10c shows significant scatter (up to 3–4 m) in the sea-level reconstructions during the Mid-Holocene. The scatter of index points on the graph of relative sea-level change includes the total influence of local-scale

Table 1
Summary of sea-level index points and limiting data from North Norfolk

Core	Elevation (m OD)	Dating method	¹⁴ C age	Lab code	Age cal BP			RWL	Error	RSL	Error	Reference
					Max	Mid	Min					
<i>Transfer function</i>												
NNC14 Warham	−5.41	IRSL			5950	5500	5050	1.33	0.18	−6.74	0.207123152	This paper
NNC14 Warham	−5.50	Calibrated ¹⁴ C	5115 ± 55	AA27230	5990	5860	5730	1.32	0.18	−6.82	0.207123152	This paper
NNC14 Warham	−12.41	Calibrated ¹⁴ C	6585 ± 65	AA27231	7590	7460	7330	0.63	0.22	−13.04	0.242693222	This paper
NNC14 Warham	−12.47	Calibrated ¹⁴ C	6860 ± 85	AA27232	7920	7740	7560	0.62	0.22	−13.09	0.242693222	This paper
NNC16 Holkham	−7.09	IRSL			6450	5100	3750	0.5	0.36	−7.59	0.374299345	This paper
NNC16 Holkham	−7.87	IRSL			7950	6400	4850	1.23	0.29	−9.1	0.30757113	This paper
NNC17 Holkham	0.54	IRSL			2700	2325	1950	1.67	0.46	−1.13	0.471274867	This paper
NNC17 Holkham	−1.44	IRSL			2920	2670	2420	1.53	0.45	−2.97	0.46151923	This paper
NNC17 Holkham	−1.61	Calibrated ¹⁴ C	2715 ± 70	AA22707	3000	2870	2740	1.51	0.45	−3.12	0.46151923	This paper
NNC17 Holkham	−2.94	IRSL			5050	4350	3650	1.75	0.4	−4.69	0.412916456	This paper
NNC17 Holkham	−300	IRSL			5450	4750	4050	1.71	0.38	−4.71	0.393573373	This paper
NNC17 Holkham	−4.88	IRSL			6450	5500	4550	1.57	0.35	−6.45	0.364691651	This paper
NNC17 Holkham	−6.10	IRSL			6850	6000	5150	1.88	0.31	−7.98	0.326496554	This paper
NNC17 Holkham	−6.36	Calibrated ¹⁴ C	5930 ± 100	AA22681	7050	6775	6500	1.75	0.27	−8.11	0.288790582	This paper
NNC29 Brancaster	−1.68	Calibrated ¹⁴ C	2700 ± 40	AA22687	2862	2776	2749	2.58	0.46	−4.26	0.471274867	This paper
NNC29 Brancaster	−1.94	Calibrated ¹⁴ C	3260 ± 45	AA22688	3577	3467	3372	2.42	0.44	−4.36	0.45177428	This paper
NNC35 Brancaster	−1.11	Calibrated ¹⁴ C	2640 ± 55	AA22691	2880	2685	2490	2.83	0.46	−3.94	0.471274867	This paper
NNC35 Brancaster	−3.17	Calibrated ¹⁴ C	4390 ± 80	AA22701	5290	5060	4830	2.12	0.36	−5.29	0.374299345	This paper
NNC35 Brancaster	−3.37	Calibrated ¹⁴ C	4690 ± 55	AA22693	5590	5450	5310	1.99	0.35	−5.36	0.364691651	This paper
NNC40 Salthouse	−3.64	Calibrated ¹⁴ C	3940 ± 50	AA22696	4530	4380	4230	2.09	0.38	−5.73	0.393573373	This paper
NNC40 Salthouse	−3.85	Calibrated ¹⁴ C	4495 ± 50	AA22697	5320	5145	4970	2.31	0.35	−6.16	0.364691651	This paper
<i>Established</i>												
NNC02 Blakeney	−4.47	Calibrated ¹⁴ C	5625 ± 50	AA23462	6528	6410	6296	2.25	0.2	−6.72	0.224722051	Andrews et al., 2000
NNC02 Blakeney	−4.55	Calibrated ¹⁴ C	5725 ± 60	AA22703	6664	6492	6409	2.47	0.2	−7.02	0.224722051	Andrews et al., 2000
NNC04 Blakeney point	−11.49	Calibrated ¹⁴ C	6705 ± 65	AA23463	7628	7534	7397	1.99	0.2	−13.48	0.224722051	Andrews et al., 2000
NNC20 Burnham overy	−0.65	Calibrated ¹⁴ C	3770 ± 60	AA22698	4348	4114	3930	2.19	0.2	−2.84	0.224722051	Andrews et al., 2000
NNC27 Burnham deepdale	0.02	Calibrated ¹⁴ C	3455 ± 85	AA23458	3921	3693	3473	2.05	0.2	−2.03	0.224722051	Andrews et al., 2000
NNC28 Scolt head	−6.53	Calibrated ¹⁴ C	5985 ± 60	AA23464	6989	6825	6677	2.3	0.2	−8.83	0.224722051	Andrews et al., 2000
NNC35 Thornham	−1.97	Calibrated ¹⁴ C	3785 ± 50	AA22692	4345	4114	3985	2.58	0.2	−4.55	0.245764115	Andrews et al., 2000
NNC37 Brancaster	−2.14	Calibrated ¹⁴ C	4105 ± 55	AA23461	4827	4565	4426	2.53	0.2	−4.67	0.224722051	Andrews et al., 2000
Brancaster	−1.03	Calibrated ¹⁴ C	2790 ± 40	SRR2368	2960	2865	2779	2.38	0.2	−3.41	0.245764115	Shennan and Horton, 2002
Brancaster	−2.05	Calibrated ¹⁴ C	3470 ± 50	SRR2387	3848	3697	3622	2.59	0.2	−4.64	0.245764115	Shennan and Horton, 2002
Brancaster	−3.80	Calibrated ¹⁴ C	4010 ± 50	SSR2388	4787	4479	4353	2.18	0.2	−5.98	0.245764115	Shennan and Horton, 2002

Cley	-3.04	Calibrated	¹⁴ C	4450 ± 60	SRR2603	5297	5013	4865	1.96	0.4	-5	0.424735212	Shennan and Horton, 2002
Holkham	-2.40	Calibrated	¹⁴ C	4480 ± 60	SRR2601	5314	5150	4984	1.98	0.2	-4.38	0.245764115	Shennan and Horton, 2002
Holkham	-1.80	Calibrated	¹⁴ C	4520 ± 50	SRR2391	5308	5151	4871	2.33	0.2	-4.13	0.245764115	Shennan and Horton, 2002
Holkham	-5.06	Calibrated	¹⁴ C	5970 ± 80	SRR2392	7006	6823	6643	2.1	0.2	-7.16	0.245764115	Shennan and Horton, 2002
Stiffkey	-2.20	Calibrated	¹⁴ C	4630 ± 50	SRR2599	5560	5316	5083	1.89	0.2	-4.09	0.245764115	Shennan and Horton, 2002
Stiffkey	-2.93	Calibrated	¹⁴ C	4880 ± 60	SRR2600	5733	5605	5480	2.1	0.2	-5.03	0.245764115	Shennan and Horton, 2002
Titchwell foreshore	-1.52	Calibrated	¹⁴ C	4560 ± 50	AA28179	5443	5292	4998	2.18	0.2	-3.7	1.027436129	Shennan and Horton, 2002
<i>Limiting</i>													
NNC04 Cley	-8.04	Calibrated	¹⁴ C	8770 ± 60	AA22702	10150	9850	9550	1.01	1.37	-9.05	1.373826772	Andrews et al., 2000
NNC04 Blakeney point	-11.73	Calibrated	¹⁴ C	7770 ± 55	AA22704	8635	8534	8415	1.006014364	1.37	-12.73601436	1.373826772	Andrews et al., 2000
NNC14 Warham marshes	-14.63	Calibrated	¹⁴ C	9265 ± 90	AA27588	10673	10443	10233	1.663039545	1.37	-16.29303955	1.373826772	Andrews et al., 2000
NNC16 Holkman meals	-8.04	Calibrated	¹⁴ C	7250 ± 95	AA22679	8323	8065	7857	1.127425828	1.37	-9.167425828	1.373826772	Andrews et al., 2000
NNC16 Holkman meals	-8.57	Calibrated	¹⁴ C	9280 ± 100	AA22680	10694	10463	10227	1.769819333	1.37	-10.33981933	1.373826772	Andrews et al., 2000
NNC17 Holkham	-6.53	Calibrated	¹⁴ C	6375 ± 60	AA23936	7424	7313	7188	0.996801773	1.37	-7.526801773	1.373826772	Andrews et al., 2000
NNC17 Holkham	-6.70	Calibrated	¹⁴ C	7760 ± 95	AA22682	8976	8549	8374	1.22938459	1.37	-7.92938459	1.373826772	Andrews et al., 2000
NNC18 Burnham overy dunes	-5.73	Calibrated	¹⁴ C	7155 ± 95	AA22684	8164	7969	7789	1.078867434	1.6	-6.808867434	1.603277892	Andrews et al., 2000
NNC19 Burnham overy marsh	-6.52	Calibrated	¹⁴ C	9680 ± 60	AA22700	11200	11074	10755	1.958469532	1.6	-8.478469532	1.603277892	Andrews et al., 2000
NNC20 Burnham overy	-0.83	Calibrated	¹⁴ C	4260 ± 50	AA22699	4964	4832	4622	0.775676698	1.6	-1.605676698	1.603277892	Andrews et al., 2000
NNC27 Burnham deepdale	-1.71	Calibrated	¹⁴ C	5795 ± 60	AA23459	6728	6597	6448	0.903858529	1.37	-2.613858529	1.373826772	Andrews et al., 2000
NNC28 Scolt head	-6.80	Calibrated	¹⁴ C	9470 ± 75	AA23460	11091	10751	10505	2.29010053	1.15	-9.09010053	1.154556192	Andrews et al., 2000
NNC29 Brancaster	-5.87	Calibrated	¹⁴ C	5845 ± 55	AA22689	6841	6670	6496	2.29010053	1.15	-8.16010053	1.154556192	Andrews et al., 2000
NNC29 Brancaster	-6.49	Calibrated	¹⁴ C	9870 ± 70	AA22690	11553	11267	11164	2.262175441	1.37	-8.752175441	1.373826772	Andrews et al., 2000
NNC35 Thornham	-3.98	Calibrated	¹⁴ C	8750 ± 75	AA22694	10142	9770	9546	1.51884471	1.6	-5.49884471	1.603277892	Andrews et al., 2000
NNC 40 Salthouse	-5.91	Calibrated	¹⁴ C	6145 ± 55	AA22695	7210	7033	6800	0.956805061	1.15	-6.866805061	1.154556192	Andrews et al., 2000
Brancaster	-4.47	Calibrated	¹⁴ C	8410 ± 50	SRR2389	9527	9445	9292	1.655105448	1.37	-6.125105448	1.377425134	Shennan and Horton, 2002
Burnham overy marsh	-6.23	Calibrated	¹⁴ C	9410 ± 110	AA22685	11090	10661	10284	1.808229838	1.6	-8.038229838	1.603277892	Shennan and Horton, 2002
Hokham	-5.79	Calibrated	¹⁴ C	7000 ± 50	SRR2393	7936	7825	7691	1.082063188	1.37	-6.872063188	1.377425134	Shennan and Horton, 2002
Titchwell foreshore	-1.52	Calibrated	¹⁴ C	6495 ± 55	AA8178	7551	7392	7280	1.428934554	1.15	-2.948934554	1.527383383	Shennan and Horton, 2002

All dates are calibrated using OxCal Program, Version 3.8 (Bronk Ramsey, 1995, 1998), using the 95% confidence limits for the probability option. The reference water level (RWL) is calculated using the transfer function or established techniques, including tidal range corrections. Relative sea level (RSL) is calculated as elevation minus the RWL. The RSL error range is calculated as the square root of the sum of squares of elevation error, sample thickness, tide range calculation error and indicative range. The indicative range (given as a maximum) is the most probable vertical range in which the sample occurs although for limiting dates the sample could occur above that range.

processes and also any differential isostatic movements. As we have estimated the influence of tidal range change, the remaining outstanding local-scale process that operates within the North Norfolk area is post-depositional sediment consolidation (Shennan et al., 2000a; Shennan and Horton, 2002). Post-depositional sediment consolidation will ‘lower’ index points from their original elevation and, unless corrected for, will lead to an over-estimate of the rate and magnitude of relative sea-level rise in North Norfolk. The effects of consolidation can be especially severe for index points which are found above and below considerable thicknesses of Holocene sediment, such as those from intercalated peats (Haslett et al., 1998; Shaw and Ceman, 1999). Shennan and Horton (2002) reviewed some of the literature on this topic and stressed that compaction of deposits with a high sand fraction is very low whilst compaction of peat may be as high as 90% by volume. This problem is reduced, but not entirely removed, by using index points from basal peats which rest at, or close to, the base of the Holocene sediment column. Subdivision of the index points into basal and intercalated peats provides an initial assessment (Fig. 10c). Most of the samples from intercalated peats lie below those from basal peats of the same age, suggesting that the influence of sediment consolidation may indeed be significant. Indeed Shennan et al. (2000a) showed significant correlations with depth of overburden and total thickness of the Holocene sequence from North Norfolk, which indicates the likely net effects of sediment consolidation. It should be noted that a greater proportion of index points produced from the transfer function approach are from intercalated sedimentary sequence compared to the established approach ($15:18_{\text{transfer function}}$; $7:18_{\text{established}}$). This may be an additional cause for the apparent differences in reconstructed former sea levels.

6. Conclusions

Through the establishment of regional transfer functions, inter-tidal foraminifera can provide a powerful tool in the reconstruction of past tidal levels. Detailed micropalaeontological evidence combined with sedimentological contexts and a comprehensive chronological framework have allowed us to establish

an accurate picture of relative sea-level change along the north Norfolk coastline during the last 10000 years which is consistent with GIA models. The methodology of sea-level reconstruction presented in this paper has advantages in terms of precision, speed of response and applicability (transfer function approach), and reduction of local uncertainties (palaeotidal range change) over established methods currently employed in sea-level research. With an increasing demand for high resolution studies of sea-level change, particularly those seeking to quantify the link between variations in ocean level and climate, it is imperative that the new generation of techniques employed are of the highest possible precision and accuracy.

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