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Robin J. Edwards
Trinity College Dublin

Benjamin P. Horton
University of Pennsylvania, bphorton@sas.upenn.edu

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Keywords

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Comments

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Developing Detailed Records of Relative Sea-Level Change Using a Foraminiferal Transfer Function: An Example from North Norfolk, UK

BY ROBIN J. EDWARDS[1] AND B.P. HORTON[2]

[1]*Departments of Geography & Geology, Trinity College Dublin, Ireland*

[2] *Sea Level Research Laboratory, Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, USA*

This paper provides a brief overview of the transfer function approach to sea-level reconstruction. Using the example of two overlapping sediment cores from the north Norfolk coast, UK, the advantages and limitations of the transfer function methodology are examined. Whilst the selected cores are taken from different sites, and display contrasting patterns of sedimentation, the foraminiferal transfer function distils comparable records of relative sea-level change from both sequences. These reconstructions are consistent with existing sea-level index points from the region but produce a more detailed record of relative sea-level change. Transfer functions can extract sea-level information from a wider range of sedimentary sub-environments. This increases the amount of data that can be collected from coastal deposits and improves record resolution. The replicability of the transfer function methodology, coupled with the sequential nature of the data it produces, assists in the compilation and analysis of sea-level records from different sites. This technique has the potential to bridge the gap between short-term (instrumental) and long-term (geological or geophysical) records of sea-level change.

Keywords: sea-level change; transfer function; foraminifera; Holocene

1. Introduction

Concerns surrounding the potential impacts of human-induced climatic change have heightened interest in the relationship between climate and sea level. The nature of the ocean-climate relationship can be investigated in a variety of ways and at a number of spatial and temporal scales. Over short periods (decades) long tide gauge records can be examined for signs of an accelerated rate of relative sea-level rise (*e.g.* Woodworth, 1990; Shennan & Woodworth, 1992; Woodworth *et al.*, 1999; Ekman, 2003). Over long periods (millennia), geophysical models of the glacio-isostatic adjustment process can be used to estimate large-scale changes in land and ocean level (*e.g.* Lambeck, 1993, 1995; Peltier *et al.*, 2002; Peltier, 2004). Both of these methods are supported by geologically based reconstructions of relative sea-level derived from morphological, sedimentological and biological sea-level indicators (*e.g.* Pirazzoli, 1996; Shennan and Horton, 2002). These are capable of reconstructing metre-scale relative sea-level changes at multi-centennial to millennial timescales. A current challenge is to refine these techniques in order to link long-term geological or geophysical estimates with short-term instrumental records. Relative sea-level reconstructions derived from foraminiferal transfer functions are a promising area of research with the potential to meet this challenge.

In the following section of this paper, the use of foraminiferal transfer functions in sea-level research is reviewed in brief. In section three, the advantages and limitations of this approach are illustrated using the example of two sediment cores collected from the Norfolk coastline, UK. The paper concludes with an assessment of the implications of these results for the development of detailed records of change capable of linking long and short-term relative sea-level records.

2. Relative sea-level reconstructions and foraminiferal transfer functions for tide level

The composition (lithology) of coastal sediments, coupled with any biological components they contain, represent a rich source of information on past changes in relative sea-level (Godwin, 1940, 1943, 1945; Godwin & Godwin, 1940; Tooley, 1978). For over twenty years, a standard approach using ‘sea-level index points’ has been advocated and refined (*e.g.* Preuss, 1979; Shennan, *et al.*, 1983; van de Plassche, 1986). This approach rests upon the principle that switches between terrestrial and marine sedimentation reflect changes in the balance between land and ocean levels, moderated by local processes such as sedimentation rate.

A sediment sample from a known location can be used as a sea-level index point if it is dated and its altitude is measured relative to a geodetic datum (Tooley, 1982; Shennan, 1982, 1986). In addition, the elevation at which it formed relative to a contemporaneous tide level (termed the indicative meaning) must also be determined in order to account for the range of heights at which different coastal sedimentary environments are found (van de Plassche, 1986). Consequently, terrestrial deposits forming at some undefined height above the marine influence, and undifferentiated inter-tidal or sub-tidal sediments, cannot be used to reconstruct former sea levels on the basis of their lithology. Instead the lithological approach is generally restricted to establishing sea-level index points at the contacts between organic (terrestrial peat) and minerogenic (marine sand, silt and clay) sediments, which occur around the elevation of mean high water of spring tides (Shennan, 1982, 1986).

Biological indicators, such as the marine protists Foraminifera, can be used in conjunction with this lithological approach to more precisely locate the transition between marine and terrestrial environments, thereby refining the indicative meaning of a sediment sample. In the simplest of cases, the switch from sediments devoid of foraminifera to those containing these marine animals can be used to pinpoint the first occurrence of marine conditions within a sequence (Scott & Medioli, 1980). Scott & Medioli (1978, 1980) observed that the strong environmental gradients across the land-sea interface produce a pronounced vertical zonation of characteristic salt marsh foraminifera. Identification of these foraminiferal zones permits a wider range of inter-tidal sediments to be assigned an indicative meaning and has been used to produce detailed records of relative sea-level change (*e.g.* Varekamp *et al.*, 1992; Gehrels, 1994; Nydick *et al.*, 1995).

The transfer function methodology is an extension of this biological approach but offers a number of advantages over it, including: an increased range of sedimentary environments that can yield relative sea-level data; improved quantitative reconstructions with defined error terms; and consistent, objective, replicable treatment of data (Edwards *et al.*, 2004*a*). Developing a transfer function for tide level begins with an investigation of the modern relationship between Foraminifera and the tidal frame. Studies of the surface distribution of inter-tidal foraminifera can provide information on the preferred elevation (ecological optimum), and range of elevations (ecological tolerance), at which individual species are found (*e.g.* Scott & Medioli, 1980; Jennings & Nelson, 1992; Horton *et al.*, 1999*a*; Scott *et al.*, 2001; Edwards *et al.*, 2004*b*). These ecological parameters are distilled by multiple regression of species relative abundance and sediment surface elevation. The transfer function then applies these species-elevation relationships to estimate the elevation of a sediment sample of the basis of the foraminifera it contains (Horton *et al.*, 1999*b*, Gehrels *et al.*, 2001; Edwards *et al.*, 2004*a*). For clarity the term 'elevation' is used in this paper to describe the height of a sample relative to mean tide level, whilst the term 'altitude' is used when referring to vertical position relative to Ordnance datum Newlyn (OD).

Each sediment sample can be assigned an indicative meaning on the basis of the microfossil assemblage contained within it. Since foraminifera and diatoms are found across the whole suite of inter-tidal sub-environments, this dramatically expands the range of sediments that can be employed in sea-level reconstruction (Edwards & Horton, 2000). This increase in data availability means that sedimentary archives can be interrogated in more detail.

The development of UK foraminiferal transfer functions for tide level has been documented in a number of publications. Horton *et al.* (1999*b*) and Gehrels *et al.* (2001) demonstrate that foraminifera in the UK can be reliably used as proxies for elevation via the transfer function technique. Horton *et al.* (2000) discuss how transfer functions can be used to improve the indicative meaning assigned to lithostratigraphic contacts, whilst Edwards (2001) used this method to reconstruct mid to late Holocene relative sea-level changes in Poole Harbour, southern Britain. In this paper, two suites of foraminiferal samples from overlapping cores are presented to illustrate how the transfer function approach permits stratigraphically constrained sea-level data to be treated as sequences, rather than as a collection of discrete points. This offers a number of opportunities to improve the resolution of relative sea-level records in ways that could not be achieved by the use of standard sea-level index points. These increases in record detail have the potential to link short and long term records of sea-level change.

3. An illustration of the transfer function approach

An extensive set of core material was recovered from the western North Sea coast as part of the Land-Ocean Evolution Perspective Study (LOEPS) and is summarised in Shennan & Andrews (2000). This paper re-examines two cores collected from the Norfolk coast as part of LOEPS: NNC-14 recovered at Warham Marsh; and NNC-17 collected at Holkham (Figure 1a). Whilst their lithostratigraphy and chronostratigraphy are presented in Andrews *et al.* (2000), associated foraminiferal data are not described in detail. In this section, these foraminiferal data (Boomer, *pers. comm.*) are used in conjunction with a foraminiferal transfer function for tide level to reconstruct relative sea-level change. These results are used to illustrate the advantages and limitations of the transfer function approach outlined in section 2. The performance of the transfer function is then assessed by comparison with the existing relative sea-level data from the region.

(a) The foraminiferal transfer function for tide level

The reconstructions presented here are derived from an expanded version of the foraminiferal transfer function for tide level successfully applied to sediment samples from the Norfolk coast by Horton & Edwards (2005). The new transfer function is derived from a modern training set of 200 samples collected from 13 study sites located around the British Isles (Figure 1b). The combination of modern samples from a wide range of sites with differing physical, biological and hydrographic characteristics maximises the range of palaeoenvironments that can be reliably interpreted by the transfer function data (Horton & Edwards, 2005). A full description of the development process is presented elsewhere (Horton & Edwards, *in press*), but for completeness, the key points are summarised below.

The modern foraminiferal data are compiled from sites ranging from macrotidal (*e.g.* 8.4 m at Roudsea Marsh) to microtidal (*e.g.* 1.2 m at Arne Peninsula). To account for this variation, the elevation of each sample is standardised after Horton & Edwards (2005). Elevation data are presented in the form of a standard water level index (SWLI), where a value of 100 is equivalent to mean high water of spring tides (MHWST), and a value of 0 corresponds to mean low water of spring tides (MLWST). The transfer function employed here produces estimates of SWLI with an associated error of ± 9 (Horton & Edwards, *in press*). Since this value is expressed as a proportion of the tidal range, reconstructions derived from microtidal sites will have smaller vertical errors than those generated from macrotidal contexts. The tidal range along the north Norfolk coast is relatively high (6.5 m) and as a consequence, the reconstructed elevations presented here have associated uncertainties of around ± 0.6 m.

The transfer function estimates the elevation of each sediment sample based on the relative abundance of foraminiferal species present within it. The resulting curve of surface elevation plots changes in sediment height above palaeo-mean tide level. These heights can be subtracted from the current altitudes of the sediment samples to reconstruct the past altitudes of palaeo-mean tide level. In common with lithological methods of sea-level reconstruction, this procedure assumes that the modern altitude of sediment samples is representative of their original altitude at the time of deposition, and that tidal range has not changed through time.

In reality, sediment compaction may lower sea-level index points, resulting in an underestimate of palaeo-mean tide level altitude (Haslett *et al.*, 1998; Paul & Barras, 1998; Allen, 2000). At present, there is no standard way of decompacting sediment sequences, and studies have to estimate the magnitude of potential lowering on the basis of comparing the altitude of index points derived from basal (presumed minimally compacted) and intercalated peat horizons. Similarly, few studies attempt to account for changes in tidal range since this commonly involves the use of specialist tidal models (*e.g.* Gehrels *et al.*, 1995; Hinton, 1995; 1996; Shennan *et al.*, 2000*b*). Recent models from the western North Sea suggest that tidal range increased during the Holocene (Shennan *et al.* 2000*a*; *b*), most notably between c. 6000 and 9000 calendar years before present (cal. cal. BP). This would result in a tendency for sea-level index points to underestimate the true altitude of sea-level, and for transfer functions to estimate larger excursions in mean tide level.

(b) The core data

The lithostratigraphy and chronostratigraphy of cores NNC-14 and NNC-17 are described in detail by Andrews *et al.* (2000). Here, the key points are summarised and illustrated in Figure 2, along with the foraminiferal data (Boomer, *pers. comm.*). The estimates of elevation generated by the transfer function are plotted alongside these data with the elevation of MHWST at each site marked for reference.

Sediment cores were recovered using a shell-auger percussion rig and all sites were levelled in to Ordnance datum Newlyn (OD) with a closure error of < 2mm (Andrews *et al.* 2000). The lithostratigraphy of both cores is typical of the region, commencing in late glacial sediments overlain by a basal freshwater peat unit. Core NNC-14, penetrating to c. -15 m OD, contains the longer of the two sequences. Here, the freshwater basal peat is overlain by a mud unit devoid of foraminifera and a second, thin peat. The sea-level record is derived from the overlying 12 m of silts and clays containing foraminifera. Below c. -7 m OD, the foraminiferal assemblages are dominated by calcareous taxa such as *Ammonia* species and *Haynesina germanica*, which are characteristic of low marsh or tidal flat environments. Above this, agglutinated taxa, such as *Jadammina macrescens* and *Trochammina inflata* become dominant. These species are associated with saltmarsh environments and indicate an increase in sediment surface elevation (Figure 2a). In contrast, agglutinated foraminifera (*e.g. Jadammina macrescens* and *Trochammina inflata*) are present at the upper contact of the basal peat in core NNC-17, reflecting the transition from a freshwater to a saltmarsh environment (Figure 2b). The sea-level record developed for Core NNC-17 is derived from the foraminifera recovered from this transgressive contact and from samples taken in the overlying 7 m of silt and clay. Unlike core NNC-14, calcareous taxa dominate the organic silty clay sediments above the basal peat, indicating that these sediments accumulated lower in the tidal frame. The general increase in species diversity upcore, coupled with the increase in sub-tidal species, indicates a trend toward decreasing sediment surface elevation (Figure 2b).

(c) Core chronologies

The chronostratigraphy for each core is provided by a combination of infrared-stimulated luminescence (IRSL) ages and radiocarbon dating. Full details of materials and methods are presented in Andrews *et al.* (2000) and Bailiff & Tooley (2000), and the results are summarised here in Table 1. Radiocarbon dates from the basal peat units provide the chronology for the lowermost portions of both cores. These age estimates are associated with 2σ errors of between ± 70 and ± 300 years (Fig. 3). Luminescence ages provide the chronology for the silt and clay sediments containing the bulk of the foraminifera, and are associated with errors of between ± 210 and ± 650 years. Age data were combined and calibrated using OxCal version 3.1 (Bronk Ramsay 1995, 2001), treating the sequence from each core separately to produce independent accumulation histories.

To construct a chronology of sea-level change, each foraminiferal sample must be assigned an age. This requires the interpolation of age data to produce a unique age-depth relationship for each core. The need to interpolate age data is a common requirement of palaeoenvironmental reconstructions derived from sediment cores, and the methods employed vary considerably. For example, the single core sea-level reconstructions from North American salt-marshes have used combinations of simple linear interpolation, polynomial curves, stratigraphically informed 'best-fit' lines and wiggle-match dating (*e.g.* Varekamp *et al*., 1992; Nydick *et al*., 1995; Gehrels, 1999, 2000; van de Plassche *et al.*, 1998; van de Plassche *et al*., 2001). The issues surrounding the construction of chronologies in sea-level research are examined in Edwards (2004). Principal challenges include uneven data distribution (temporal and spatial) and the differing magnitude of associated error terms, which results in variable age control through a sediment sequence. These limitations provide fundamental constraints on the precision of interpolated chronologies, the success of which depends upon a combination of data quality, quantity and sediment accumulation variability.

In this paper, the chronology for each core is derived from three separate interpolations of the maximum, minimum and mean ages of the dated horizons. This approach produces three accumulation histories for each core, representing the uncertainty associated with the dating methods used.

(d) Reconstructed elevation change

The foraminiferal data summarised in Figure 2 show the reconstructed sediment elevation (relative to mean tide level) plotted against sample altitude (relative to Ordnance datum). These data, when combined with the accumulation histories describing the age-altitude relationships for each core, result in the curves of elevation change through time presented in Figure 4. The white squares show the reconstructed elevation for the mean chronology, whilst the dark shaded envelope describes the vertical uncertainty associated with the transfer function reconstructions. The pale shaded envelope behind the elevation curve is derived from the maximum and minimum age chronologies and represents the extent to which the elevation curve can be shifted along the time axis as a consequence of the age uncertainties. It should be noted that whilst the timing of the reconstructed changes can vary as a consequence of these dating limitations, the sequence and elevation of the changes is not altered.

The diagrams in Figure 4 reflect the local balance between sedimentation and relative sea-level at the sample sites. For example, an increase in surface elevation reflects a local fall in water level. This occurs when the rate of sedimentation outpaces the rate of relative sea-level rise, and may reflect an alteration in one or both of these parameters.

The record from the longer core NNC-14, extends back to around 7400 cal. BP (Figure 4a). At this time, the transfer function reconstructs the sediment surface at around 0.9 m above mean tide level. In general, the foraminiferal assemblages from the lower portion of the core are interpreted as indicating sediment surface elevations around 1.5 m above mean tide level, which equates to a low marsh or tidal flat environment. As the core accumulates, there is a general emergence trend with elevations increasing to levels approximating MHWST. This dominant emergent trend is characteristic of the infilling of accommodation space as sedimentation rate outpaces the long-term rate of relative sea-level rise.

In contrast, the elevation diagram of NNC-17 exhibits a general trend toward increasing water depth (decreasing surface elevation), falling from an initial elevation equivalent to modern MHWST at *c.* 6500 cal. BP, to between 1.5 and 2.0 m above mean tide level (Figure 4b). This indicates that at Holkham, the rate of sedimentation was outpaced by the rate of relative sea-level rise and the sample site was inundated.

(e) Reconstructing mean tide level

In order for these core-specific records of elevation to be used as records of relative sea-level change, it is necessary to account for variations in sedimentation. This is simply achieved by including the altitude at which each sample is taken. By subtracting the reconstructed value of elevation (height above mean tide level) from the sample altitude, the former altitude of mean tide level can be determined. In this way, the transfer function produces a sea-level index point (with an interpolated age) for each sample. This has the effect of converting a relative record into an absolute record of change that should no longer be specific to an individual site.

This operation is performed on both cores and the results are presented in Figure 5. Whilst the two cores displayed very different patterns of elevation change (Figure 4), now that sediment accumulation has been taken into account, they exhibit similar records of mean tide level change through time. For much of the overlapping portions of the record, the curves from both cores show close agreement and can be brought in line with each other by minor alterations in their interpolated accumulation histories. In addition, both curves show inflections centred around 6000 cal. BP and declining rates of relative sea-level rise from *c.* 5000 to 3000 cal. BP. This demonstrates that both cores exhibit similar sequences of change. It should be noted that these two records are entirely independent of each other, since the altitude reconstructions are derived from different foraminiferal samples, and the core chronologies are generated from separate sets of dates.

To provide a further test of the transfer function reconstructions, the relative sea-level records from both cores are plotted alongside existing sea-level index points from the area, comprising 31 dates from 13 sites (Figure 6). In addition, the estimated position of modelled mean sea level derived from the geophysical model ICE4G (Peltier *et al.*, 2002) is also shown as a solid line. The transfer function reconstructions plot through the middle of the scatter in the conventional sea-level index points, and follow the general trend estimated by the geophysical model. The sea-level index points from other sites extend the record slightly further back in time to around 8000 cal. BP, but the pattern of change indicated by the early portion of the relative sea-level records from the transfer function is consistent with these data. The transfer function reconstructions show more variability than the modelled mean sea-level estimates, but this is to be expected since ICE4G does not reproduce sub-millennial variability.

(f) Discussion

The two cores presented above serve to illustrate the increase in information that can be provided by foraminiferal transfer functions. Traditional methods based on lithostratigraphic data could produce a maximum of two sea-level index points from the material presented here (established at the contacts between peat and silty clay). In contrast, the foraminiferal transfer function approach produces 35 relative sea-level reconstructions, thereby exploiting the wider range of datable sedimentary contexts.

The principal limitation of the records is the coarsely constrained chronology which results in large uncertainties in the timing of changes between c. 3000 and 6000 cal. BP. This limitation, which arises from the use of IRSL dates with large error terms (over 1000 years), produces the broad band of uncertainty around the reconstructions (Figures 5 & 6). It should be noted however, that this error band is of the same magnitude as the scatter in existing sea-level index points (Figure 6). This illustrates how foraminiferal records, recovered from only two marshes, can produce sea level data comparable to lithostratigraphic index points collected from 13 sites.

The sequential nature of the foraminiferal reconstructions means that it is much easier to compare and combine records. The combination of data, especially chronological information, has the potential to further refine the patterns of change that can be discerned. For example, when sea-level index points are combined, there is sometimes no direct overlap of data making inter-site comparison difficult. If index points from one site fall in the gaps between index points from another, it is hard to gauge whether apparent variations in the composite record reflect actual relative sea-level changes from a coherent region, or are caused by inter-site differences in local relative sea-level. Where index points of comparable age are available from different sites, any vertical disagreement between them is equally hard to interpret, since the stratigraphic relationship between them can rarely be ascertained with any certainty. In contrast, the comparison of records from multiple cores produced by the transfer function approach is much more straightforward since, unless portions of the records have been removed, all should exhibit similar sequences and patterns of change (Horton & Edwards, in press). Rather than comparing reconstructed altitudes in isolation, sequences of change can be used to match suites of data together. Distinctive features of the curves can be used to assist in correlating between cores in much the same way that records from other terrestrial and marine environments are examined. In turn, discrepancies that arise from limitations in the chronology of accumulation, perhaps due to variations in sedimentation rate, or the removal of portions of the sedimentary record, will be more easily identified.

This can be illustrated with reference to Figure 5. At around 6000 – 6500 cal. BP both records indicate a still-stand in mean tide level at -9 to -10 m OD. Whilst the uncertainties in the chronology for NNC-17 can only place this still-stand at between 5500 and 7000 cal. BP due to the large uncertainties associated with the IRSL dates from this interval, core NNC-14 has a radiocarbon date at c. 6000 cal. BP which fixes the record from this core more precisely. On this basis, it is likely that the mean chronology for NNC17 is slightly too old for this interval (*c.* 500 years) and could be adjusted accordingly. It is interesting to note that such an adjustment would bring the two curves into agreement for the remainder of the interval for which overlapping records exist. Similarly, core NNC-17 is tightly constrained by a radiocarbon date and matching IRSL date at c. 2500 cal. BP, fixing a second apparent still-stand or fall in mean tide level around 3000 cal. BP. It is clear that the collection of more data (*e.g.* additional dates) from critical periods will serve to refine records of change in a way that adding more sea-level index points to a scatter of data cannot.

Reconstructions for the same time period are derived from samples resting on different sediment thicknesses, and loaded with different overburdens. Consequently, reconstructions from basal samples or less compactable substrates can be used to evaluate data from contexts that are more prone to post-depositional lowering. In the case of Cores NNC-14 and NNC-17, the fact that similar reconstructions are produced from contrasting sediment thicknesses and contexts suggests that compaction is not a first order control on reconstructions from these predominantly minerogenic sequences. Inspection of Figure 6 suggests that the curves may be displaced as much as 2 m below the basal index points, although around 4500 cal. BP both curves rest at or above the altitude of the closest basal index point.

4. Developing detailed records of relative sea-level change

The foraminiferal transfer function approach outlined in this paper has the potential to furnish precise and detailed records of relative sea-level change from inter-tidal environments around the world. For example, recent foraminiferal transfer functions developed in Connecticut, USA, and the Great Barrier Reef, Australia, have precisions of ± 0.09 m (Edwards *et al.*, 2004*b*) and ± 0.07 m (Horton *et al.*, 2003) respectively. The records of relative sea-level change presented here are comparatively coarse due to the large tidal range of the area which induces vertical errors of ± 0.6 m. This illustrates the fact that site selection is a critical component of research seeking to discern subtle changes in relative sea-level during the late Holocene period. Sites with large tidal ranges will usually produce records with greater vertical uncertainties.

The two foraminiferal records presented here are of relatively low precision for two further reasons. Firstly, both cores possess only skeleton foraminiferal counts with samples commonly spaced 50 to 100 cm apart. The frequency of foraminiferal sampling is primarily governed by available time for analysis, and cores can be sampled every centimetre if required to produce very high-resolution elevation records (*e.g.* Edwards *et al.*, 2004*b*). Secondly, the chronologies for both cores are poorly constrained due to the limited availability of organic deposits suitable for precise radiocarbon dating, and the use of IRSL dates with large age uncertainties. More detailed chronologies will need to be developed if geological and instrumental data are to be linked. In areas where coastal deposits are highly organic, such as along the Atlantic coast of North America, large numbers of AMS radiocarbon dates can be collected and wiggle-matched to produce high precision accumulation histories (van de Plassche *et al.*, 2001). The combination of short-lived radionuclides (*e.g.* ^{210}Pb, ^{137}Cs), radiocarbon and thermoluminescence data, coupled with biological or chemical chronohorizons has the potential to provide a strong chronological framework for the late Holocene period upon which the transfer function reconstructions can be pinned. In addition, the AMS radiocarbon dating of calcareous foraminifera also offers the potential for increasing the temporal precision of the resulting relative sea-level records (Horton *et al.*, 2000). In this way detailed foraminiferal data and precise chronologies can produce high-resolution records of relative sea-level change capable of distilling decimetre and century scale variations that can be compared with tide gauge records (*e.g.* Gehrels *et al.*, 2002).

The ability to reconstruct relative sea-level change from a wide range of sedimentary sub-environments increases the amount of data that can be collected from coastal sequences. In addition, the fact that comparable records of relative sea-level change can be derived from cores with different accumulation histories means that reconstructions from single cores are less sensitive to the influence of local scale processes. The application of regional-scale transfer functions means that records produced from different sites are directly comparable. This replicability, coupled with the sequential nature of these data, assists in the compilation and construction of relative sea-level curves and permits higher resolution variability to be distinguished. The development of these records will need to proceed in concert with improved methods of dating sediments and further refinements to the transfer function approach. Nevertheless, microfossil transfer functions are now capable of bridging the gap between proxy and instrument data, and have the potential to enable us to investigate the relationship between climate and sea level at centennial timescales.

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References

Allen, J.R.L. 2000 Holocene coastal lowlands in NW Europe: autocompaction and the uncertain ground. In Pye, K. and Allen, J.R.L. (eds.) *Coastal and Estuarine Environments: sedimentology, geomorphology and geoarchaeology*. Geological Society, London, Special Publications 175, 239-252.

Andrews, J.E., Boomer, I., Bailiff, J., Balson, P., Bristow, Chroston, P.N., Funnell, B. M., Harwood, G.M., Jones, R., Maher, B.A., & Shimmield, G.R. 2000 Sedimentary evolution of the north Norfolk barrier coastline in the context of Holocene sea-level change. In Shennan, I., and Andrews, J. (eds.), *Holocene land-Ocean Interaction and Environmental Change around the North Sea*. Geological Society Special Publications 166, 219-251.

Bailiff, I.K., & Tooley, M.J. 2000 Luminescence dating of fine-grain Holocene sediments from a coastal setting. In Shennan, I., and Andrews, J. (eds.), *Holocene land-Ocean Interaction and Environmental Change around the North Sea*. Geological Society Special Publications 166, 55-67.

Bronk Ramsey, C. 1995 Radiocarbon Calibration and Analysis of Stratigraphy: The OxCal Program. *Radiocarbon* **37(2)**, 425-430 .

Bronk Ramsey, C. 2001 Development of the Radiocarbon Program OxCal. *Radiocarbon* **43(2A)**, 355-363.

Edwards, R.J. 2001 Mid- to late Holocene relative sea-level changes in Poole Harbour, southern England. *Journal of Quaternary Science* **16 (3)**, 201-220. (DOI: 10.1002/jqs.585)

Edwards, R.J. 2004 Constructing chronologies of sea-level change from salt-marsh sediments In: Buck C.E., Millard A.R. (eds.) *Tools for Constructing Chronologies: Crossing Disciplinary Boundaries*. Springer Verlag (London) Ltd. pp 191-213.

Edwards, R.J. & Horton, B.P. 2000 High Resolution Records of Relative Sea-Level Change from U.K. Salt-marsh Foraminifera. *Marine Geology* **169**, 41-56. (DOI:10.1016/S0025-3227(00)00078-5)

Edwards R.J., Wright A.J., & van de Plassche O. 2004*a* Surface distributions of salt-marsh foraminiferal from Connecticut, USA: Modern Analogues for high resolution sea-level studies. *Marine Micropaleontology* **51**,1-21. (DOI:10.1016/j.marmicro.2003.08.002)

Edwards, R.J., Wright, A.J., & van de Plassche, O. 2004*b* Assessing Sea-Level Data From Connecticut, USA, Using A Foraminiferal Transfer Function For Tide Level. *Marine Micropaleontology* **51**, 239-255. (DOI:10.1016/j.marmicro.2003.11.003)

Ekman, M. 2003 The World's Longest Sea Level Series and a Winter Oscillation Index for Northern Europe 1774-2000. *Small Publications in Historical Geophysics* **No.12**, 1-29.

Hinton, A. 1995 Holocene tides of The Wash, UK: the influence of water-depth and coastline-shape changes on the record of sea-level change. *Marine Geology* **124**, 87-111. (DOI:10.1016/0025-3227(95)00034-V)

Hinton, A. 1996 Tides in the northeast Atlantic: considerations for modelling water depth changes. *Quaternary Science Reviews* **15**, 873-894. (DOI:10.1016/S0277-3791(96)00061-3)

Gehrels, W.R., 1994 Determining relative sea-level change from saltmarsh foraminifera and plant zones on the coast of Maine, USA. *Journal of Coastal Research* **10**, 990-1009.

Gehrels, W.R., 1999 Middle and late Holocene sea-level changes in eastern Maine reconstructed from foraminiferal saltmarsh stratigraphy and AMS 14C dates on basal peat. *Quaternary Research* **52**, 350-359. (DOI:10.1006/qres.1999.2076)

Gehrels, W.R., 2000 Using foraminiferal transfer functions to produce high-resolution sea-level records from salt-marsh deposits, Maine, USA. *The Holocene* **10**, 367-376.

Gehrels, W.R., Belknap, D.F., Pearce, B.R., & Gong, B. 1995 Modelling the contribution of M2 tidal amplification to the Holocene rise of mean high water in the Gulf of Maine and the Bay of Fundy. *Marine Geology* **124**, 71-85. (DOI:10.1016/0025-3227(95)00033-U)

Gehrels. W.R., Roe, H.M., & Charman, D.J. 2001 Foraminifera, testate amoebae and diatoms as sea-level indicators in UK saltmarshes: a quantitative multiproxy approach. *Journal of Quaternary Science* **16**, 201-220.

Gehrels, W.R. Belknap, D.F., Black, S., & Newnham, R.M., 2002 Rapid sea-level rise in the Gulf of Main, USA since AD1800. *The Holocene* **10**, 367-376.

Godwin, H. 1940. Studies of the post-glacial history of the British vegetation: III Fenland Pollen Diagrams; IV Post-glacial changes in relative land- and sea-level in the English Fenland. *Philosophical Transactions of the Royal Society* **B570**,239-303.

Godwin, H. 1943 Coastal peat beds of the British Isles and North Sea. *Journal of Ecology* **31**, 199-247.

Godwin, H. 1945. Coastal peat beds of the North sea region, as indices of land- and sea-level changes. *New Phytologist* **44 (1)**, 29-69.

Godwin, H., & Godwin, M.E. 1940. Submerged Peat At Southampton - Data for the Study of Post-Glacial History. V. *New Phytologist* **39**,303-307.

Haslett, S.K., Davies, P., Curr, R.H.F., Davies, C.F.C., Kennington, K., King, C.P. & Margetts, A.J. 1998 Evaluating late-Holocene relative sea-level change in the Somerset Levels, southwest Britain. *The Holocene* **8**, 197-207.

Horton, B.P. & Edwards R.J. 2005 The application of local and regional transfer functions to reconstruct former sea levels, North Norfolk, England. *The Holocene* **15**(2), 216-228.

Horton, B.P. & Edwards R.J., in press. Quantifying Holocene Sea Level Change Using Intertidal Foraminifera: Lessons from the British Isles. *Journal of Foraminiferal Research, Special Publication*.

Horton, B.P., Edwards, R.J. & Lloyd, J.M. 1999*a* UK intertidal foraminiferal distributions: implications for sea-level studies. *Marine Micropalaeontology* **36**, 205-223. (DOI:10.1016/S0377-8398(99)00003-1)

Horton, B.P., Edwards, R.J. & Lloyd, J.M. 1999*b* Reconstruction of former sea levels using a foraminiferal-based transfer function. *Journal of Foraminiferal Research* **29**, 117-129.

Horton, B.P., Edwards, R.J. & Lloyd, J.M. 2000 Implications of a microfossil transfer function in Holocene sea-level studies. In: Shennan, I. & Andrews, J. E. (eds.) *Holocene land-ocean interaction and environmental change around the western North Sea*, 41-54, Geological Society Special Publication, 166.

Horton, B. P. Larcombe, P. Woodroffe, S. A., Whittaker, J. E., Wright, M. W., & Wynn, C., 2003 Contemporary foraminiferal distributions of the Great Barrier Reef coastline, Australia: implications for sea-level reconstructions. *Marine Geology* **198**, 225-243. (DOI: 10.1016/S0025-3227(03)00117-8).

Jennings, A.E., & Nelson, A.R., 1992 Foraminiferal assemblage zones in Oregon tidal marshes - relation to marsh floral zones and sea level. *Journal of Foraminiferal Research* **22,** 3-29.

Lambeck, K., 1993. Glacial rebound of the British Isles. II. A high-resolution, high-precision model. *Geophysical Journal International* **115**, 960-990.

Lambeck, K., 1995. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *Journal of the Geological Society of London* **152**, 437-448.

Nydick, K.R., Bidwell, A.B., Thomas, E., & Varekamp, J.C., 1995 A sea-level rise curve from Guilford, Connecticut, USA. *Marine Geology* **124**, 137-159. (DOI:10.1016/0025-3227(95)00037-Y)

Paul, M.A. & Barras, B.F. 1998 A geotechnical correction for post-depositional sediment compression: examples from the Forth valley, Scotland. *Journal of Quaternary Science* 13, 171-176.

Peltier, W. R., 2004. Global glacial isostasy and the surface of the ice-age Earth The ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences* **32**, 111-149.

Peltier, W.R., Shennan, I., Drummond, R., & Horton, B. 2002 On the postglacial isostatic adjustment of the British Isles and the shallow viscoelastic structure of the Earth. *Geophysical Journal International* **148**, 443-475. (DOI:10.1046/j.1365-246x.2002.01586.x)

Pirazzoli, P.A. 1996 *Sea-Level Changes – The Last 20 000 Years.* John Wiley & Sons: Chichester. 211 pp.

Preuss, H. 1979 Progress in computer evaluation of sea level data within the IGCP Project no. 61. *Proceedings of the 1978 International Symposium of Coastal Evolution in the Quaternary*, 104-134.

Scott, D. B., & Medioli, F. S., 1978 Vertical zonation of marsh foraminifera as accurate indicators of former sea levels. *Nature* **272**, 528-531.

Scott, D. B., & Medioli, F. S., 1980 Quantitative studies of marsh foraminifera distribution in Nova Scotia: Implications for sea-level studies. *Journal of Foraminiferal Research, Special Publication*, **17**, 1-58.

Scott, D. B., Medioli, F. S., Schafer, 2001 *Monitoring in coastal environments using foraminifera and thecamoebian indicators*. Cambridge University Press:Cambridge, 177 p.

Shennan, I., 1982 Interpretation of the Flandrian sea-level data from the Fenland, England. *Proceedings of the Geologists' Association* **93**, 53-63.

Shennan, I., 1986 Flandrian sea-level changes in the Fenland, II: Tendencies of sea-level movement, altitudinal changes and local and regional factors. *Journal of Quaternary Science* **1**, 155-179.

Shennan, I. & Horton, B.P. 2002 Holocene land- and sea-level changes in Great Britain. *Journal of Quaternary Science* **17**, 511-526. (DOI: 10.1002/jqs.710)

Shennan, I. & Woodworth, P.L. 1992 A comparison of late-Holocene and twentieth-century sea-level trends from the UK and North Sea region. *Geophysical Journal International* **190**, 96-105.

Shennan, I, & Andrews, J. 2000 An introduction to Holocene land-ocean interaction and environmental change around the western North Sea. In Shennan, I. and Andrews, J. (eds.) *Holocene Land-Ocean Interaction and Environmental Change around the North Sea*. Geological Society, London, Special Publication 166, 1-7.

Shennan, I., Tooley, M. J., Davis, M. J. & Haggart, B. A., 1983 Analysis and interpretation of Holocene sea-level data. *Nature* **302**, 404-406.

Shennan, I., Lambeck, K., Horton, B., Innes, J., Lloyd, J., McArthur, J. & Rutherford, M. 2000*a* Holocene isostasy and relative sea-level changes on the east coast of

England. In Shennan, I. and Andrews, J. (eds.) *Holocene Land-Ocean Interaction and Environmental Change around the North Sea*. Geological Society, London, Special Publication 166, 275-298.

Shennan, I., Lambeck, K., Flather, R., Horton, B., McArthur, J., Innes, J., Lloyd, J., Rutherford, M., Wingfield, R. 2000*b* Modelling western North Sea palaeogeographies and tidal changes during the Holocene. In Shennan, I. and Andrews, J. (eds.) *Holocene Land-Ocean Interaction and Environmental Change around the North Sea*. Geological Society, London, Special Publication 166, 299-319.

Tooley, M.J. 1978 *Sea-level Changes: North-west England During the Flandrian Stage*. Clarendon Press, Oxford.

Tooley, M.J. 1982 Sea-level changes in northern England. *Proceedings of the Geologists' Association* **93**, 43-51.

van de Plassche, O., 1986 *Sea-level research: a manual for the collection and evaluation of data.* Geobooks, Norwich, 617p.

van de Plassche, O., Borg K. van der, & de Jong A.F.M. 1998 Sea level – climate correlation during the past 1400 yr. *Geology* **26**, 319-322.

van de Plassche, O., Edwards R.J., Borg K. van der, & de Jong A.F.M. 2001 14C wiggle-match dating in high-resolution sea-level research. *Radiocarbon* **43** (2A) 391-402.

Varekamp, J.C., Thomas, E., & van de Plassche, O. 1992 Relative sea-level rise and climate change over the last 1500 years. *Terra Nova* **4**, 293-304.

Woodworth, P.L. 1990 A search for accelerations in records of European mean sea level. *International Journal of Climatology* **10**, 129-143.

Woodworth, P.L., Tsimplis, M.N., Flather, R.A., & Shennan, I. 1999 A review of the trends observed in British Isles mean sea level data measured by tide gauges. *Geophysical Journal International* **136**, 651-670.

Edwards & Horton: Table 1.

Table 1. Chronological data for cores NNC-14 and NNC-17 (data from Andrews *et al.*, 2000). Dates are calibrated using the program OxCal ver. 3.1 (Bronk Ramsay, 1995; 2001) and show two sigma errors.

Core	Code	Altitude (m OD)	Method	Age (^{14}C or IRSL)	Error	Cal. Year (BP)		
						Max	Mean	Min
NNC-14	AA27231	-12.41	^{14}C	6585	65	7590	7460	7330
NNC-14	AA27230	-5.5	^{14}C	5115	55	5590	5455	5320
NNC-14	NNC-14-4	-3.2	IRSL	5300	750	5550	5125	4700
NNC-14	NNC-14-1	-0.73	IRSL	3000	450	3300	2975	2650
NNC-17	AA22681	-6.36	^{14}C	5930	100	7050	6750	6450
NNC-17	NNC-17-1	-6.1	IRSL	5900	900	6550	6000	5450
NNC-17	NNC-17-4	-4.88	IRSL	5700	1100	6150	5500	4850
NNC-17	NNC-17-6	-3	IRSL	4500	600	5000	4625	4250
NNC-17	NNC-17-5	-2.94	IRSL	4700	700	4850	4400	3950
NNC-17	AA22707	-1.61	^{14}C	2715	70	2720	2520	2320
NNC-17	NNC-17-2	-1.44	IRSL	2800	500	2690	2480	2270
NNC-17	NNC-17-3	0.54	IRSL	2300	350	2550	2250	1950

Figure 1. Location maps showing: (a) boreholes NNC-14 and NNC-17; (b) study marshes contributing the surface foraminiferal data used to produce the transfer function for tide level (full details in Horton & Edwards, *in press*).

Figure 2. Summary lithostratigraphy, biostratigraphy and chronostratigraphy for: (a) core NNC-14; (b) core NNC-17. Lithostratigraphy is taken from Andrews *et al*. (2000). Shaded bars show foraminiferal data (Boomer, *pers. comm.*) presented as percentages of the total count and grouped according to test composition. Reconstructed sample elevation derived from the transfer function is plotted with the associated error bars. Sample elevation is expressed as metres above mean tide level with local mean high water of spring tides (MHWST) marked for reference. Age estimates (calendar years before present) provided by radiocarbon and infrared stimulated luminescence dating are marked with arrows.

Figure 3. An age-altitude plot of the chronological data used to construct the accumulation histories for cores NNC-14 (open symbols) and NNC-17 (shaded symbols). Squares indicate radiocarbon dates (C14) whilst diamonds represent infrared stimulated luminescence dates (IRSL). Two sigma errors are shown as horizontal bars and indicate the relatively large uncertainties associated with some of the IRSL dates.

Figure 4. Reconstructions of sediment surface elevation change through time for cores NNC-14 and NNC-17, produced by combining the transfer function results and chronological data. Sample elevation is expressed as metres above mean tide level with local mean high water of spring tides (MHWST) marked for reference. White squares show the reconstructions associated with the mean chronology (see text for details). The dark shaded band reflects the elevation errors (vertical) associated with the transfer function. The pale shaded envelope shows the extent to which these curves may be shifted along the time-axis if alternate chronologies are used (see text for details).

Figure 5. The changing altitude of mean tide level through time reconstructed by combining the transfer function estimates of sample elevation (height above mean tide level) with sample altitude and interpolated age (see text for details). The darker band and pale error envelope shows the reconstructions derived from core NNC-17, whilst the lighter band and dashed envelope shows the reconstructions derived from core NNC-14.

Figure 6. The reconstructions of mean tide level change through time produced by the transfer function, plotted against existing geological sea-level data and geophysical model predictions for the Norfolk coast. The transfer function reconstructions are shown as shaded bands (see Figure 5 and text for details). Lithologically based sea-level index points are plotted as shaded rectangles encompassing their altitude and age errors. Index points from basal contexts (assumed largely compaction free) are outlined in bold. The modelled mean sea level curve produced by the ICE4G model is shown as a solid line (see Peltier *et al*., 2002).

Edwards & Horton: Figure1

Fig. 1a

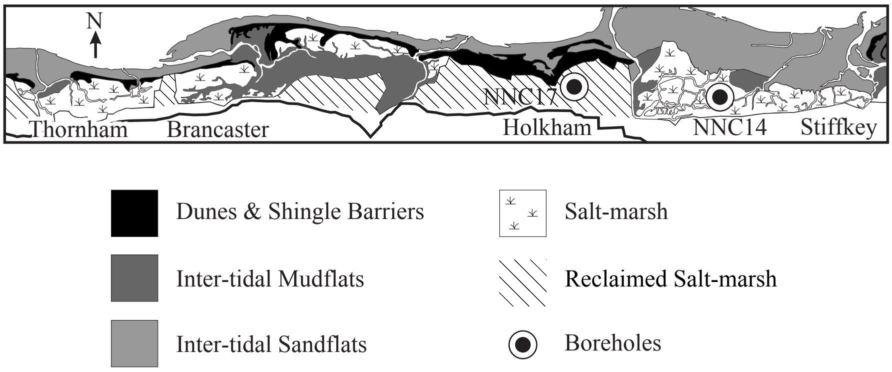
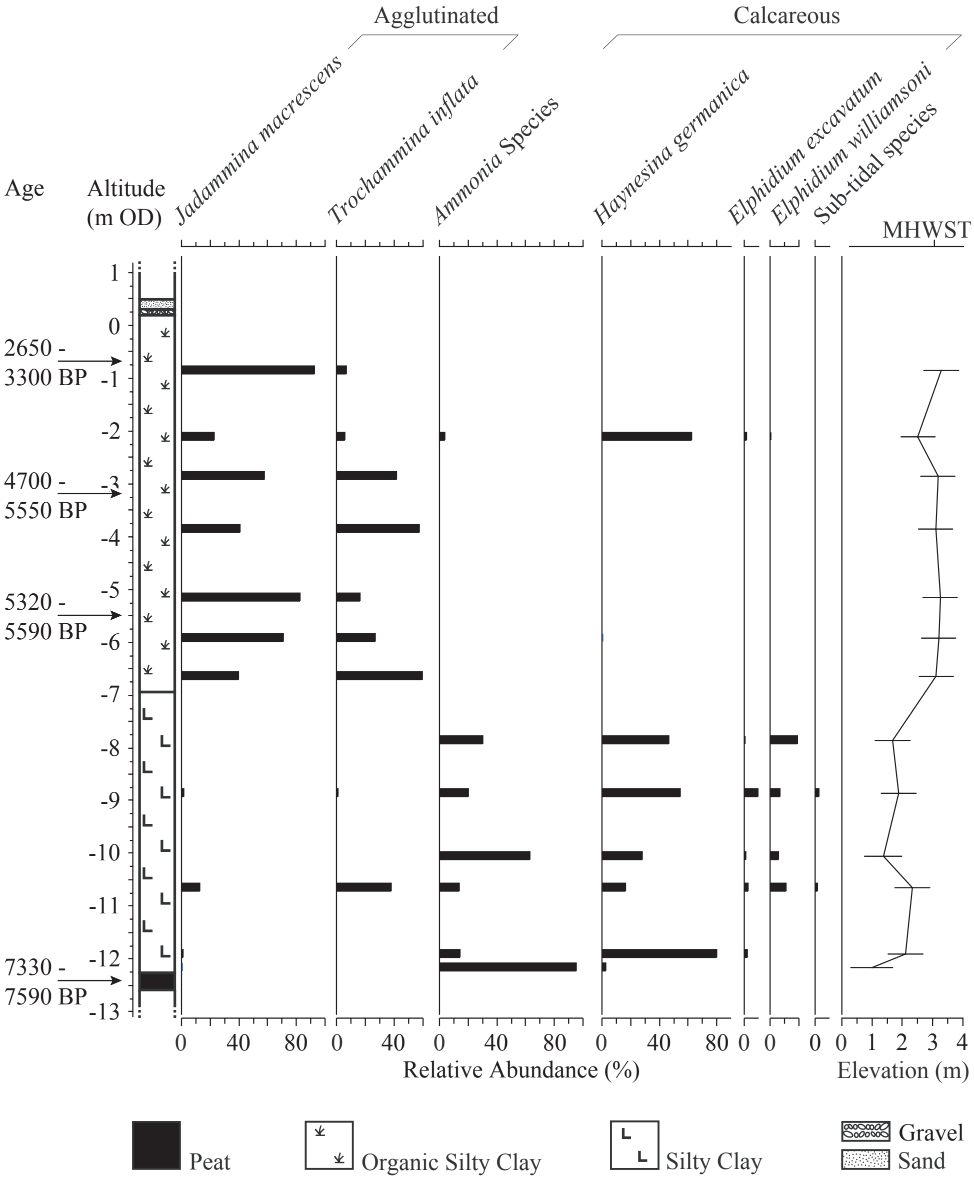
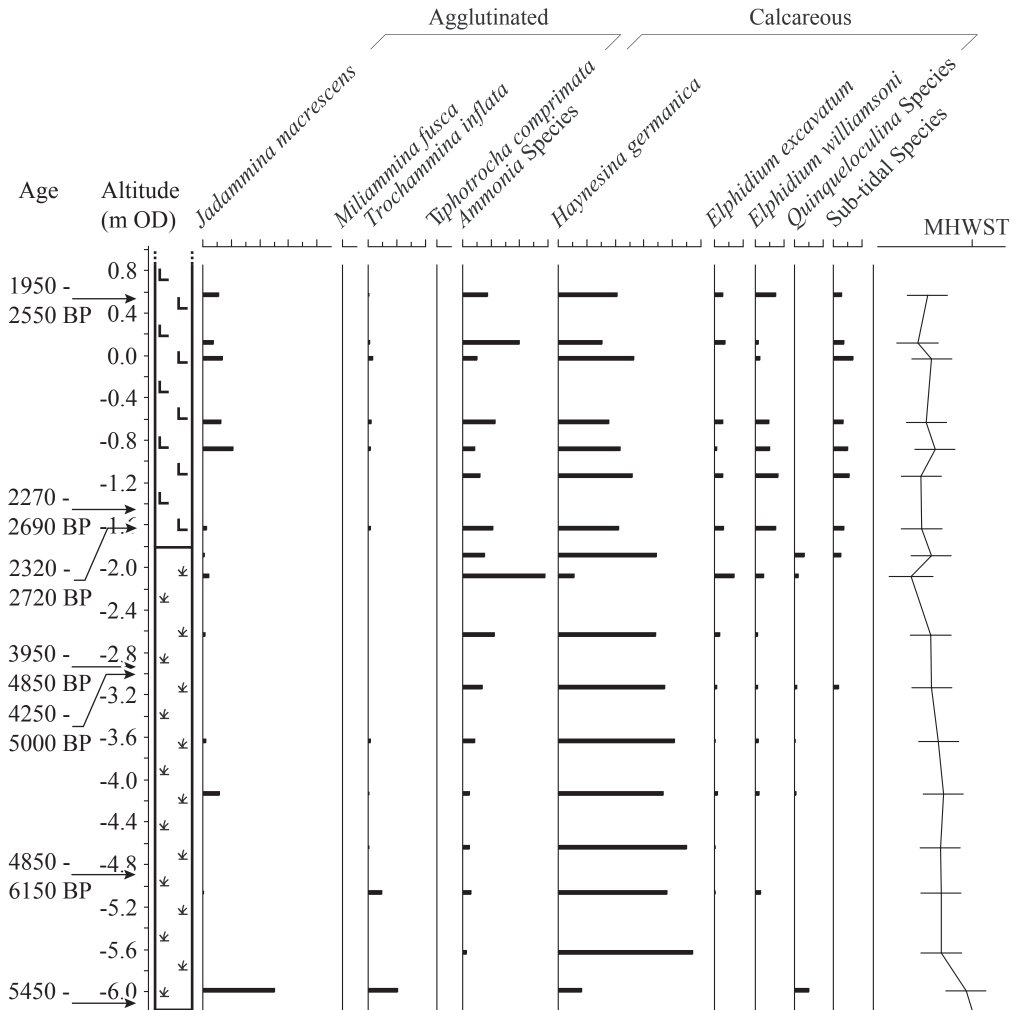


Fig. 1b

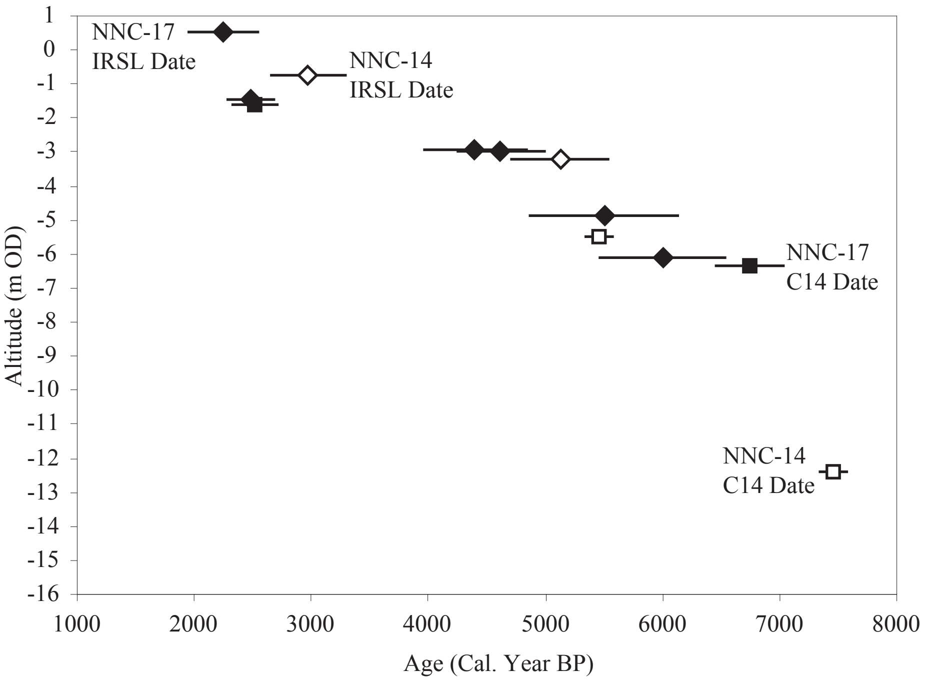
Edwards & Horton: Figure 2a



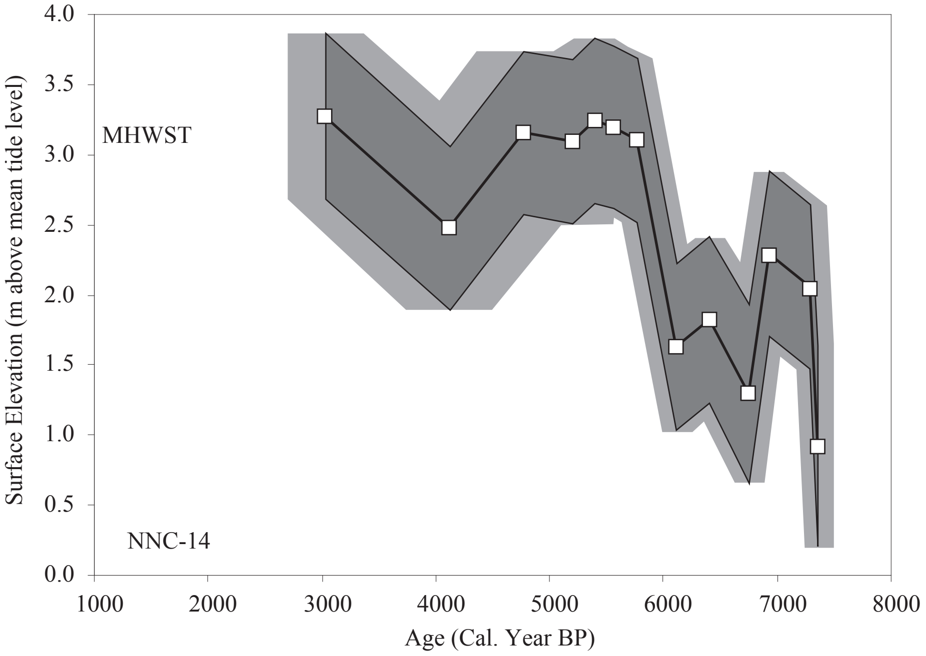
Edwards & Horton: Figure 2b

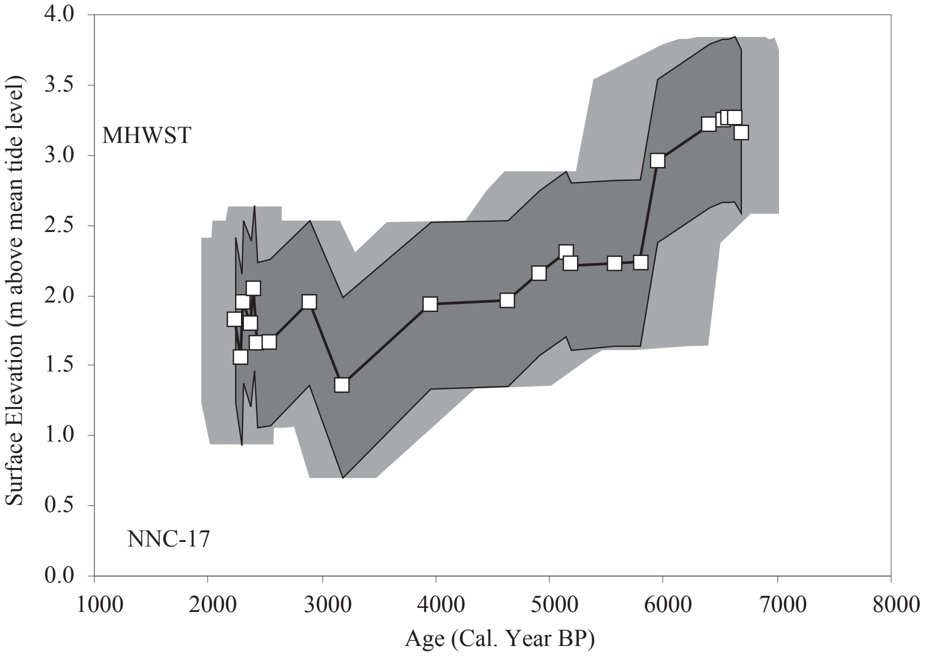


Edwards & Horton: Figure 3

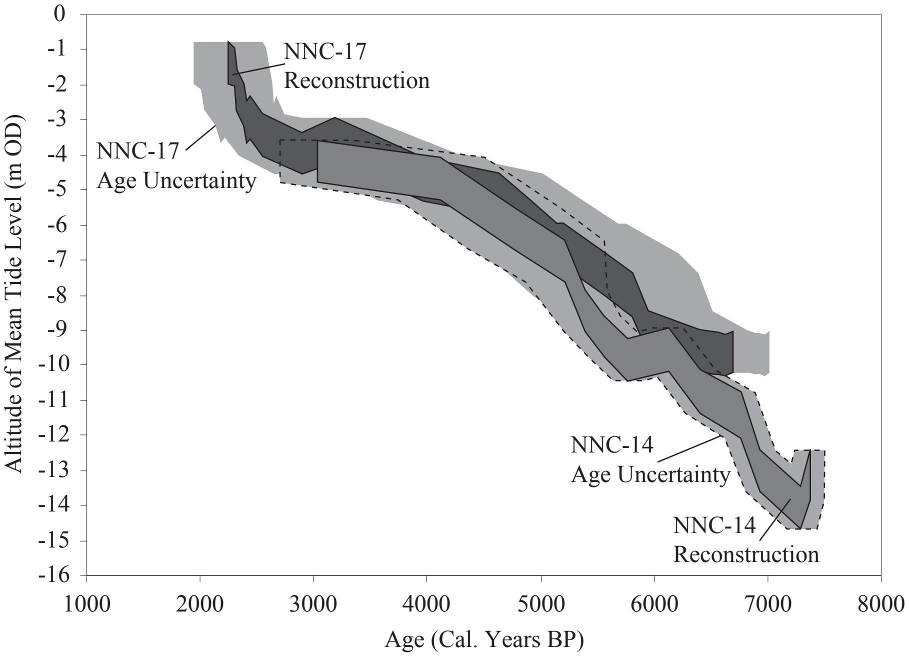


Edwards & Horton: Figure 4





Edwards & Horton: Figure 5



Edwards & Horton: Figure 6