Sedimentary Indicators of Relative Sea-Level Changes - Low Energy

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ABSTRACT

Fine grained sediments associated with low energy conditions have proven to be useful archives of relative sea-level data. Low energy inter-tidal environments, such as saltmarshes and mangroves, are closely linked to the tidal frame. Sediments accumulating in these environments, and the plant and animal remains they contain, can therefore be used to reconstruct the former position of relative sea level in time and space. A number of methodologies employing a combined lithostratigraphic, biostratigraphic and chronostratigraphic approach have been developed to extract sea-level signals from low energy sedimentary environments. This chapter outlines these methodologies and the nature of the records they produce.

KEYWORDS

coast; estuary; Holocene; inter-tidal; isolation basin; low energy; mangrove; marsh elevation diagram; relative sea-level change; saltmarsh; sea level index point; sea level indicator; sea level tendency; sediment

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Introduction

Relative sea-level (RSL) change is the product of variations in ocean level (eustatic) and vertical land movements (isostatic). Throughout the Quaternary, both eustatic and isostatic changes have accompanied the waxing and waning of large, high latitude, continental ice sheets. The RSL changes experienced at locations around the globe are predominantly influenced by proximity to these ice sheets, and generalized patterns of RSL change can be predicted on the basis of geographical location and ice-sheet history. The most detailed records of RSL currently available are concerned with changes that have occurred since the end of the last Quaternary glaciation ca. 11,000 years ago, during the Holocene.

Relative sea-level changes are reconstructed from physical features and biological organisms whose distributions are related to sea level in a consistent manner (see Lambeck et al., 2010). Information concerning RSL change can be extracted from geomorphological evidence (e.g., wave-cut platforms and tidal notches) or from sedimentary environments and their associated flora and fauna. Sea-level data from these diverse sources have produced RSL records from locations around the globe.

This article examines the evidence for RSL change that is contained within low-energy sediments. It begins by outlining the principal, low-energy coastal environments that are sources of RSL data. It then considers the nature of the sea-level information they contain, and the methods employed to generate and analyse these data. It examines the relative strengths and weaknesses of these methodologies, highlighting recent developments and areas of current research interest.

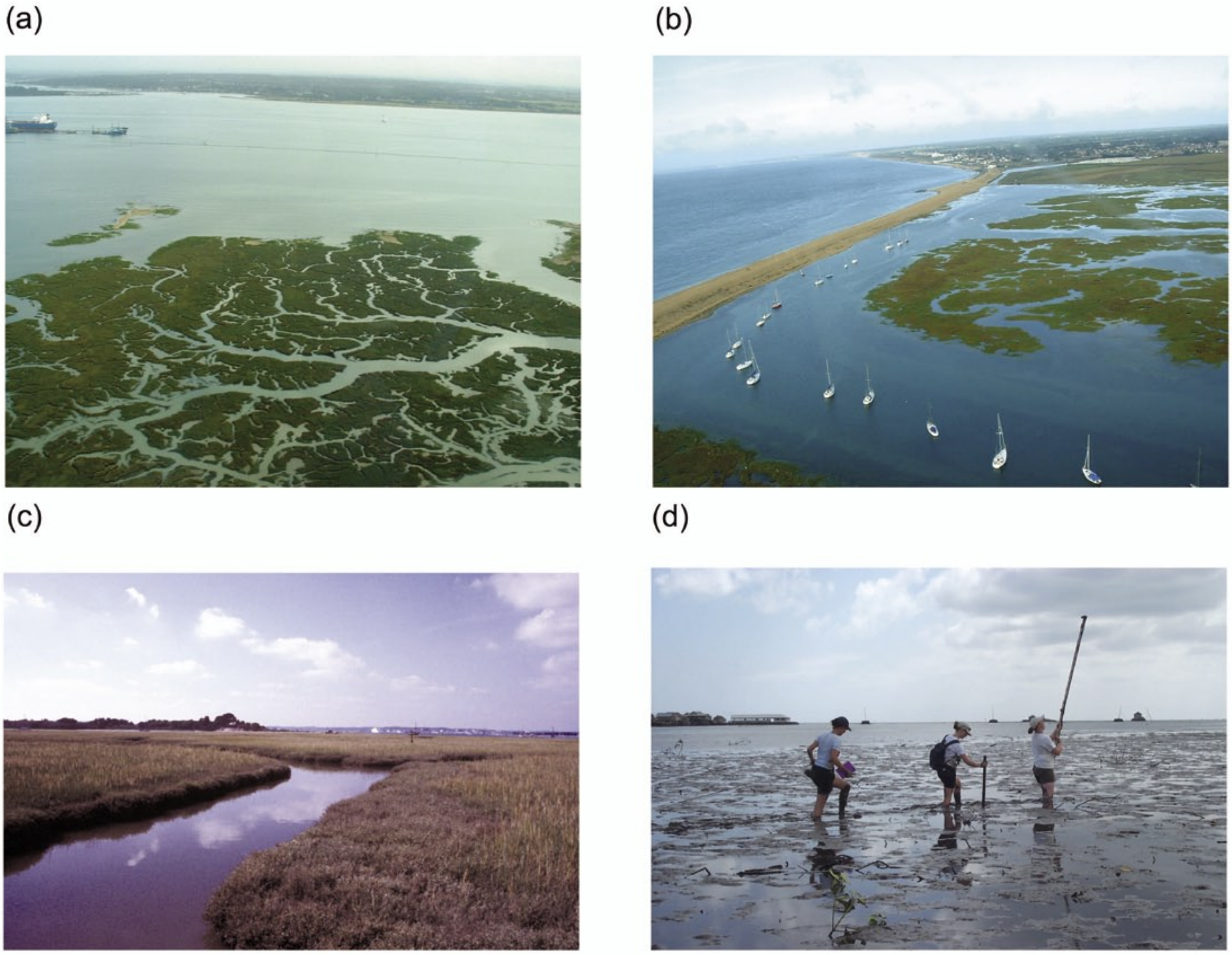

Figure 1. Some examples of low energy sedimentary environments: a) An estuarine fringing salt-marsh in Southampton Water, southern Britain, showing a meandering, dendritic tidal creek network. © Photograph, A.J. Long; b) A back-barrier salt-marsh accumulating behind a large, high-energy gravel barrier in southern Britain. © Photograph, A.J. Long; c) A flat, well-vegetated, mature salt-marsh accumulating in a micro-tidal lagoon in southern Britain. © Photograph, R.J. Edwards; d) Open, low energy mudflats fronting a mangrove swamp in Indonesia. © Photograph, B.P. Horton.

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Low-Energy Sedimentary Environments

Low-energy coastlines are common in regions around the globe where waves and tides are small and currents slow. They are typified by accumulations of fine-grained sediment (silty sand to clay) that accrete to form intertidal flats with distinctive floral and faunal communities. The lowest-energy environments are typically found in small, sheltered embayments, lagoons and estuaries with restricted fetch (Woodroffe, 2002). Local hydrodynamic conditions may also give rise to low-energy environments in certain parts of an inlet, such as in the lee of a higher-energy gravel spit or sand bar. Whilst most common in these protected areas, lower-energy sediments can also be found along open coasts where large tidal ranges promote the accumulation of extensive intertidal flats that dampen wave action. Some examples of low-energy sedimentary environments are illustrated in Figure 1.

Sources of Sea-Level Data

The lithological and biological characteristics of low energy intertidal sediments are intimately linked to the tidal frame. As a consequence of their position at the interface between land and sea, intertidal zones exhibit strong environmental gradients. The highest elevations at the upper limit of tidal influence are associated with terrestrial organisms that can withstand periodic inundation by saline waters, or marine organisms that can withstand prolonged periods of subaerial exposure. As elevation decreases (hydroperiod increases), environmental conditions change, and plant and animal communities alter until almost marine conditions are reached at the lowest tidal levels. This vertical zonation related to tide level means that RSL information can be extracted from intertidal sediments. This is achieved by analysing the nature of the sediments themselves (e.g., grain size, organic content, elemental/isotopic composition) and the plant and animal remains preserved within them.

Characteristic Intertidal Environments

Intertidal environments can be broadly subdivided into low elevation, unvegetated tidal flats, and higher-elevation vegetated surfaces. Tidal flats are commonly low-relief accumulations of sand, silt and clay that are covered by most high tides. These flats may be dissected by tidal creeks, the size and density of which are related to the tidal range (Allen, 2000). Whilst sediment source varies with location, in low-energy environments most material is redistributed across the intertidal flats by gentle wave action and tidal currents. The deposition of finer grained sediments is facilitated by flocculation and biological packaging (e.g., production of faecal pellets). Similarly, the cohesive nature of clay sediments, coupled with consolidation due to escaping pore water, and binding by organisms (e.g., algal mats), reduces the subsequent remobilization of deposited material.

The accumulation of sediment elevates intertidal surfaces, reducing the depth and period of tidal inundation. When sufficiently high relative to the tidal frame, these surfaces become vegetated. At this point, minerogenic sedimentation is augmented by the additional supply of organic material from above and below ground production (Allen, 2000). The presence of vegetation tends to slow currents and dampen waves, permitting the accumulation of more finer-grained sediments. Vegetation may also serve to bind intertidal sediments, reducing their propensity for erosion and transport. Together, these processes promote the accumulation of characteristic high-elevation organic-rich deposits. The nature of the organic-rich sediments will vary depending on the vegetation communities they support. In high to middle latitudes, saltmarsh plants occupy these high-elevation environments, whilst towards the tropics, mangrove swamps become widespread (Bird, 2000).

Saltmarshes

The floral character of a saltmarsh reflects a number of factors such as location, local hydrographic conditions, salinity regime, substrate and elevation relative to the tidal frame (Allen and Pye, 1992). In many areas, the general stages of saltmarsh evolution outlined in Figure 2 can be recognized, although the precise species involved and their links to tidal levels may vary. Low-elevation sediments are first colonized by pioneer species such as *Spartina* and *Salicornia* (Fig. 2A). A saltmarsh dominated by these environments is referred to as being youthful or immature (Frey and Basan, 1985). As the saltmarsh develops, the vegetated platform increases in elevation and reduces in gradient as sediments infill the available accommodation space (Fig. 2B). A mature or old marsh has a larger proportion of taxa associated with high elevation environments, such as *Puccinellia* and *Phragmites* species.

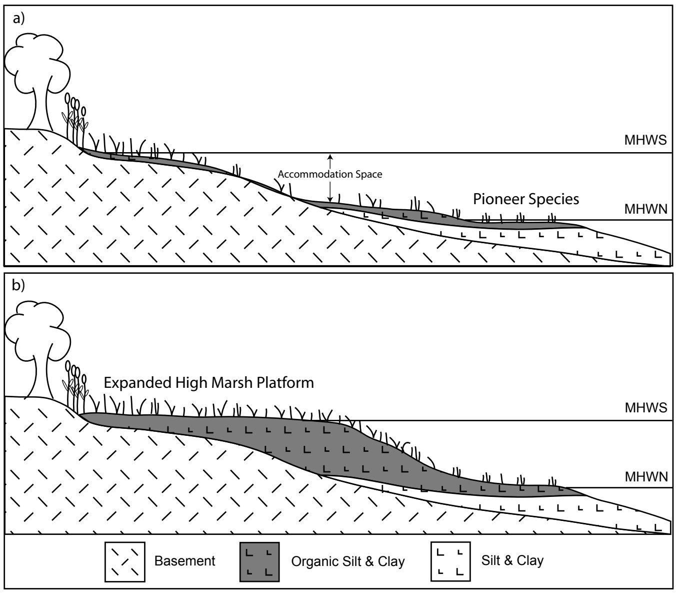

Figure 2. A sketch of the evolution of a typical minerogenic salt-marsh: a) Pioneer species colonise unvegetated inter-tidal flats, enhancing sediment accumulation, and promoting infilling of available accommodation space. Low marsh species dominate, and the salt-marsh is referred to as immature. b) Sediment accumulation results in an elevated salt-marsh surface and an expanded platform colonised by high marsh species. An increased proportion of high marsh environments indicates a mature salt-marsh. MHWS = mean high water of spring tides. MHWN = mean high water of neap tides.

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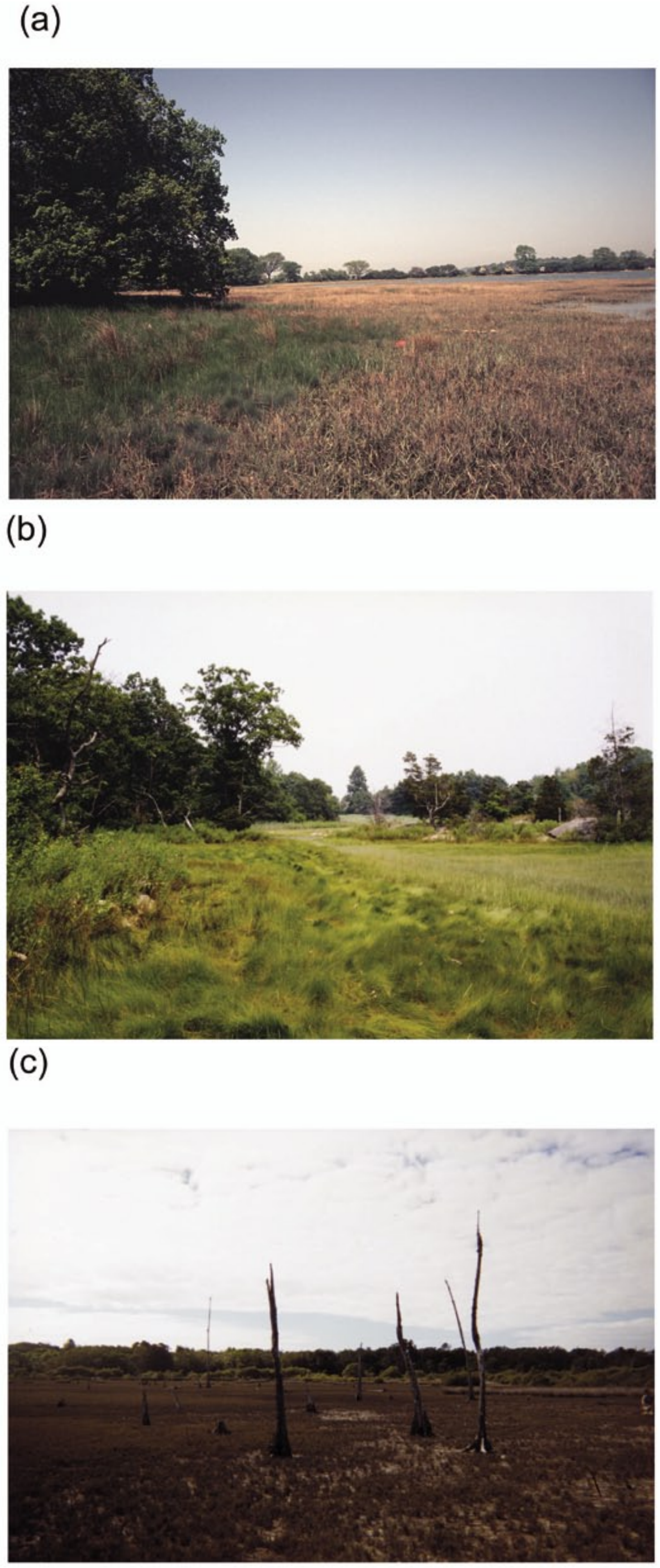

Figure 3. Three examples of vegetated salt-marshes from around the world: a) A minerogenic salt-marsh in Poole Harbour, southern Britain, showing defined inter-tidal vegetation zones grading into terrestrial woodland; b) An organogenic salt-marsh from Connecticut, USA, showing a similar vegetation zonation of inter-tidal species, backed by woodland; c) a sparsely vegetated, high elevation salt-marsh plain backing mangroves in southeastern Australia. © All Photographs, R.J. Edwards.

Figure 3 shows three examples of contrasting saltmarsh environments. Minerogenic saltmarshes (Fig. 3A) are typical of low-energy coasts around northwest Europe. The organic content of their sediments and the preservation of plant material is much lower than organogenic saltmarshes such as those encountered on parts of the eastern coast of North America (Fig. 3B). Finally, Figure 3C shows a wide, flat expanse of saltmarsh accumulating behind a mangrove swamp in southeast Australia. This region has experienced a general encroachment of mangrove communities into saltmarsh areas in recent years. The cause of this environmental change may be due to a number of factors, including changes in RSL, tidal prism, sedimentation and surface elevation (Rogers et al., 2005).

Mangroves

In tropical regions, saltmarsh vegetation is largely replaced by mangrove communities (Fig. 4A). Mangrove trees grow best in low-energy environments with muddy substrates and can form extensive fringes where tidal ranges are large (Bird, 2000). They share a number of features in common with the saltmarsh systems outlined above. The presence of mangroves traps sediment suspended in tidal waters, promoting accretion and elevating the sediment surface. Low elevation surfaces are characterized by pioneering species such as *Avicennia*, pictured in Figure 4B with its pneumatophores protruding from the adjacent unvegetated inter-tidal flats. As the sediment surface elevation increases, these pioneers are replaced by other mangrove species such as *Rhizophora*.

The Utility of Low-Energy Sedimentary Environments

The use of intertidal environments in sea-level research stems from the fact that subenvironments can be distinguished on the basis of their sedimentary character (lithostratigraphy) and associated flora or fauna (biostratigraphy); and that these subenvironments can be linked to the tidal frame (van de Plassche, 1986). Traditionally, attention has been focused on the easily recognizable transition between marine and terrestrial conditions that is expressed in the lithostratigraphy by the interchange of minerogenic and organic-rich deposits (e.g., Tooley, 1978). The age of organic, peaty deposits can be established by radiocarbon dating, permitting a chronology for the sedimentary sequence to be developed (chronostratigraphy). In recent years, advances in the methods used to discriminate between subenvironments (e.g. microfossil analysis), and improvements in dating techniques (e.g., AMS radiocarbon dating), and short-lived radionuclides such as Cs^{137},Pb^{210} etc) have expanded the range of sedimentary contexts from which RSL data can be extracted.

In comparison with their higher-energy counterparts, low-energy sedimentary environments are less susceptible to processes such as erosion and transport. Given sufficient sediment and accommodation space, it is possible for relatively unbroken sequences to accumulate, and these provide ideal sources of RSL data.

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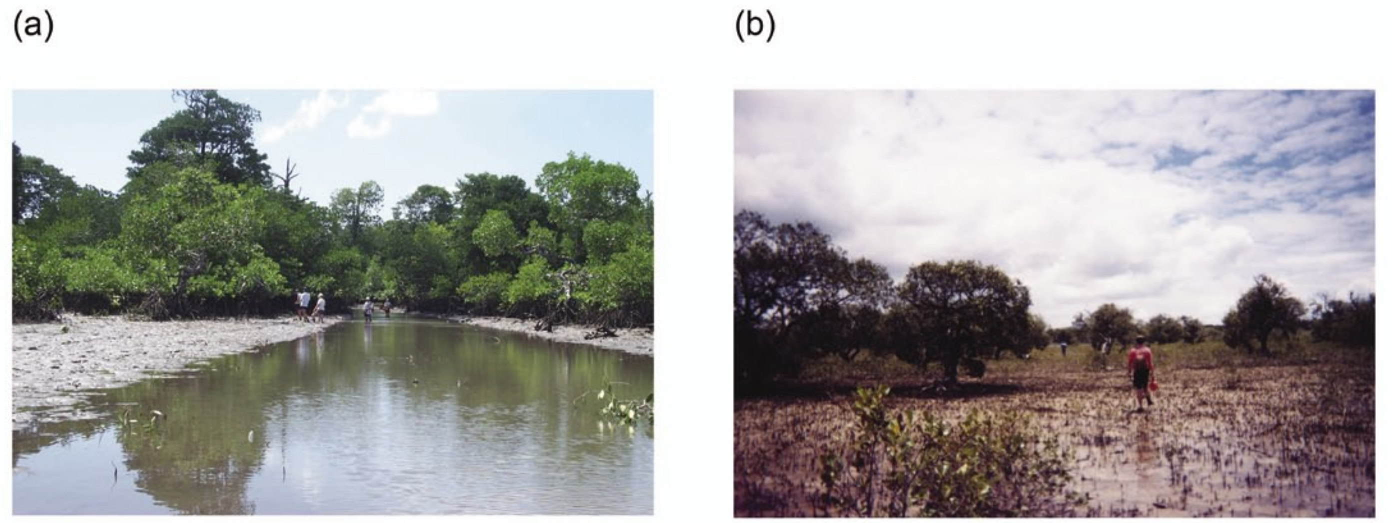

Figure 4. a) A tropical mangrove swamp fronted by fine-grained inter-tidal mudflats, Indonesia. © Photograph, B.P. Horton; b) An open, temperate mangrove stand showing pneumatophores extending into unvegetated inter-tidal flats. © Photograph, R.J. Edwards

Despite their potential utility, the records of RSL change preserved within these sequences are not always straightforward to extract. Whilst sea-level studies are inherently concerned with extrinsic controls on saltmarsh development, marsh morphodynamics will inevitably involve a wider range of phenomena which can also leave imprints in the sedimentary record (e.g. autocyclicity (Singh Chauhan, 2009)). This reinforces the fact that the sequences themselves do not comprise direct measurements of sea level, but rather record changes in a number of proxies for sea level. These proxies are influenced by other factors in addition to RSL change and therefore represent composite signals that require deconvolution. Consequently, the resulting records will be affected by the particular indicator used, the capacity of that indicator to register change, and the preservation of this signature in the geological record. This will, in turn, depend on a number of factors including the magnitude and rate of RSL change, the sensitivity and precision of the indicator used, and the successive environmental conditions experienced after its incorporation into the sedimentary sequence.

Reconstructing RSL change from low-energy sedimentary environments

A variety of strategies and methodologies are employed to distil the RSL signals from the composite records contained within low-energy sediments. These are all underpinned by the multiproxy approach, employing a combination of litho-, bio-, and chronostratigraphic data. Lithostratigraphy is usually determined from a series of sediment cores collected at a study site and described in the field (Fig. 5). In some circumstances, lithostratigraphy may also be examined in exposed sections (Allen and Haslett, 2002). Selected cores or monoliths are then returned to the laboratory for further analysis. This analysis may include quantitative sedimentology (e.g., grain size or loss on ignition), geochemical assessment (e.g., stable isotopes and elemental ratios of organic carbon and total nitrogen) and micropaleontology (e.g., pollen, diatoms, or foraminifera) to establish the nature of the environment in which the sediment accumulated. The age of sediment samples is then commonly inferred by radiocarbon dating the organic material they contain.

Sea-Level Indicators

An ideal sea-level indicator will be related to sea level in a consistent and quantifiable manner. In this way, changes in the indicator can be used as proxies for changes in RSL (Pirazzoli, 1996). For example, the altitude of past RSL can be inferred from a sediment sample if the current altitude of that sample is known, and if the environment in which it formed has a quantified vertical relationship to sea level. Quantifying this vertical relationship (termed the indicative meaning) is important to account for the differing vertical distributions of coastal subenvironments and associated sea-level indicators (van de Plassche, 1986). Figure 6 illustrates the components of an indicative meaning which are defined in relation to the tidal frame. Any unquantified change in tidal range through time will introduce vertical error into RSL reconstructions. Samples from low-energy sedimentary environments are used to reconstruct RSL change in two principal ways: (1) by attempting to fix the vertical position (altitude) of sea level relative to a geodetic datum; and (2) by examining switches in depositional environment indicating an increase or decrease in marine influence. A selection of approaches to RSL reconstruction that employ one or both of these perspectives are illustrated below. Detailed descriptions of these approaches, along with their associated errors and limitations are discussed in van de Plassche (1986), Shennan (1986) and Tooley and Shennan (1987).

Sea-Level Index Points

An established methodology for reconstructing vertical changes in RSL from sedimentary environments has been developed as part of several International Geosciences Programme (IGCP)

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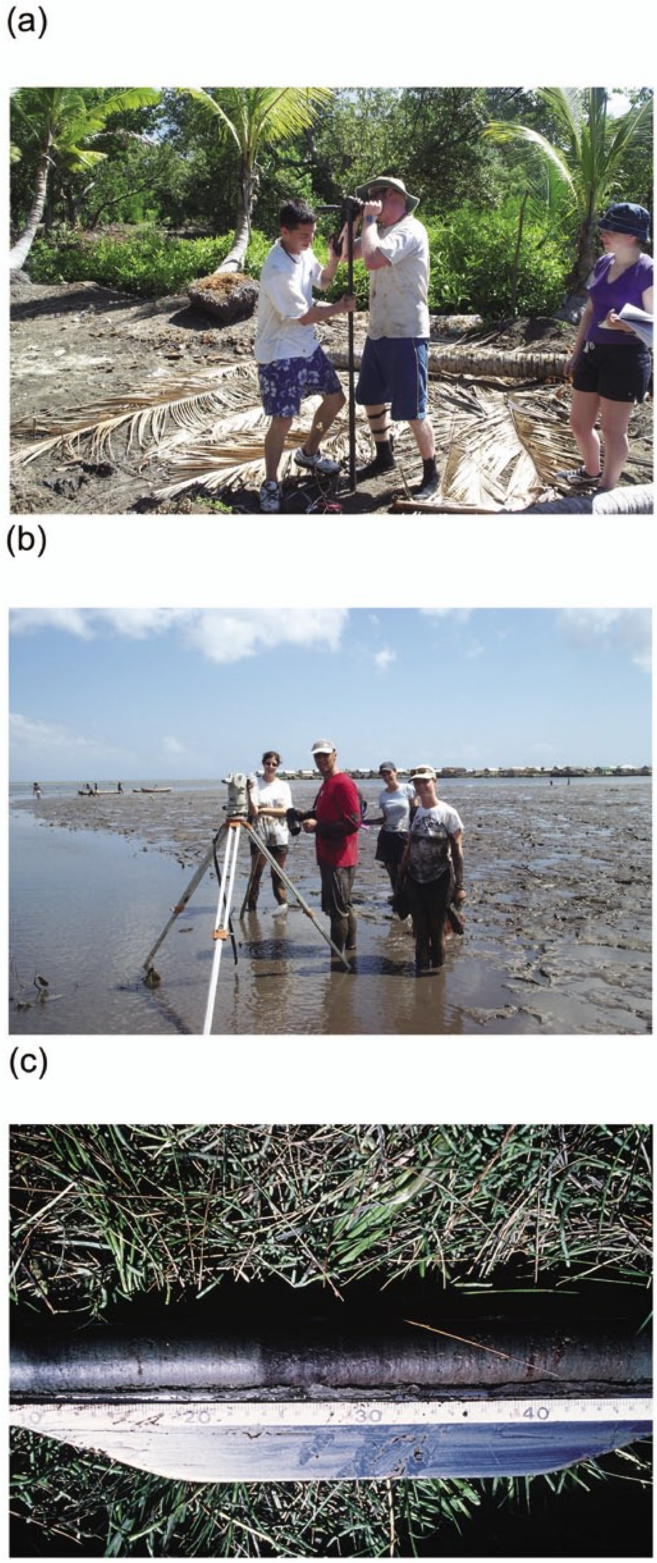

Figure 5. a) Lithostratigraphic data is commonly collected in the field using hand-corers. Here, a narrow-bore gouge auger is being used to investigate sediments in an Indonesian mangrove © Photograph, B.P. Horton; b) The altitude of sediment samples and boreholes must be measured, and their vertical relationship to tide level established. Here a total station is being used to level samples from inter-tidal flats in Indonesia © Photograph, B.P. Horton; c) Salt-marsh sediments recovered in a russian-type corer are described in the field before being removed for laboratory analysis. In this section, bands of dark peat alternate with pale silty clay. © Photograph, R.J. Edwards.

Projects (Tooley, 1985). This methodology uses sea-level index points (SLIPs) that fix the altitude of former RSL in time and space (Shennan, 1986). In order to be established as a SLIP, a sediment sample must possess information concerning its location (latitude and longitude), altitude (relative to a levelling datum), age (commonly inferred from radiocarbon dating), and its indicative meaning (Fig. 6).

Traditionally, SLIPs have been established from lithostratigraphic contacts between terrestrial and marine sediments, with supporting microfossil data (e.g., pollen, foraminifera, diatoms) being used to delimit the onset or removal of brackish/marine conditions and to confirm that the contacts are conformable (Tooley, 1985; Shennan, 1986). This focus on a restricted set of depositional environments arose because of the need to establish an indicative meaning (derived from the nature of the lithostratigraphy above and below a contact) and the requirement of organic material suitable for radiocarbon dating. The lithostratigraphic change from terrestrial peat to marine mud is referred to as a transgressive contact, whilst the switch from marine mud to terrestrial peat is termed a regressive contact. Transgressive and regressive contacts indicate an increase or decrease in marine influence respectively. They are used as purely descriptive terms that do not imply an underlying cause or process. For example, a regressive contact (intertidal mud to terrestrial peat) may arise from the accumulation of sediment with or without a change in RSL.

Considerable attention has been directed towards quantifying the magnitude of uncertainty associated with determining the age and altitude of a SLIP (Shennan, 1986). For example, in the case of the age of a SLIP, these may relate to the uncertainties inherent with calibrating radiocarbon dates, or may be associated with contamination by allochthonous carbon (e.g., rootlet penetration). Additional errors can be introduced if the lithological contacts from which dateable material is recovered are associated with breaks in sedimentation, erosion or reworking. In the traditional lithologically-based scheme, the SLIP approach requires contacts to be conformable so that up-core changes reliably reflect the transitions between spatially adjacent subenvironments (Shennan, 1986). This may be difficult to establish from sedimentology alone and can be a particular problem for transgressive contacts where reworking mixes material to produce 'pseudo-transitional' deposits (Waller et al., 2006). For these reasons, supporting data (e.g. biostratigraphy) is required to demonstrate that the dated sample forms part of a sequence of change extending across the contact but not restricted to it.

Whilst biostratigraphy is the preferred tool for elucidating variations in marine influence across lithological contacts, poor microfossil preservation can result in insufficient data to reliably determine the nature of environmental change. In recent years there has been growing interest in potential alternative geochemical approaches to supplement the information provided by biostratigraphy. The isotopic signature of bulk organic carbon ($\delta^{13}C$) and the elemental ratio of organic carbon and total nitrogen (C/N) are routinely used to examine the source of organic matter in coastal and estuarine environments. In

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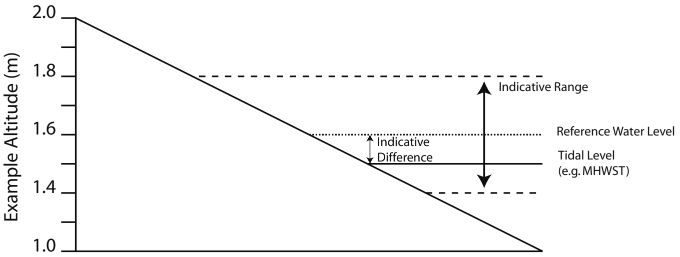

Figure 6. A sketch showing the components of an indicative meaning. The indicative range describes the vertical interval over which a sea-level indicator is found. The indicative difference describes the position of the indicative range (called the reference water level) relative to a defined component of the tidal frame. In this example, the reference water level is MHWST + 0.1 m, and the indicative range is ± 0.2 m.

many cases, a good correlation exists between salinity and $\delta^{13}C$, suggesting that isotopic signatures can be used to distinguish between terrestrial, brackish and marine environments (e.g. Yu et al., 2010). In regions where C3 and C4 plants occupy different saltmarsh elevation zones, the potential exists to recover an isotopic fingerprint of this biological zonation, although inputs from allochthonous carbon and/or diagenetic changes (e.g. decomposition) can distort these signatures (see Kemp et al., 2010). In the future, compound-specific analyses may provide one means of avoiding the complication of in-washed material (e.g. Johnson et al., 2007; Tanner et al., 2007).

Where C4 plants are absent from saltmarsh environments, the combination of $\delta^{13}C$ and C/N ratio has been used to detect relative shifts in marine influence on the basis that tidally introduced (allochthonous) particulate organic carbon will decrease with increasing elevation (see Wilson et al., 2005; Lamb et al., 2006). In this case, it is the trends in $\delta^{13}C$ and C/N ratio rather than the precise values which are considered diagnostic, with particularly marked excursions being associated with the upper limit of marine influence. Whilst further work is needed to better understand the role of complicating factors, geochemical signatures have the potential to provide information on RSL change in Holocene sediments (Lamb et al., 2007). However, at present, the resulting SLIPs will be associated with larger vertical error terms than those produced by microfossil-based reconstructions due to the difficulties of precisely quantifying sample indicative meaning.

Uncertainties relating to reliably establishing indicative meaning are not the only potential sources of vertical error associated with SLIPs. In addition to altitude errors that may be introduced during fieldwork (e.g., levelling to a datum, measuring depth in core, etc.), perhaps the most significant unknown variable is the extent to which samples may have been lowered through time due to autocompaction of the sediment column (Allen, 2000). In general terms, the effects of compaction are most pronounced in organic-rich sequences and will have greatest impact on the altitudes of SLIPs established from the transgressive contacts of thick, intercalated coastal peat deposits. At present, there is no agreed protocol for dealing with the effects of sediment compaction, although its effects are widely recognised (e.g. Long et al., 2006b; Tornqvist et al., 2008; van Asselen et al., 2009; Horton & Shennan, 2009). Whilst a range of approaches have been used to investigate and address its impacts (e.g. Paul & Barras, 1998, Edwards, 2006, Massey et al, 2006; Brain et al., 2011), an initial assessment can simply be made by distinguishing between SLIPs from differing stratigraphic contexts (see Horton & Shennan, 2009).

In light of these collected uncertainties, SLIPs are plotted on age-altitude graphs as individual data points with associated error bars. The magnitude of these error terms are an important limiting factor in determining the maximum resolution at which RSL changes can be measured using this methodology. Sea-level index points fix the former altitude of RSL in time, but do not provide any information on the nature of sea-level change between points. As a result, the number, distribution and quality of data points provide fundamental constraints on the detail with which patterns of RSL change can be reconstructed.

An example of the age-altitude approach

To illustrate the SLIP approach, a hypothetical sedimentary sequence with associated radiocarbon dates is presented in Figure 7. The lithostratigraphic section (Fig. 7A) is typical of the intercalated low-energy sedimentary sequences found beneath minerogenic saltmarshes in northwest Europe (Allen, 2000; Long et al., 2000). The type of litho- and chronostratigraphic data furnished by a transect of sediment cores is shown in Figure 7B and these data are used to produce an age-altitude plot (Fig. 7C). For simplicity, in this example all transgressive and regressive contacts are assigned an indicative meaning equivalent to the elevation of MHWST ± 0.5 m.

In addition to the SLIPS, two dated samples without indicative meanings are included on the diagram. Whilst these cannot be directly linked to a former RSL, given knowledge of their depositional environment they can be used to define the limit of possible RSL altitude (and are thus referred to as limiting dates). In this example, one limiting date is derived from the base of a terrestrial peat (Core E) and must have accumulated above the limit of marine influence (RSL below). Conversely, a second limiting date is taken from subtidal sediments in the same core (RSL above). These dates can be used to constrain the band of sea-level change drawn around the scatter of SLIPs (Fig. 7C).

The age-altitude plot in Figure 7C exhibits a number of features typical of these kinds of record. Data are not evenly distributed through time with the result that there are intervals of 1,000 years or more for which no sea-level data are available. Where data coverage is good, vertical scatter is introduced by differential sediment compaction. This is evident by the tendency for intercalated SLIPs (open boxes) to plot below basal SLIPs (grey boxes) of similar age. For example, a large amount of compaction in Core E is responsible for the scatter of points around 1,000 BP. Finally, the calibration of radiocarbon dates results in age uncertainties of differing magnitude, and this produces SLIPs with variable age errors. In reality, many of the SLIPs would also be associated with differing altitude errors. The combination of these limitations means that a generalized

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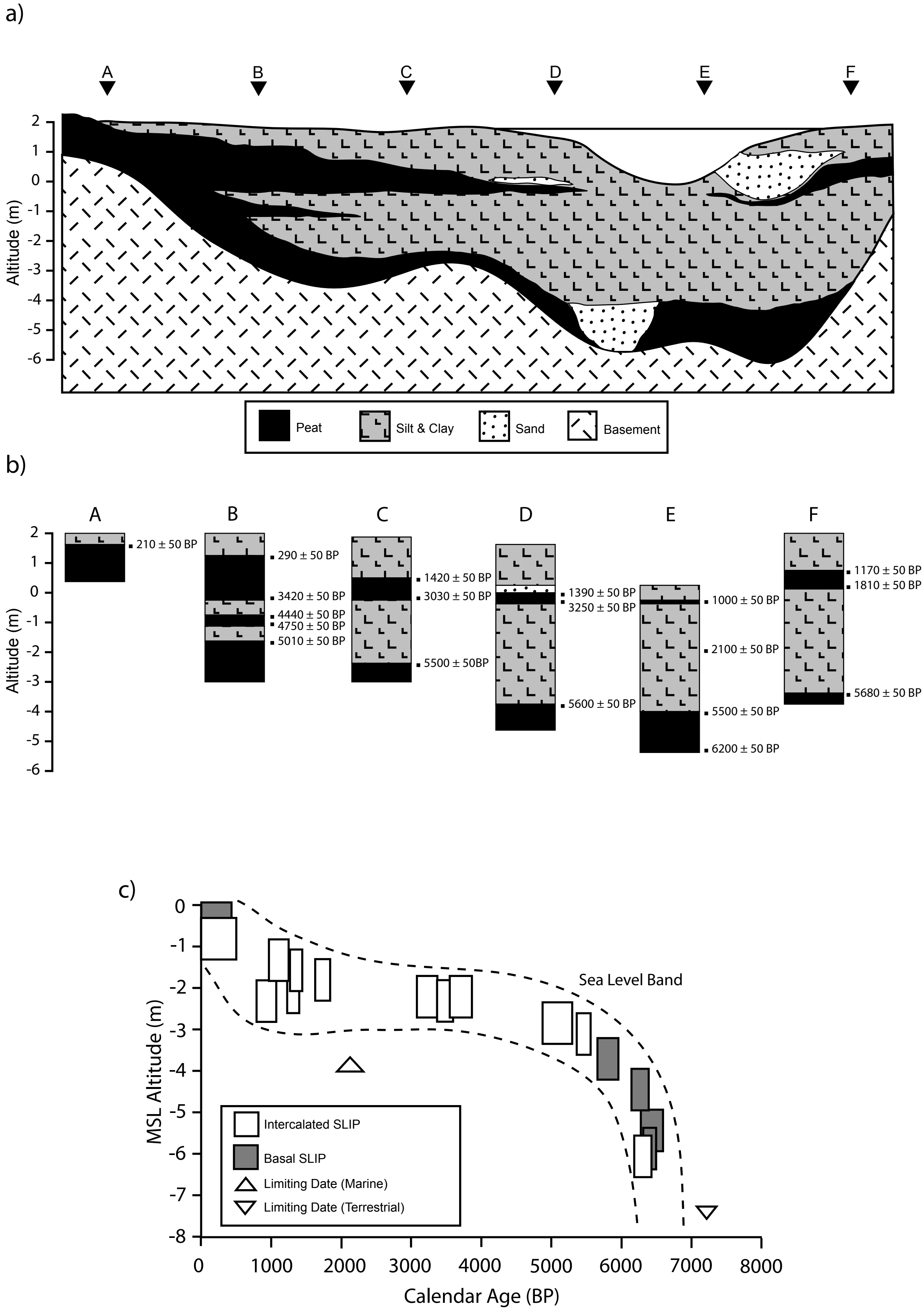

Figure 7. An example stratigraphic sequence used to furnish sea level index points (SLIPs) for age-altitude analysis. a) A cross section of the hypothetical lithostratigraphy indicating the location of a transect of boreholes. b) The lithostratigraphy as represented by six boreholes, with associated chronological data provided by a series of hypothetical radiocarbon dates. c) The resulting age-altitude plot of SLIPs plotting changes in mean sea level over time. The height and width of the boxes represents the altitude and age uncertainties associated with each SLIP. Mean high water spring tides (MHWST) is defined as 2m above mean sea level. All SLIPs were assigned an indicative meaning of MHWST ± 0.5 m. Two limiting dates (without indicative meanings) are shown as triangles.

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band of RSL change is plotted around the data. The thickness of this band defines the upper limit of resolution at which the record can be reliably interrogated.

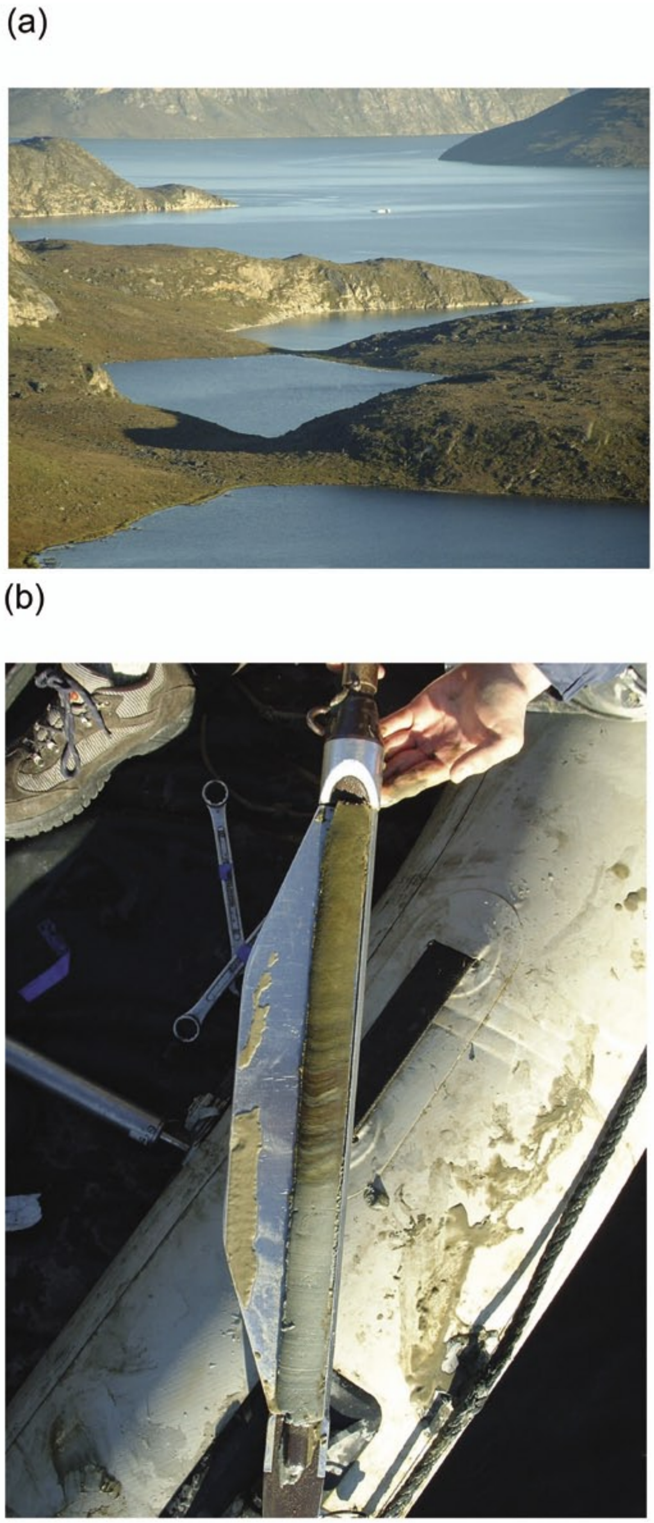

Figure 8. a) A staircase of isolation basins in western Greenland. The rock sills separating each basin are clearly visible © Photograph, A.J. Long; b) Sediments recovered from an isolation basin using a russian-type corer. This section shows a classic isolation sequence, changing from a marine, grey silty clay at the base, through to a brown, organic gyttja © Photograph, A.J. Long.

A variant of the age-altitude approach

A modified version of the SLIP methodology has been employed to extract sea-level data from isolation basins. These rocky basins may be located along high-energy coasts, but contain sedimentary sequences that have accumulated in low-energy conditions, protected from the open sea behind a rock sill (Fig. 8). Classic examples of isolation basins are found along coastlines experiencing long-term crustal uplift (e.g., Greenland, Scandinavia, Scotland). This uplift results in relative sea-level fall and the isolation of these sedimentary basins from marine influence (Fig. 9). This isolation is recorded by microfossil assemblages (e.g., diatoms, foraminifera) that are sensitive to changes in salinity. These microfossils are preserved within isolation basin sediments and record changes from marine through brackish to freshwater depositional environments (Fig. 9).

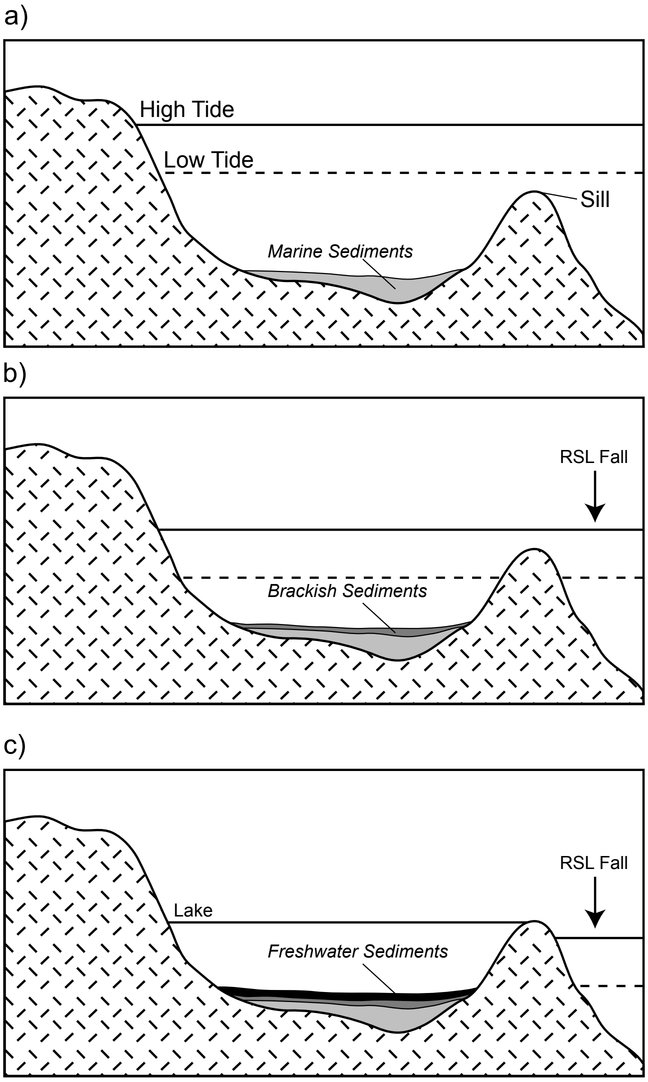

Figure 9. A schematic diagram showing the isolation of a tidal basin by falling relative sea level. a) The basin is inundated at all stages of the tide and marine sediments accumulate. b) The basin is isolated from the sea at low tides and brackish conditions are experienced. c) High water is now below the height of the sill and the isolation basin becomes a freshwater lake.

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In rapidly uplifting areas (e.g., Greenland), this isolation occurs comparatively quickly and is recorded in the litho- and biostratigraphy by an abrupt isolation contact. This contact can be dated and used as a SLIP, although the altitude of the index point is reconstructed differently from those established in saltmarshes. Instead of using the altitude of the sediment sample, SLIPs from isolation basins use the altitude of the lowest part of the rock sill separating the basin from the open sea (Fig. 9). In this way, isolation basins have provided important, long records of RSL change from regions close to former centers of ice loading. Whilst these index points are not susceptible to the influence of sediment compaction, their reliable interpretation relies on successfully locating the lowest point of the sill and assumes that the sill itself is impermeable to seawater. Figure 10 shows a simplified example of data collected from an isolation basin study in western Greenland (see Long et al. (2006a) for details). A transect of boreholes were recovered from an isolation basin with a sill 1.61m above modern sea level (Figs. 10A, B). A series of diatom samples were taken across the transition from a marine grey silt clay into a freshwater gyttja, and an AMS radiocarbon date from this contact returned an age of 4,150 ± 50 BP (Fig. 10C). These data were used to establish a SLIP which, when plotted on an age-altitude diagram with other SLIPs from the area, charts RSL change over the last 8,000 years (Fig. 10D).

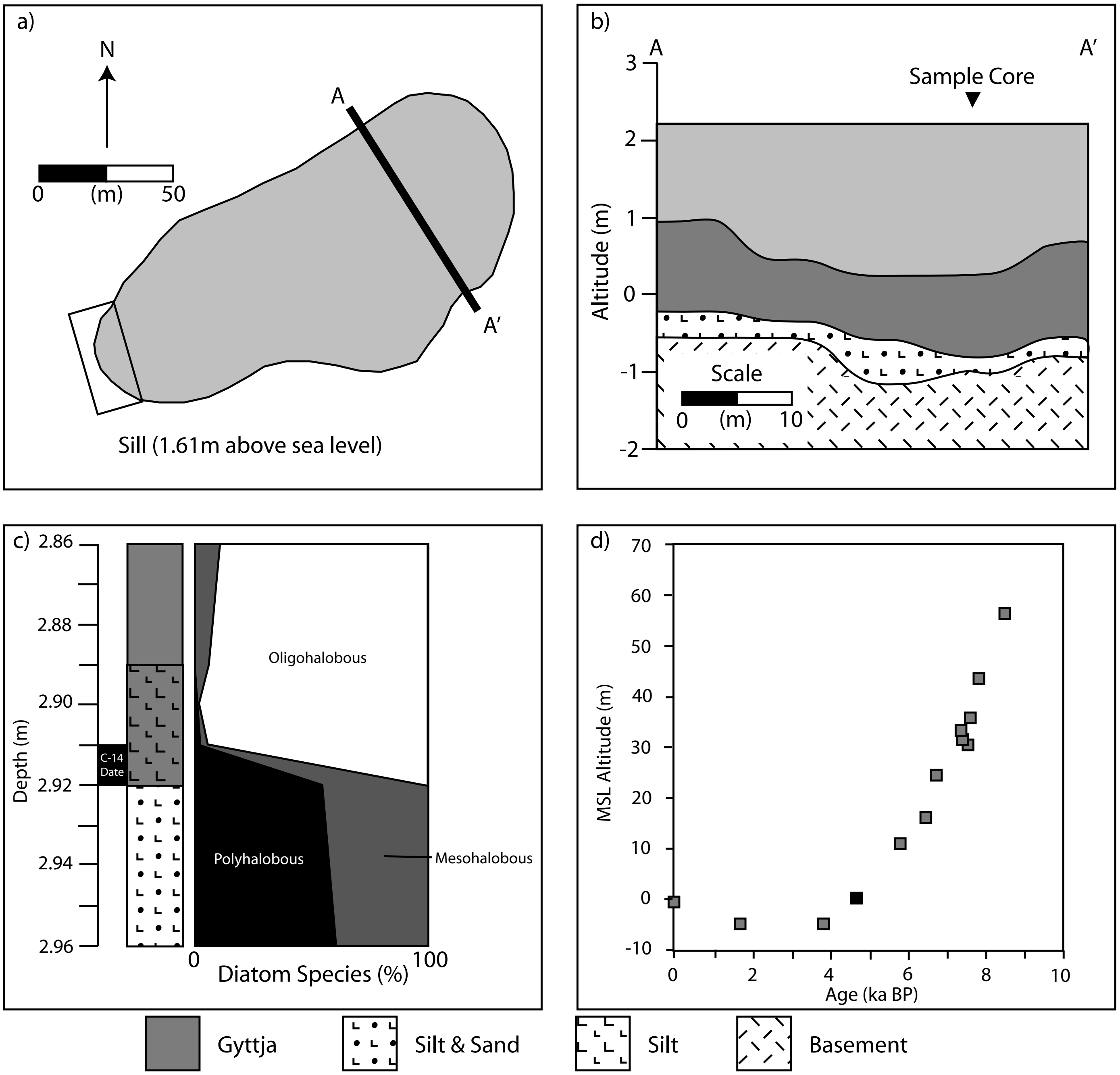

Figure 10. Example sea level data from an isolation basin in western Greenland. a) Plan of the isolation basin showing transect location and position of sill. b) Lithostratigraphy of the isolation basin showing sample core location. c) A simplified stratigraphic column plotted with a summary of the diatom analysis which shows the shift from polyhalobous species (indicative of marine conditions) to oligohalobous species (associated with freshwater conditions). d) An age-altitude plot derived from isolation basin data collected in western Greenland (example site data plotted as a grey box). Figures compiled and adapted from Long et al. (2005).

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In regions associated with smaller amounts of uplift (e.g., northwest Scotland) complete isolation from the sea takes much longer with the result that brackish water, transitional sediments accumulate in greater thicknesses, and stratigraphic contacts are less abrupt. This complicates the identification and interpretation of the isolation contact and ongoing research is focusing on improving reconstructions from these transitional environments, either by a more sophisticated treatment of microfossil data, or by additional isotopic / elemental analysis (e.g. Mackie et al., 2007).

Sea-Level Tendencies

An alternative and complementary perspective to age-altitude analysis can be supplied by considering the timing and nature of changes in depositional environment. Instead of attempting to quantify vertical RSL movements, attention is focused on delimiting periods of time when sea-level indicators from a particular area display increases or decreases in marine influence. Increases in marine influence are termed positive sea-level tendencies, whilst decreases in marine influence are called negative sea-level tendencies (Shennan, 1986).

Sea-level tendencies have been defined, employed, and (mis)interpreted in differing ways in the literature, which has led some authors to suggest the terms are potentially misleading and no longer helpful (Allen, 2003). If they are to be used with sedimentary archives, it is important to recognize that sea-level tendencies are the product of a balance between sedimentation and local tide-level changes and consequently are not synonymous with rises and falls in RSL. Whilst in mature marshes or settings with well-quantified sedimentation rates, they can provide insights into changes in the rate of RSL rise, even similar tendencies observed across a region need not be related to RSL change. For example, in southern Britain, rapid colonization by *Spartina anglica*, a hybrid saltmarsh grass capable of withstanding long periods of submergence, produced dramatic increases in sediment accumulation and saltmarsh growth throughout the region during the early part of the twentieth century (see Allen, 2000 and references therein). This gave rise to a widespread negative sea-level tendency during a time in which instrumental measurements indicate rising RSL.

Whilst it should therefore be used with caution, the tendency approach can help tackle certain limitations inherent with age-altitude analysis. For example, in some instances SLIPs from closely spaced transgressive and regressive contacts in the same core are indistinguishable on an age-altitude plot, resulting in a loss of stratigraphic information (e.g., Core B in Fig. 7). However, these contrasting SLIPs will be clearly distinguished by tendency analysis. Tendencies can also be useful in identifying inflections in the RSL curve when dealing with SLIPs from isolation basins, since these records are unaffected by variations in sedimentation rate. Another potential strength of the tendency approach is that it expands the range of material that can be used to provide sea-level information. All dateable indicators that show increases or decreases in marine influence can be considered, irrespective of whether their altitude or indicative meaning is quantified. Ultimately, in order to be successful, the tendency approach requires a large number of dated indicators, and this, coupled with its inherent ambiguities, may be one of the reasons why it is not widely applied in sea-level studies.

Marsh Elevation Diagrams

Improvements in microfossil-based reconstructions of RSL have increased the accuracy of indicative meanings and expanded the range of sediments that can be employed in sea-level studies. A new generation of sea-level curves is seeking to combine detailed marsh elevation diagrams with precise SLIPs. These records are of sufficient resolution that they can be compared with proxy climate data, or combined with tidal records (Horton and Edwards, 2006). This type of approach is currently being developed to investigate the relationship between climate and sea level at multi-decadal to centennial scales (e.g. Gehrels et al., 2005, 2006, 2008; Kemp et al., 2009). The use of marsh elevation diagrams (sometimes called palaeoenvironmental curves) was developed in the organogenic marshes of the eastern USA (e.g. Varekamp et al., 1992). Multiple sediment samples are collected from individual cores, and the microfossils (commonly foraminifera) contained within them used to precisely fix the former elevation of the sediment surface relative to the local tidal frame (Fig. 11A). The organic-rich nature of the sediments permits large numbers of radiocarbon dates to be collected for each core, and detailed accumulation histories can be developed (Fig. 11B). By combining these two detailed datasets, the pattern of tide-level change through time can be determined, in this case shown as a curve of MTL rise (Fig. 11C).

The marsh elevation diagram approach produces, in effect, a series of stratigraphically constrained sea-level index points from a single core, with ages determined by its accumulation history. These records can be used to plot general changes in the altitude of RSL but are also capable of capturing more subtle variations in water level. In theory, whilst marsh elevation diagrams will vary across a study site, reflecting the local balance between sediment accumulation and RSL (Fig. 11A), when they are combined with detailed accumulation histories (Fig. 11B), the same record of RSL change will be extracted (Fig. 11C). In reality, a record may contain breaks in sedimentation or changes in rate that are not reliably captured by the available age data. In this event, the resulting pattern of RSL change may be distorted (Horton and Edwards, 2006). Consequently, the success of this approach requires a strong age framework (Edwards, 2004), and should incorporate a detailed programme of lithostratigraphic investigation to ensure that the sample borehole is located in a position that captures the dominant environmental changes experienced at a site.

Given the importance of accurately determining accumulation history, attention is increasingly being focussed on the construction of composite chronologies that employ a range of dating methods to infer the age of intertidal sediments. Approaches have employed various combinations of short-lived radionuclides (e.g. Pb^{210}, Cs^{137}, Am^{241}), chronostratigraphic markers (e.g. tephra, pollen, spheroidal carbonaceous particles,

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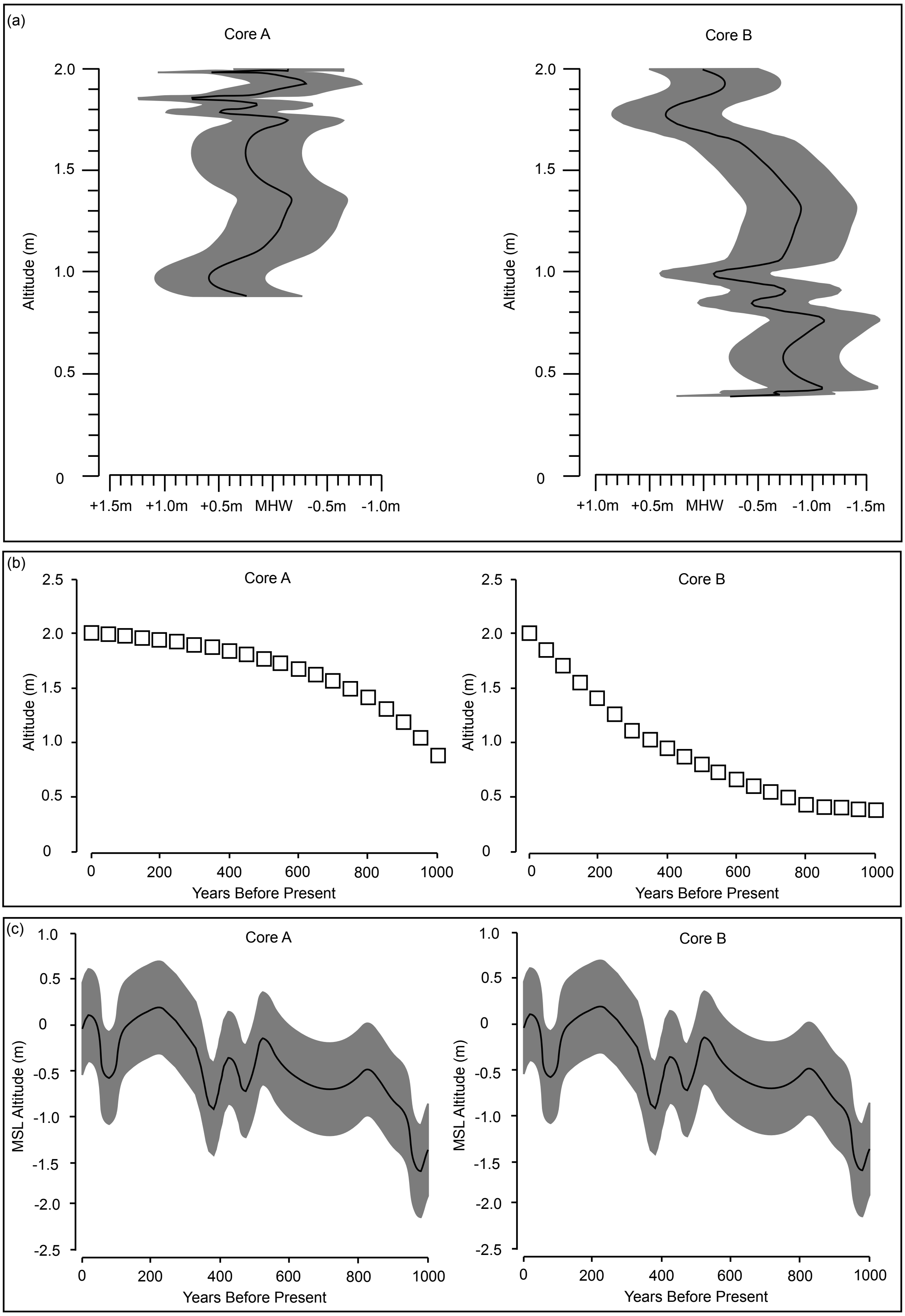

Figure 11. A hypothetical example showing the marsh elevation diagram approach. a) Marsh elevation diagrams produced from two cores at the same site. Marsh surface elevation is plotted relative to mean high water, which is 2 m above mean tide level. b) Accumulation curves for both cores. The contrasting age-depth relationships reflect local differences in sediment accumulation rate. c) Plots of MTL rise produced by combining the marsh elevation diagrams with the accumulation curves. The example demonstrates that the same RSL record can be extracted from both cores.

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lead isotopic signatures), palaeomagnetism and a range of techniques based around AMS radiocarbon dating (e.g. Gehrels et al., 2006; Marshall et al., 2007, 2009). Increasingly sophisticated statistical manipulations of age data also have the potential to improve the development of age-depth relationships (e.g. van de Plassche et al., 2001; Heegaard et al., 2005; Blaauw et al., 2007; Parnell et al., 2008), although these will ultimately be limited by the fidelity of the sedimentary sequences themselves (Edwards, 2007).

Records produced using marsh elevation diagrams will also be susceptible to the influence of sediment compaction in a similar manner to intercalated SLIPs. Some studies remove the long-term RSL trend in their data, which reflects the overall influence of factors like glacio-isostatic movement and sediment compaction. Other studies endeavour to decompact their records by incorporating age-altitude data from basal sea-level index points (e.g. Gehrels et al., 2005).

Figure 12 shows an example record developed from replicate cores recovered from two saltmarshes in North Carlolina, USA (Kemp et al., 2009). Marsh elevation reconstructions developed from a foraminiferal transfer function for tide level are combined with detailed chronologies derived from pollen analysis, short-lived radionuclides (Pb^{210}, Cs^{137}), bomb-spike and high precision AMS radiocarbon dating. The resulting records, which exhibit similar patterns of change, show good agreement with data from neighbouring tide gauges and extend these instrumental records back to AD 1500. Analysis of the long-term trends in records such as these can be used to examine the timing and magnitude of any recent acceleration in the rate of RSL rise. Ongoing research aims to produce multiple records of this sort with the ultimate aim of identifying common features that may reflect larger scale, climate related changes in ocean level (see discussion in Gehrels, 2010).

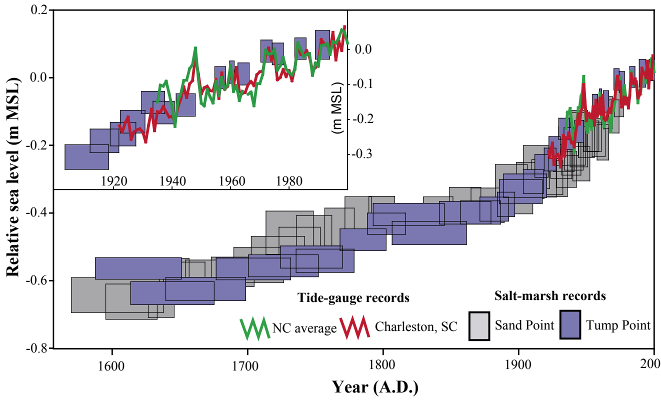

Figure 12. An example of high-resolution sea-level reconstruction developed for two sediment cores from North Carolina, USA (after Kemp et al., 2009). Sample elevation was reconstructed from a foraminiferal transfer function for tide level. Sediment accumulation histories were developed with composite chronologies comprising a pollen chronohorizon, short-lived radionuclides (^{210}Pb, ^{137}Cs), and AMS radiocarbon dating (including the use of 'bomb-spike' and high-precision radiocarbon dating). The inset illustrates the good agreement between reconstructed RSL and the instrumental record from two neighbouring tide gauges (see Kemp et al., 2009 for details).

Concluding Remarks

Low-energy sedimentary environments and their biological components are rich sources of RSL information. Collections of SLIPs, which are predominantly sourced from low-energy sedimentary environments, enable the spatial patterns of RSL change to be established. In turn, these patterns are used to elucidate climate-ice-ocean relationships and the local scale processes that influence their expression in the sedimentary record (e.g. Engelhart et al., 2009; Horton & Shennan, 2009). The provision of reliable RSL data in the form of SLIPs plays a central role in glacial isostatic adjustment modelling and several efforts are underway to compile and disseminate databases of index points to facilitate this process (e.g. Brooks & Edwards, 2006; Brooks et al., 2008). Ongoing research is seeking to improve the precision and resolution of existing RSL records and to expand the range of environments from which sea-level data can be obtained. Advances in dating techniques, especially those involving minerogenic sediments, and improvements in establishing sample indicative meaning, will help to bridge the gap between short duration instrumental records and longer-term geological reconstructions. Understanding sea-level rise and variability is a critical endeavour, both in terms of the range of scientific disciplines that use sea-level data and the wider societal issues associated with the impacts of future sea-level rise on our heavily populated coastlines (Church et al., 2010). Whilst considerable uncertainty currently exists regarding the nature of this rise and its impacts, low-energy sedimentary environments will unquestionably play a critical role in future efforts to improve our understanding of sea level change.

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