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Sediment supply and barrier dynamics as driving mechanisms of Holocene coastal change for the southern North Sea basin.

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Abstract

The combined effects of climate change and human impact lead to regional and local coastal responses that pose major challenges for the future resilience of coastal landscapes, increasing the vulnerability of communities, infrastructure and nature conservation interests. Using the Suffolk coast, southeast England, as a case study, we investigate the importance of sediment supply and barrier dynamics as driving mechanisms of coastal change throughout the Holocene. Litho-, bio- and chronostratigraphic methods are used to decipher the mechanisms of coastal change from the record preserved within coastal stratigraphy. Results suggest that local coastal configuration and sediment supply were the most influential in determining coastal change during the mid- and late Holocene, against a background control of sea-level rise. The importance of sedimentological and morphological factors in shaping Holocene coastal changes in the southern North Sea basin must therefore be considered when using the database of evidence from this region as an analogue for future change under accelerated sea-level rise.

Keywords

Sediment supply; Barrier dynamics; Holocene; Coastal environments; Stratigraphy; Diatoms

1. Introduction

The rate of relative sea-level (RSL) rise increased at the end of the 20th century and this is projected to continue in future climate change scenarios (AR5-RCPs) (Church et al., 2013), putting the future resilience of coastal landscapes, and their associated communities, infrastructure and nature conservation interests at risk. Resilient coastlines have the capacity to respond and evolve to forcing by natural and anthropogenic processes and are the desired outcome of coastal management strategies (Nicholls and Branson, 1998; Long et al., 2006). Coastal resilience is best framed by understanding the local coastal response to global forcing mechanisms and how this fits within the regional setting. Understanding the role of coastal configuration and sediment supply in moderating coastal change is essential for informing coastal management strategies. Extending understanding beyond the instrumental era enables the relative importance of the driving mechanisms of coastal evolution, and their spatial and temporal variability, to be investigated, aiding the production of informed management strategies (Plater et al., 2009). The Holocene record of coastal geomorphological change preserved within coastal stratigraphy can help with evidence based management decision-making of barrier coasts by improving understanding of the complex behaviour of barrier systems and their response to climate and geomorphic change. The southern North Sea Basin is an ideal site for exploring this for the mid- to late Holocene, when morphological and sedimentological factors are likely to be at their most influential for coastal evolution due to low background rates of RSL rise. This paper aims to establish the extent to which variations in sediment supply and barrier dynamics can be determined from the Holocene back-barrier stratigraphic record. Using the Suffolk coast as a case study, litho-, bio- and chronostratigraphic methods are utilised to establish driving mechanisms of coastal change and understand their relative importance for Holocene coastal evolution.

Barrier coasts form approximately 15 % of the world's coastline and protect sensitive back-barrier wetlands and adjacent coastal environments from the direct impacts of storms and erosion (Cooper et al., 2018). Barrier and back-barrier evolution are controlled by; RSL change, sediment supply, barrier grain-size, substrate gradient, geological inheritance, wave and tidal energy (Roy, 1984; Roy et al., 1994; Cooper et al., 2018). The interconnected nature of these processes requires investigation in unison, as they can result in a range of responses, dependent on the geomorphological character of the coast (Carter and Woodroffe, 1994). For example, sea-level rise could manifest itself through a range of responses, such as barrier overtopping, overwashing or breaching, dependent on the ability of the coast to accommodate geomorphic stress (Carter and Woodroffe, 1994).

Back-barrier sediments can be utilised to identify variation in barrier coherence and determine the mechanisms controlling barrier evolution (e.g. Spencer et al., 1998; Lario et al., 2002; Clarke et al., 2014). Tidal inlets are dynamic features of barrier coastlines that allow tidal waters to penetrate landwards each tidal cycle, providing a connection between the ocean and back-barrier environments (Fitzgerald et al., 2002; 2008). The morphology and sedimentary structure of tidal inlets is continually altered by the complex interactions of waves, tides and currents (Fitzgerald et al., 2002; 2008; Long et al., 2006; Mellett et al., 2012). The location of tidal inlets relative to a barrier coastline influences sediment input to the coastal system and as a result, the pattern of sediment processing (Long et al., 2006). Sediment supply directly influences the importance of RSL rise for barrier (e.g. barrier rollover, overstepping or erosion) and back-barrier evolution (Carter, 1988; Carter et al., 1989; Forbes et al., 1995; Jennings et al., 1998; Rosati, 2005; Fitzgerald et al., 2008; Plater and Kirby, 2011). A reduced sediment supply can result in sediment reworking and thinning, weakening barrier architecture and increasing the likelihood of tidal inundation to back-barrier environments (Orford et al., 1991). In contrast, an adequate sediment supply, coupled with a low or stable rate of RSL rise, can cause barrier stabilisation or progradation, protecting back-barrier environments from tidal inundation (Roy et al., 1994).

2. Study Site

2.1 Suffolk coast, United Kingdom

The Suffolk coast, southeast England (Fig. 1) is on the northwestern boundary of the southern North Sea basin (Fig. 1A). The region has high conservation value with large portions protected by the Suffolk Coast and Heaths Area of Outstanding National Beauty (AONB), the Suffolk Coast National Nature Reserve, the Minsmere-Walberswick Heaths and Marshes Site of Special Scientific Interest (SSSI), the Minsmere-Walberswick Heaths and Marshes Special Area of Conservation (SAC), Minsmere-Walberswick Special Area of Protection (SPA), and the Minsmere-Walberswick Ramsar. The coastline alternates between cliffs formed from soft unconsolidated Quaternary sediments and low-lying wetlands, separated from the sea by a narrow beach-barrier system. The study area (Fig. 2) is a region of low-lying brackish and freshwater marshes containing shallow lagoons and extensive drainage channels behind a narrow barrier ridge of coarse sand and gravel which is susceptible to breaching and overtopping during storm surges (Steers, 1953; Pye and Blott, 2009). The tidal regime on the Suffolk coast is semi-diurnal with an average mean spring tidal range between Southwold and Minsmere of c. 2 m. The wave regime is bimodal, with waves approaching predominantly from the north and northeast or south and southwest, and moderate, with 76 % of the waves not exceeding 2 m (Pye and Blott, 2006; 2009; Brooks and Spencer, 2010). The underlying geology is a sandstone containing shells (Coralline Crag, Norwich Crag, and Red Crag) dating from the Pliocene and Pleistocene (Hamblin et al., 1997).

The current stability of the Suffolk coast is significantly compromised by long-term subsidence (Shennan and Horton, 2002), RSL rise, and a lack of sediment supply (Pye and Blott, 2006; Haskoning, 2009). The coastline is particularly vulnerable to storms, experiencing high rates of erosion (up to 4.5

m a^{-1}) throughout the 20th century (Cambers, 1975; Carr, 1981; Brooks and Spencer, 2010; 2012). Historical records evidence the catastrophic impact storms have had on the coast of Suffolk over the last 1000 years, with over 90 % of the medieval port settlement of Dunwich now submerged due to coastal recession (Sear et al., 2011). Adaptive and sustainable strategies are necessary to manage the coast effectively due to the significant infrastructure (e.g. Sizewell B nuclear power station and the planned Sizewell C nuclear new build) as well as high conservation value.

Data points and associated glacial isostatic adjustment model output from East Anglia, in addition to Fenland, North Norfolk and Essex, record a predominantly continuous RSL rise trend during the Holocene, although the rate of RSL rise declined gradually throughout this period (e.g. Shennan et al., 2018). Global mean sea level rose at a rate of 1.2 to 1.9 mm yr^{-1} between the mid-to-late 19th century and 20th century, a rate comparable with the late Holocene period (Woodworth et al., 2009; Cazenave et al., 2018). However, satellite altimetry has determined a global mean sea level rise rate of 3.1 ± 0.3 mm yr^{-1} for the last 25 years (Cazenave et al., 2018), exceeding the late Holocene average.

Information on the existing Holocene stratigraphy of the Suffolk coast is spatially and temporally limited, hindering an understanding of the system's long-term behaviour. Existing research has focused on Norfolk and Essex, to the north and south of Suffolk respectively, revealing large stratigraphic differences between the two regions. Research completed in northern Suffolk (Bure-Yare-Waveney estuary and Blyth estuary) identified lithostratigraphic similarities with the Holocene sequence of intercalated peat horizons from east Norfolk (Coles and Funnell, 1981; Alderton, 1983; Brew et al., 1992; Boomer and Godwin, 1993; Horton et al., 2004) but contrasts with southern Suffolk. Here, clastic estuarine sedimentation dominates and peat is limited or absent (Brew et al., 1992). Reconstructions of palaeogeography in central Suffolk, between the Southwold and Sizewell, are primarily based upon historical records (e.g. Pye and Blott, 2006). The resulting conceptual models reconstruct small open coast estuaries, which existed along this coast prior to the Middle Ages but were blocked and enclosed by gravel and sand barriers between the 14th and 18th century (Chant, 1974; Parker, 1978; Comfort, 1994; Pye and Blott, 2006).

2.2 Driving mechanisms of coastal change in southern North Sea basin

Back-barrier stratigraphy contains a complex record of the driving mechanisms of coastal change, which varies through space and time, modulated by coastal processes. Research investigating the evolution of the coastal plains of the Netherlands, Belgium and southern England during the Holocene has shown that the driving mechanisms of coastal change vary spatially and temporally. The rate of RSL rise, for example, greatly influenced the southern North Sea depositional record during the early and mid-Holocene. Minerogenic sedimentation, representative of tidal environments, dominates the early Holocene depositional history of the southern North Sea basin as high rates of RSL rise resulted in landward advancement of the coast. For example, RSL rose by over 20 m OD between 8.8-5 ka in southeast England (Long and Innes, 1993) whilst on the Belgian and Holland coast the RSL rise rate decreased from over 7 mm yr^{-1} to less than 3 mm yr^{-1} after 7 ka (van de Plassche, 1982; Denys and Baeteman, 1995; Beets and van der Spek, 2000; Baeteman and Declercq, 2002). The relative dominance of a driving mechanism will also vary spatially and temporally. Thus, in the southern North Sea basin the transition from the early to mid-Holocene is denoted by a shift in the relative importance of RSL rate vs sediment supply. The decline in RSL rise rate after 7 ka enabled sediment supply to balance, and eventually surpass, the creation of accommodation space, halting the landwards migration of tidal sedimentary environments and stabilising the shoreface, resulting in shoreline progradation (Beets and van der Spek, 2000; Baeteman and Declercq, 2002). By 5.5-4.5 ka, freshwater marsh and peat sedimentation dominated the majority of the Belgian coastal plain (Beets and van der Spek, 2000; Baeteman and Declercq, 2002) whilst the central section of the Dutch coast prograded nearly 10 km between c. 5 ka and 2 ka (Beets and van der Spek, 2000).

Local factors, such as variation in sediment supply, morphology of the pre-flooded surface, barrier presence and status, and the influence of river catchments, modulate how the sedimentological signal is recorded (Beets et al., 1992; Beets and van der Spek, 2000; Baeteman and Declercq, 2002; Pierik et al., 2017). The late Holocene is characterised by a return to minerogenic, tidal sedimentation and the culmination of a 2000-3000 year period of peat accumulation. The mechanisms responsible for the cessation of peat sedimentation are likely to be various. Local factors have been suggested as potential explanations; inadequate conditions for the preservation of organic sedimentation (Long et al., 2000); coastal barrier breach and the formation of drainage networks, enhanced by digging and excavating for industrial purposes (Vos and van Heeringen, 1997); creation of accommodation space caused by the compaction of the peat following reclamation and drainage (Baeteman et al., 2002; Mrani-Alaoui and Anthony, 2011) and the influence of natural preconditions, i.e. the geological setting such as coastal plain extent and sediment delivery (Pierik et al., 2017).

3. Methods

Stratigraphy across each site was investigated using a 30 mm diameter Eijkelkamp gouge corer and sediments logged following the Troels-Smith (1955) classification scheme. The Crag underlying the region is composed mainly of sand with thinner sandy gravel units and occasional silty-clay laminae.

All cores bottomed-out in saturated, irrecoverable sand or Crag. Sampled cores for laboratory analysis were collected using a 50 mm diameter Russian corer, wrapped in cling film, placed in plastic tubing and refrigerated in the dark at 4° C. All cores were surveyed relative to the UK Ordnance Datum (OD) using a Topcon differential GPS (10 cm precision).

Palaeoenvironmental reconstruction of cores is based on diatom analysis, supported by particle size analysis, sediment organic content, and identification of foraminifera. Diatom distribution is strongly controlled by salinity (e.g. Kolbe, 1927; Hustedt, 1953; Kjemperud, 1981), enabling marine, brackish and freshwater palaeoenvironments and the boundary between these to be characterised (Palmer and Abbott, 1986; Vos and De Wolf, 1993; Denys and De Wolf, 1999). Diatom preparation followed the standard method summarised by Palmer and Abbott (1986) and Battarbee (1986). A minimum of 250 diatoms were counted per slide and species identification followed Van der Werff and Huls (1958-1974), Krammer and Lange-Bertalot (1991; 1997) and Hartley et al. (1996). Diatoms were classified based on their life-form (Vos and De Wolf, 1988; 1993) and salinity tolerance, using the Halobian classification scheme (Kolbe, 1927; Hustedt, 1953; Simonsen, 1962; Schuette and Schrader, 1981). Species greater than 5 % of the total diatom valves counted are presented graphically using C2 (Juggins, 2003) and grouped using the halobian classification (Hustedt, 1953) and lifeform (Vos and De Wolf, 1988; 1993). The count sheet for diatom species exceeding 5 % of the total diatom valves counted are presented for each core in the Supplementary Material. Diatoms assemblages are zoned based on stratigraphically constrained cluster analysis using the constrained incremental sum of squares (CONISS) software in TILIA (Grimm, 1987). Foraminifera identification followed the method summarised by Scott and Medioli (1980) at stratigraphic transitions where diatoms were not preserved. Where possible, a minimum of 100 foraminifera were counted per sample.

A Beckman Coulter LS13320 granulometer was used for particle size determination and identified the dimensions of particles ranging from 0.04 to 2000 µm using the laser diffraction method. The aggregating effects of organics were avoided using the hydrogen peroxide digestion method (Kunze and Dixon, 1987) and Calgon was added to deflocculate particles prior to analysis. The bivariate plot of mean grain size against standard deviation was used to determine the depositional energy of a sediment sample using the environment specific graphic envelopes identified by Tanner (1991a; 1991b) and later modified by Lario et al. (2002). Mean grain size and standard deviation are hydraulically controlled, therefore positively correlated with the energy of the environment and degree of sediment processing, i.e. transportation and deposition processes (Tanner, 1991a; 1991b; Long et al., 1996; Lario et al., 2002; Priju and Narayana, 2007). Organic content was determined using the loss-on-ignition (LOI) methodology (Ball, 1964; Plater et al., 2015). Approximately 5 g of sediment was dried overnight at 105 °C and weighed to two DP. The sample was ignited at 550 °C for 4 hours and reweighed after being cooled in a desiccator (Heiri et al., 2001). Organic content was calculated as the percentage weight of the original sample. AMS radiocarbon dating of plant macrofossils provided a chronology for the sampled material. Horizontally aligned plant macrofossils and seeds were selected for analysis for all samples, excluding the basal sample from OTM-16-13 which is based on wood. Radiocarbon measurements were completed at the Natural Environmental Research Council (NERC) Radiocarbon Facility in East Kilbride, Scotland and BETA Analytic, Miami. Dates were calibrated using CALIB Radiocarbon Calibration (Stuiver et al., 2018) and the IntCal13 calibration curve (Reimer et al., 2013) and are presented as $\mu \pm 2\sigma$ cal BP within the text. The uncalibrated and calibrated ages for all material radiocarbon dated are presented in Table 1.

4. Results

Results are presented for two sites Great Dingle Hill and Oldtown Marsh (Fig. 2), situated within the Walberswick National Nature Reserve between Southwold and Dunwich (Fig. 1B).

4.1 Great Dingle Hill

Representative stratigraphy at the site consists of five main sediment units outlined in Table 2, with corresponding Troels-Smith (1955) log, for the sampled core (GDH-16-2; TM48486 73145). GDH-16-2 contains a well humified sandy peat unit (200-196 cm), lower well humified peat unit (196-179 cm) subdivided by a silty clay peat unit (190-185 cm), overlain by a mottled silty clay unit (179 cm to 36 cm) and an upper unit comprised of organic-rich sand (36 cm to 0 cm) (Fig. 3). Organic content decreases from 40 % near the base (190 cm) to 8 % (128 cm) in the upper sampled section, with a minor peak below the overall trend at 199 cm (23 %) due to the proximity to basement substrate (Fig. 4). The sediments from GDH-16-2 plot within the graphic sedimentary domain defined by Lario et al. (2002) as indicative of open to closed estuarine environments (Fig. 5).

Five diatom assemblage zones are identified based on the diatom flora and lithostratigraphy (Fig. 4). Brackish epieplic diatom taxa dominate Zone 1, indicating a marine influence. The peat unit contains an increase in minerogenic content between 190 cm and 185 cm, associated with the presence of brackish diatom taxa in Zone 1. The onset of peat deposition has been constrained to 2870 ± 87 cal BP. Brackish epipelic diatoms dominate Zone 2 whilst Zone 3 is delineated by an increase in marine planktonic species. This increase in marine conditions coincides with a transition from well-humified peat to silty clay peat and is associated with a decrease in organic content and gradual coarsening upwards. The increase in planktonic taxa across the transition coincides with the near disappearance of brackish aerophilous species. The increase in marine species at the transgressive contact is constrained to 2530 ± 172 cal BP. Brackish-marine species, with planktonic and epipelic ecology, continue to dominate the assemblage for Zone 4 and 5, with the organic content remaining consistently between 8 to 14 %.

4.2 Oldtown Marsh

The stratigraphy at Oldtown Marsh contains a series of alternating organic and minerogenic units (Fig. 6), very similar to the Holocene sequence found further north in the Blyth estuary (Brew et al., 1992). Sample core OTM-16-13 (TM48610 73838) consists of seven main sediment units (Table 3): an organic sand (580-572 cm) a lower, variably humified, peat unit with occasional wood fragments (572- 332.5 cm); overlain by an organic clayey silt unit (332.5-254 cm); a fibrous woody peat unit (254-216 cm); silty peat unit (216-210 cm); a clayey silt unit (210- 45 cm); and an upper fibrous peat unit (45 cm to 0 cm).

Diatom preservation was variable throughout OTM-16-13 (Fig. 7). As a result, where diatom preservation was poor, foraminifera were counted. Five diatom assemblage zones are identified between 300 and 170 cm based on diatom flora and lithostratigraphy.

At 330 cm (-3.21 m OD), 2.5 cm above the sharp transition from variably humified peat to organic clayey silt, *Jadammina macrescens*, a high-marsh foraminifera species occurs (Fig. 7), recording marine inundation at this site (Gehrels, 2002). LOI values decrease sharply from 88 % to 7 % between 334 and 326 cm, indicating that this is an erosive contact. Diatom analysis within the organic clayey silt unit (332.5-254 cm) identified brackish epipelic and marine planktonic species, with the former dominating Zone 1. Particle size analysis identified an upwards fining within Zone 1 that is initially gradual and increases more rapidly in Zone 2, after 278 cm, coincident with a similar trend in organic content.

Jadammina macrescens is abundant at the upper boundary of the organic clayey silt unit (258 cm) in Zone 3 (Fig. 7). Organic content values ranging from 60 - 80 % at the upper and lower boundary of the organic clayey silt and middle fibrous peat units, respectively, indicate a transitional shift in sedimentation within Zone 3. The timing of this shift in sedimentation and occurrence of high-marsh foraminifera is constrained to 860 ± 69 cal BP. Organic content decreases to 45 % by 213 cm following the onset of deposition of the middle peat unit. Freshwater tychoplanktonic diatoms dominate Zone 4, with a brackish epipelic component also present.

The transition to silty clay sedimentation (214.5 cm) (870 ± 82 cal BP), correlates with the near disappearance of fresh tychoplanktonic diatoms and increasing dominance of marine planktonic and brackish epipelic species at the transition from Zone 4 to 5. Marine taxa gradually increase in abundance into Zone 5 and organic content remains very low. Brackish epipelic and marine planktonic diatoms dominate the clayey silt unit, whilst freshwater epiphytes disappear within this zone. Marine planktonic diatoms peak in abundance at 202 cm, followed by a shift to brackish epipelic species. Particle size analysis reveals an initial, highly variable, upwards fining associated with the onset of minerogenic sedimentation at 211 cm, succeeded by a shift to upwards coarsening at c. 190 cm into the silty clay unit. When plotted, a cluster of the sediments sampled (c. 204 – 172 cm) plot within the closed- basin domain of the bivariate plot (Fig. 5).

5. Discussion

5.1. Palaeoenvironmental interpretation- Great Dingle Hill

Minerogenic sedimentation dominates the stratigraphic transect completed at Great Dingle Hill. The onset of minerogenic sedimentation in GDH-16-2 is associated with a sustained increase in marine conditions after 2530 ± 172 cal BP, indicating that Great Dingle Hill was tidally influenced throughout the late Holocene. Reduced barrier integrity, enabling tidal ingress, is a likely explanation for the continued dominance of marine and brackish conditions. A high magnitude event could have created a breach in the barrier whilst alternatively a restricted sediment supply could have led to sediment reworking and increased barrier instability and permeability. The onset of minerogenic sedimentation within the stratigraphic transect is not associated with the presence of sand or, indeed, other indicators of a high magnitude event.

The brackish epipelic taxa dominating the diatom assemblage of the peat unit are associated with intertidal to lower supratidal mudflats and creeks, and subtidal marine basins and lagoons (Vos and De Wolf, 1988; 1993). Marine and brackish planktonic taxa, characteristic of sub-tidal areas or large tidal channels (Vos and De Wolf, 1988; 1993; Zong and Tooley, 1999), increase in abundance at 176 cm (Fig. 4). The slight upwards coarsening, associated with the shift to minerogenic sedimentation, indicates an increase in depositional energy. The changes in diatom ecology (i.e. salinity and life form) associated with this sedimentation shift indicate an increase in tidal influence during the late Holocene. The increased input of planktonic species, previously identified as allochthonous (Simonsen, 1969; Vos and De Wolf, 1993), strongly indicates tidally influenced hydrodynamic conditions. Increases in these taxa have been previously attributed to episodes of barrier breaching (Sáez et al., 2018) and the opening of tidal inlets (Bao et al., 1999; Freitas et al., 2002).

Barrier breaching, or further reduced barrier integrity, is identified as the most likely cause for the transition from organic to minerogenic sedimentation at 2530 ± 172 cal BP. The dominance of brackish epipelic taxa prior to this indicates that Great Dingle Hill was already tidally influenced, potentially via channel inlets through the barrier. The return to minerogenic sedimentation associated with marine conditions by 2530 ± 172 cal BP could be explained by RSL rise, and the associated creation of accommodation space outpaced organic accumulation, however this is unlikely as the rate of RSL rise decreased during the mid- to late Holocene (Shennan et al., 2018). Particle size, and the bivariate plot (Fig. 5), do not record coarse sedimentation followed by a fining upwards sequence, which would be indicative of a high-magnitude event and subsequent recovery. Sediment supply would have become more important for driving coastal change as the rate of RSL decreased during the Holocene. If sufficient, the sediment supply would stabilise the position of the barrier and halt the landwards movement of tidal environments however the results indicate this was not the case.

5.2. Palaeoenvironmental interpretation- Oldtown Marsh

Peat sedimentation initially dominates the seaward end of the stratigraphic transect at Oldtown Marsh, indicating that the coastline was stable and the back-barrier environments initially protected. The onset of the lower minerogenic unit (332.5-254 cm) in OTM-16-13 is associated with high marsh foraminifera, succeeded by a dominance of brackish epipelic diatoms and the occurrence of marine planktonic taxa, indicative of a tidal mudflat environment. The upwards fining and increasing organic content within the organic clayey silt unit (from c. 278 cm) reflects a decrease in the depositional energy and gradual increase in position within the tidal frame, interpreted as a transition from intertidal mud flat to salt marsh.

Vertical changes in sea level are unlikely to be responsible for this initial marine inundation due to the low RSL rise rate during the mid- and late Holocene (Shennan et al., 2018). Possible explanations include impeded drainage (Baeteman, 1981), or repeated reactivation of tidal channels resulting in peat dewatering (Spencer et al., 1998), surface lowering and landward migration of tidal influence (Baeteman and Denys, 1995). Similar shifts in sedimentation throughout the southern North Sea basin have been attributed to imbalances in sediment budget (e.g. Beets et al., 1992; 1994; Baeteman, 1999; Brew et al., 2000). The erosive nature of this contact (332.5 cm) may have occurred post-deposition, due to rapid inundation, possibly caused by peat dewatering and collapse or by barrier breakdown.

Freshwater tychoplanktonic taxa (e.g. *Staurosira construens* and *Pseudostaurosira elliptica*) dominate the diatom assemblage of the peat (254 cm to 214.5 cm) (Vos and De Wolf, 1993) and when combined with a small brackish component can be associated with a shallow fresh to brackish water lagoon environment, low-energy hydrodynamic conditions and aquatic vegetation (Bao et al., 1999). The organic content however initially remains high, following the transition to fibrous peat (254 cm), indicating a gradual transition from a high-marsh environment. The gradually decreasing organic content and upwards coarsening may indicate gradual barrier breakdown, enabling an increasing tidal ingress into a barrier estuary. Diatoms are not preserved at the lower boundary of the middle fibrous peat, so it is not possible to determine if tidal influence is increasing within this unit.

The reduced marine influence and onset of peat accumulation (254 cm) may have been strongly influenced by barrier dynamics from 860 ± 69 cal BP, especially since there is no evidence in the available RSL record, or any plausible mechanism for a sea-level driven process at this time (Shennan et al., 2018). An adequate sediment supply is a prerequisite for a stable barrier position, as a barrier with an abundant sediment supply will have better capabilities for internal reorganisation and growth. Back-barrier environments will accrete sediment rapidly when sediment supply exceeds the accommodation space created by RSL rise resulting in less frequent tidal inundation (Baeteman et al., 2011). With time, salt marsh environments replace mud flat and peat begins to accumulate due to the asymptotic relationship between sediment accretion rates and time if sediment supply is sufficient (Jennings et al., 1995). Therefore, it is most likely that local factors (e.g. sedimentological or morphological) were responsible for the deposition of the middle peat unit recorded within the stratigraphic transect.

Particle size data indicate that the site was highly dynamic, with variable tidal influence, following the onset of clayey silt sedimentation at 214 cm. Marine planktonic taxa increase in abundance, indicating that the site's position within the tidal frame was lowering or that the widening of a barrier opening was enabling tidal influence to penetrate further landwards. The diatom and particle size analysis indicate a mud flat environment experiencing an increasing tidal influence. The absence of full marine conditions and occurrence of freshwater taxa until 206 cm indicates that the tidal influence on this site was initially marginal. The dominance of brackish epipelic taxa from 202 cm indicates that tidal influence is decreasing and is coincident with an initial coarsening and consistent particle size, indicating an initial increase in depositional energy followed by a stabilisation of the environment. The model of Tanner (1991a; 1991b) supports this interpretation as sedimentation transitions from an estuarine environment to a closed basin by 204 cm, until 172 cm. The decreasing tidal influence may indicate that a tidal inlet or previous barrier breach is annealing. Diatoms are not preserved in the top 1.5 m of the Oldtown Marsh core, hampering interpretations for the upper core section.

The timing of the upper transgressive contact at Oldtown Marsh coincides with a period of coastal reorganisation between Southwold and Dunwich. Conceptual palaeogeographical reconstructions, based on historical evidence, depict the Blyth River diverted south by a spit, Kingsholme, estimated to have developed between c. 1500 and 700 AD, to form an estuary from Roman times (Gardner, 1754; Steers, 1927; Chant, 1974; Parker, 1978; Comfort, 1994; Pye and Blott, 2006). Spit development was halted during the 13th and 14th century due to storms (1287 and 1328) which blocked the entry to the haven, connecting the distal point with the Dunwich cliffs (Steers, 1927). An insufficient sediment supply to the barrier system would have resulted in sediment recycling within the spit, creating points of weakness and eventually leading to progressive breakdown, which in turn would influence the back-barrier sediment record. Litho- and bio-stratigraphic research on nearby Dingle Marshes, neighbouring Dunwich, identified an environmental shift in a freshwater retting pit to marine saltmarsh and estuarine mud at c. 1100 AD, attributed to storms breaching a gravel barrier or spit (Sear et al., 2015). There is no sedimentological evidence to attribute marine inundation at Oldtown Marsh at 870 ± 82 cal BP (1080 ± 82 cal AD) to a high magnitude event. The differences in sedimentary record between Oldtown and Dingle Marshes (Sear et al., 2015) may reflect differing proximities to the coast. Additionally, the populations of Dunwich, Walberswick and Blythburgh are likely to have influenced the back-barrier sediment record as they attempted to maintain access to the sea by creating artificial breaches in the spit, for example following the choking of the haven in the 14th century (Comfort, 1994).

5.3. Regional perspectives on Holocene coastal evolution

Comparisons of the late Holocene sediment record from Great Dingle Hill and Oldtown Marsh with northern Suffolk (Blyth estuary) and eastern Norfolk (Bure-Yare-Waveney estuary and Horsey) illustrate substantial variability in sedimentary response between sites with the same regional pattern of sea-level tendency. For example, the shift from organic to minerogenic sedimentation in the Blyth estuary is constrained to 4920 ± 292 cal BP (Brew et al., 1992). In contrast, the onset of minerogenic sedimentation further north, in the Bure-Yare-Waveney estuary system, occurs later, at 3000-2000 cal BP (Coles and Funnell, 1981; Alderton, 1983; Horton et al., 2004). The timing of this transition in the Bure-Yare-Waveney estuary system is comparable with Great Dingle Hill, where minerogenic sedimentation associated with the development of an intertidal mudflat environment is sustained from 2530 ± 172 cal BP until near present-day.

At Oldtown Marsh, however, a prolonged period of minerogenic sedimentation only occurs from 870 ± 82 cal BP, overlapping with the transition to marine saltmarsh and estuarine mud at Dingle Marshes, Dunwich (Sear et al., 2015). Local factors (e.g. sedimentological and morphological) are likely to have had a greater influence on the reconfiguration of the coast during the late Holocene than vertical changes in sea level due to the low rate of RSL rise (Shennan et al., 2018). This is clearly supported by the variable sedimentary response across Suffolk and Norfolk, highlighting the importance of sediment supply to facilitate late Holocene barrier building (or barrier breakdown) and the creation of discrete sedimentary basins within the estuaries (Brew et al., 1992). Sediment availability and barrier dynamics are hypothesised to have been highly influential for the evolution of the Suffolk coast during the late Holocene. The susceptibility of the back-barrier to inundation would have increased during the late Holocene if the sediment supply was not sufficient for barrier development and the southwards progradation of Kingsholme spit. Insufficient sediment supply was one mechanism proposed to explain the culmination of late Holocene peat growth elsewhere in the southern North Sea basin (Beets et al., 1992; 1994; Baeteman, 1999).

5.4 Sediment supply and barrier dynamics as driving mechanisms of Holocene coastal change

Analysis of the sediment sequences from Oldtown Marsh and Great Dingle Hill indicate that sediment supply and barrier dynamics were key driving mechanisms of Holocene back-barrier sedimentation in Suffolk. RSL change, however, was only a background control when the back-barrier record was deposited at these sites, exerting a minimal control on the significant changes in coastal evolution reported here. Attributing shifts from organic to minerogenic sedimentation, and vice-versa, to changes in sea level can result in the oversimplification of the sediment record and often fails to consider the complex interplay between sediment supply, barrier dynamics, accommodation space and the rate of RSL rise, in addition to temporal variations in their relative importance. This simplified approach can lead to erroneous interpretations – for example in Germany where intercalated peats within Holocene marine sediment were attributed to a regression, reflecting a falling sea level (Behre, 2007), is at best equivocal when errors are fully considered and other processes explored (Baeteman et al., 2011). Mid- to late Holocene analogues from the southern North Sea basin therefore give a false impression with regard to future coastal change under accelerated sea-level rise. The importance of a regional approach when distinguishing between sediment-driven and RSL-driven changes recorded in the sediment record has been previously highlighted (Jennings et al., 1995). Changes in marine and terrestrial conditions preserved in back-barrier palaeoenvironmental records have been shown to not necessarily reflect changes in sea level (Duffy et al., 1989). For example, barrier dynamics, including its initiation, establishment and breakdown, will influence the back-barrier environment and have implications for the depositional environments formed (Orford et al., 1991).

The late Holocene was associated with barrier building and the creation of discrete sedimentary basins within estuaries (Brew et al., 1992). Spit development and barrier dynamics were identified as primary controls of the Holocene coastal evolution, and resulting sediment record, in the Blyth estuary (Brew et al., 1992). The development of these features would have placed increased demands on the sediment supply required to maintain landform integrity. Variations in sediment supply are therefore likely to have been highly influential to the evolution of the Suffolk coast during this period.

Throughout the instrumental era, a limited and temporally and spatially variable sediment supply has greatly influenced the evolution of the Suffolk coast. At present, the sediment supply to Suffolk's gravel beaches is insufficient to ensure the coastline is resilient to storms. Studies have indicated that during periods of RSL rise and increased storminess, the barrier moves shoreward in places in order to evolve in response to forcing (Haskoning, 2009). Suffolk's cliffs, a major input into East Anglia's sediment budget, have exhibited high rates of spatially and temporally variable historical change, over decadal timescales, highlighting a well-defined north-south trend of cliff retreat (Cambers, 1973; 1975; Robinson, 1980; Carr, 1981; McCave, 1987; Brooks and Spencer, 2010; Burningham and French, 2017). Dynamic offshore bank systems complicate regional sediment transport, potentially acting as a sediment sink and morphologically influencing the wave climate and tidal currents (Lees, 1983; Brooks and Spencer, 2010). Research into the evolution of the Sizewell-Dunwich Bank system, situated offshore of the Dunwich-Minsmere cliffs, map the extension of the Sizewell Bank, its coalescence with the Dunwich Bank in the 1920s, and their landwards movement (Carr, 1979). Substantial spits, such as Orford Ness and Landguard Point, are also current features of the Suffolk coastline.

Cluster analysis of the relative position of the shoreline (1881-2015), combined with metrics of shoreline change, identified multiple modes of shoreline change on the Suffolk coast and noted the importance of sediment budget variations as a driver of multi-decadal coastal behaviour (Burningham and French, 2017). Predictions of future shoreline retreat also identified that the sediment release behaviour of the Suffolk cliff system exhibits a switching of states, between on, off and no change (Brooks and Spencer, 2012). The late Holocene data presented in this paper indicates that a series of sediment release and supply pathways, which change their location through time, have existed on this coastline since at least 3 ka. Fig. 8 illustrates this concept, depicting the influence of changes in sediment release and supply pathways through time on back-barrier environments. Transitions between organic and minerogenic sedimentation in a given location may reflect temporal changes in this spatial pattern of sediment release and storage, due to erosion and deposition. The late Holocene data presented, in addition to historical and instrumental data, suggest that the vulnerability of the Suffolk coast has varied spatially, dependent on the location of a site relative to the pattern of sediment release and supply at a given time. The vulnerability or resilience of a given site, based on this concept, would therefore be difficult to determine due to changes in this spatial pattern through time.

6. Conclusions

Sediment supply and barrier dynamics have been identified as key driving mechanisms moderating the coastal evolution of the Suffolk coast during the mid- and late Holocene. Our findings illustrate that a temporally variable spatial pattern of sediment release and supply was an important control on coastal evolution through the late Holocene, a period when the rate of RSL change was low. Coastal systems throughout the southern North Sea basin, including Suffolk, are now responding to a rate of RSL rise which is faster than that identified for the mid- and late Holocene (Defra, 2006; Church et al., 2013; Burningham and French, 2017; Cazenave et al., 2018). The future response of anthropogenically modified coastal landscapes to a temporally variable spatial pattern of sediment release and supply pathways, whilst RSL is rising, is an uncertainty which requires consideration and incorporation into coastal management strategies. Coastal managers must therefore be cautious in advocating 'successes' from recent past practice. Future outcomes for the Suffolk coast will differ due to the increase in sea-level rise and this may result in the failure of previously effective interventions.

The difficulty of teasing apart the driving mechanisms of coastal change and the interplay between sediment availability, barrier dynamics and the rate of RSL change from back-barrier sediment records has been highlighted by the substantially variable sedimentary response preserved. Inter-regional comparisons are required to distinguish between the multifactorial processes driving the Holocene evolution of a coastal system. Sediment records from northern Suffolk and southern Norfolk contain similar patterns; however, the chronologies differ, indicating the importance of local processes (e.g. Coles and Funnell, 1981; Alderton, 1983; Brew et al., 1992; Horton et al., 2004). Stratigraphic data are limited between Dunwich and Aldeburgh and expanding the study area further south may help to explain the differing records of coastal geomorphological change preserved.

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9. Tables and Figure captions

Table 1: AMS radiocarbon dates produced for Great Dingle Hill and Oldtown Marsh.

Site	Laboratory code	^{14}C age (1σ) BP	Calibrated age (2σ) BP	Calibrated age (2σ) AD/BC	Stratigraphic context	Altitude (m OD/cm)	
Great Dingle Hill	SUERC-72912	2440 ± 35	2701-2357	752-408 cal BC	Well humified peat with irregular rootlets	-2.09	180
	SUERC-76469	2775 ± 37	2956-2783	1006-834 cal BC	Basal peat	-2.29	200
Oldtown Marsh	SUERC-72907	965 ± 39	952-789	1161-998 cal AD	Silty peat with clay trace	-2.03	212
	BETA-498399	970 ± 30	933-796	1154-1017 cal AD	Woody peat	-2.45	253.5
	SUERC-72911	5209 ± 35	6170-5906	4221-3957 cal BC	Basal peat	-5.64	573

Table 2: Description of main sediment units identified within the sampled sediment sequence from Great Dingle Hill (GDH-16-2) and associated Troels-Smith (1955) classification.

Unit depth (cm)	Description	Troels-Smith log
0-36	Organic-rich sand	Ga2 Sh1 As1 Th^{1}+ Th^{0}+ nig 3+ strat 0 elas 0 sicc 2+
36-179	Silty clay with black mottling and occassional rootlets which increase with depth	As3 Ag1 Sh+ Th^{1}+ nig 2+ strat 0 elas 0 sicc 2+ lm.sup 1
179-185	Well humified, crumbly peat with irregular rootlets and trace of clay	Sh4 Th^{1}+ Th^{0}+ As+ nig 4 strat 0 elas 0+ sicc 1+ lm.sup 3
185-190	Silty clay peat with irregular rootlets and black mottling	As1+ Ag1 Sh2 Th^{1}+ Th^{0}+ nig 2+ strat 0 elas 0 sicc 2 lm.sup 2
190-196	Well humified, crumbly peat with irregular rootlets and trace of clay	Sh4 Th^{1}+ Th^{0}+ As++ nig 4 strat 0 elas 0+ sicc 1+ lm.sup 1
196-200	Well humified sandy peat	Sh2 Ga2 Th^{0}+ Th^{1}+ As+ nig 3++ strat 0 elas 0+ sicc 1+ lm.sup 0

Table 3: Description of main sediment units identified within the sampled sediment sequence from Oldtown Marsh (OTM-16-13) and associated Troels-Smith (1955) classification.

Unit depth (cm)	**Description**	**Troels-Smith log**
0-45	Fibrous peat with abundant phragmites	Sh2 Th^{0}2 Ag+ nig 3 strat 0 elas 1 sicc 1+
45-210	Clayey silt with increasing traces of organics with depth	Ag2+ As2 Th^{0}+ Th^{1}+ Sh+ nig 2+ strat 0 elas 0 sicc 2+ lm.sup 2
210-216	Silty peat	Sh3 Ag1+ Th^{0}+ Th^{1}+ As+ nig strat 0 elas 0 sicc 2+ lm.sup 1
216-254	Fibrous woody peat	Sh2 Th^{1}2 Th^{0}+ Dl++ As+ Ag+ nig 3+ strat 0 elas 1 sicc 1+ lm.sup 0
254-332.5	Clayey silt with abundant rootlets and patches of organics	Ag2+ As2 Th^{1}+ Th^{2}+ Sh+ nig 2+ strat 0 elas 0 sicc 2+ lm.sup 0
332.5-572	Peat with rootlets, traces of silt and clay and sections of wood throughout	Sh2 Th^{1}1 Th^{2}1 As+ Ag+ Dl+ nig 4 strat 0 elas 0+ sicc 1+ lm.sup 4
572-580	Organic sand	Ga4 Sh++ Gmaj+ As+ Ag+ Dl+ nig 2 strat 0 elas 0 sicc 2+ lm.sup 0

Fig. 1- A. Map of southern North Sea basin with the county of Suffolk highlighted in dark grey and outline of Fig. 1B highlighted by the dashed box. B. Suffolk coast with locations mentioned in the text included. The red box highlights the location of the Walberswick National Nature Reserve, which contains Oldtown Marsh and Great Dingle Hill.

Fig. 2 - Stratigraphic transects completed at Oldtown Marsh and Great Dingle Hill. The white filled circles denote the sediment sequences sampled for analysis whilst the red circle represent gouge cores. Aerial imagery: © Getmapping Plc.

Fig. 3 - Stratigraphic transect from Great Dingle Hill, including radiocarbon dates from sampled sediment sequence.

Fig. 4 - Lithostratigraphy, organic content and particle size (PSA), and summary diatom data from the sampled sediment sequence from Great Dingle Hill (GDH-16-2). The diatom summary is based on taxa exceeding 5 % of the total valves counted and are grouped using the halobian classification (Hustedt 1953) and subdivided by lifeform (Vos and De Wolf 1988; 1993).

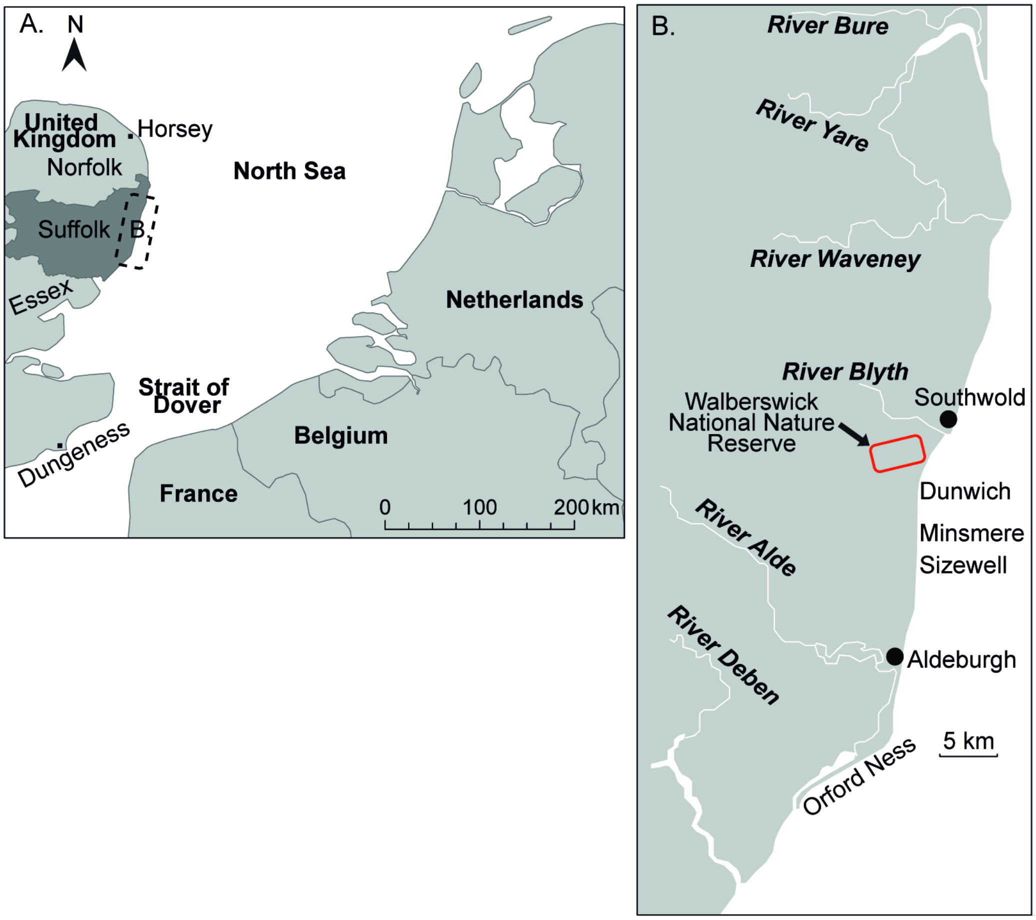
Fig. 5 - Bivariate plot of mean against standard deviation (phi) for sediments from Great Dingle Hill (GDH-16-2) and Oldtown Marsh (OTM-16-13). The graphic sedimentary domains determined by Tanner (1991), and later modified by Lario et al. (2002) are overlain onto this plot. The particle size sample location for Great Dingle Hill and Oldtown Marsh is shown on Figure 4 and 7 respectively.

The stratigraphic position of samples from Oldtown Marsh that plotted in the closed basin sedimentary domain is illustrated on Figure 7.

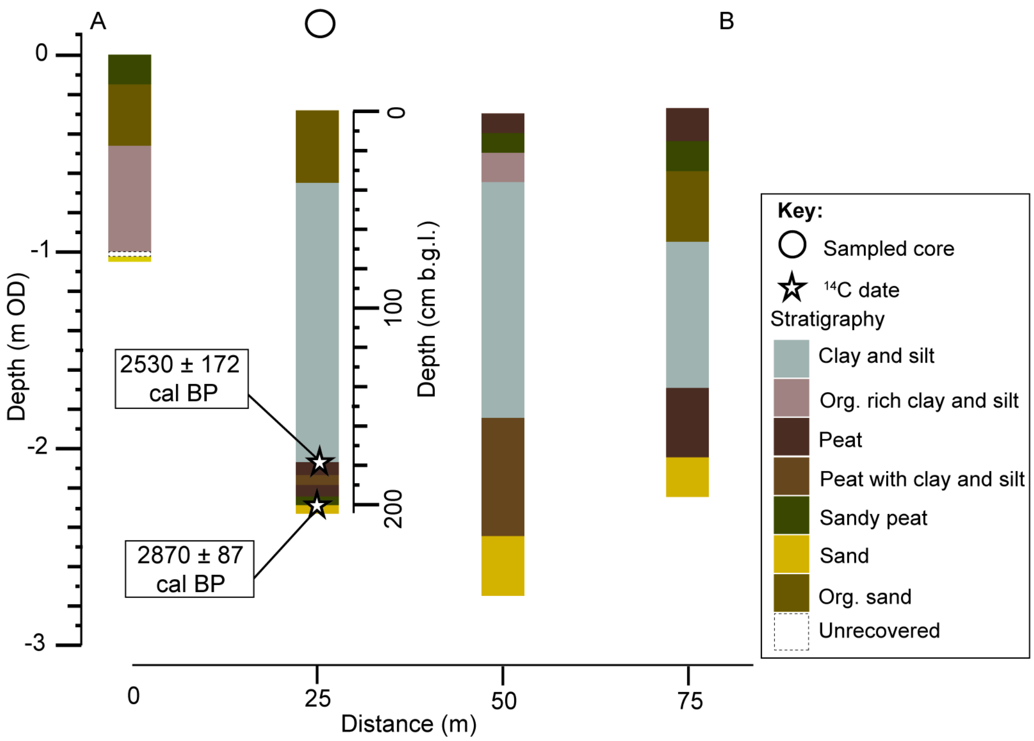
Fig. 6 - Stratigraphic transect from Oldtown Marsh, including radiocarbon dates from sampled sediment sequence.

Fig. 7 - Lithostratigraphy, organic content and particle size (PSA), foraminifera (Jm- Jadammina macrescens, Mf- Miliammina fusca, Ti- Trochammina inflata) and summary diatom data from the sampled sediment sequence from Oldtown Marsh (OTM-16-13). The abundance (D- dominance, T- trace) of foraminifera species is noted for each sample. The diatom summary is based on taxa exceeding 5 % of the total valves counted and are grouped using the halobian classification (Hustedt 1953) and subdivided by lifeform (Vos and De Wolf 1988; 1993). The basal radiocarbon date for OTM-16-13 is shown in Fig. 6.

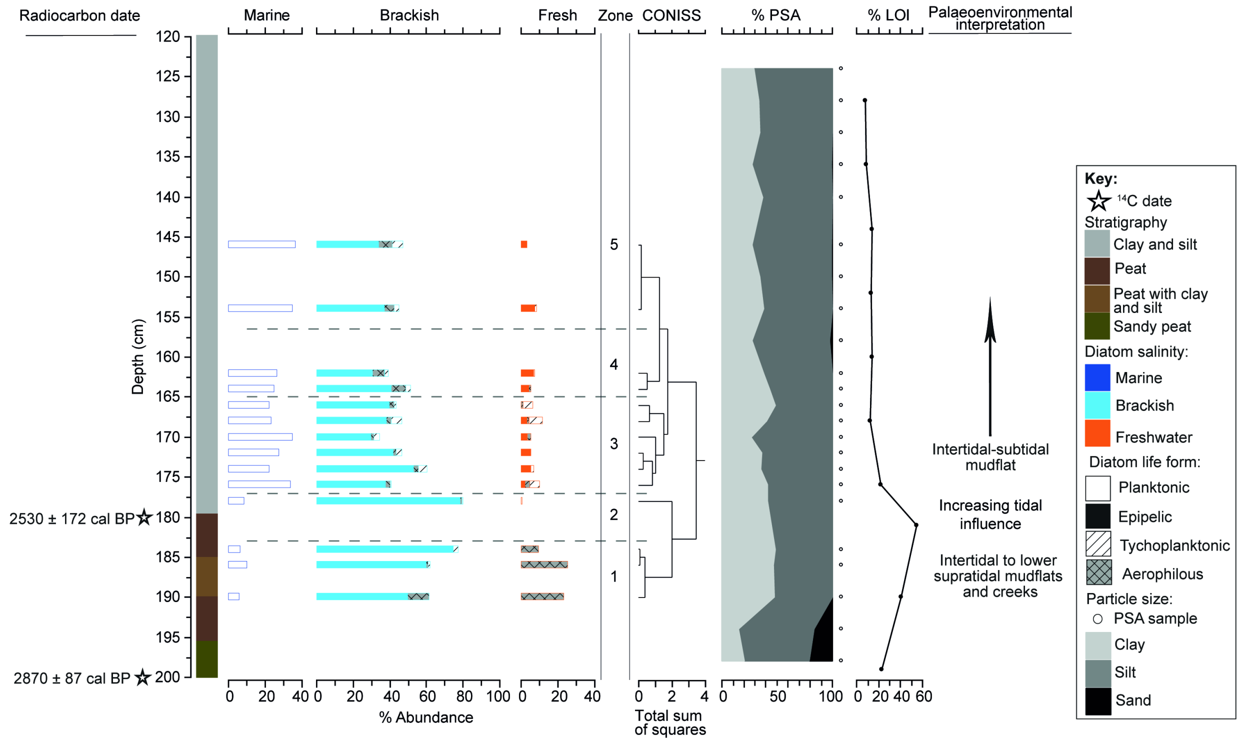
Fig. 8 – Schematic illustrating the temporally and spatially variable pattern of sediment release and supply pathways identified from the late Holocene data presented in this paper. Phase 1 and 2 show a southwards migration of a sediment supply pathway. The vulnerability of sections of the barrier is increased due to the sediment supply being limited. Phase 2 shows the barrier breach which has resulted from a weak point in the barrier, creating a barrier estuary. Phase 3 shows a shift in the spatial pattern of sediment release and supply. The breach has annealed as a result of temporal changes in the spatial pattern of sediment release and storage, resulting from erosion and deposition.


A.
N
United Kingdom
Horsey
Norfolk
North Sea
Suffolk
B
Essex
Netherlands
Strait of Dover
Belgium
Dungeness
France
0
100
200 km
B.
River Bure
River Yare
River Waveney
River Blyth
Southwold
Walberswick National Nature Reserve
Dunwich
Minsmere
Sizewell
River Alde
River Deben
Aldeburgh
5 km
Orford Ness

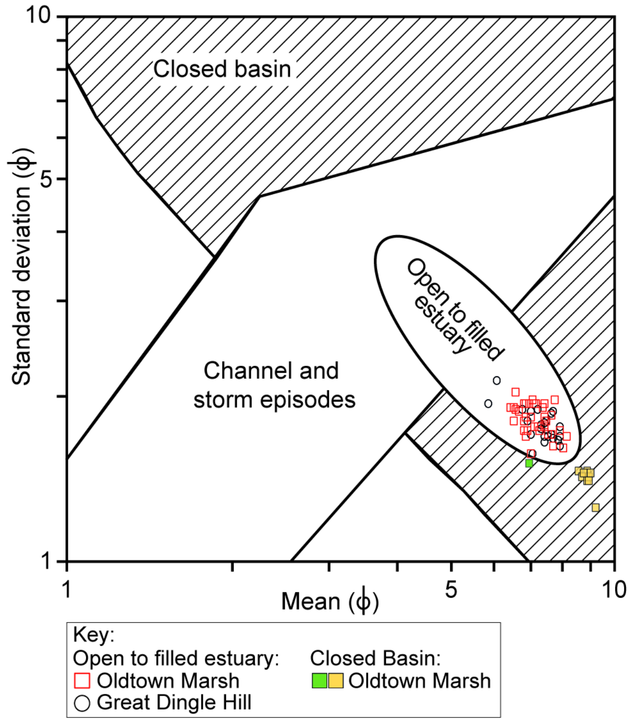
A
OLDTOWN
MARSH
OTM-16-13
B
A
B
GDH-16-2
GREAT
DINGLE
HILL
N
Sampled core
Transect core
300 m

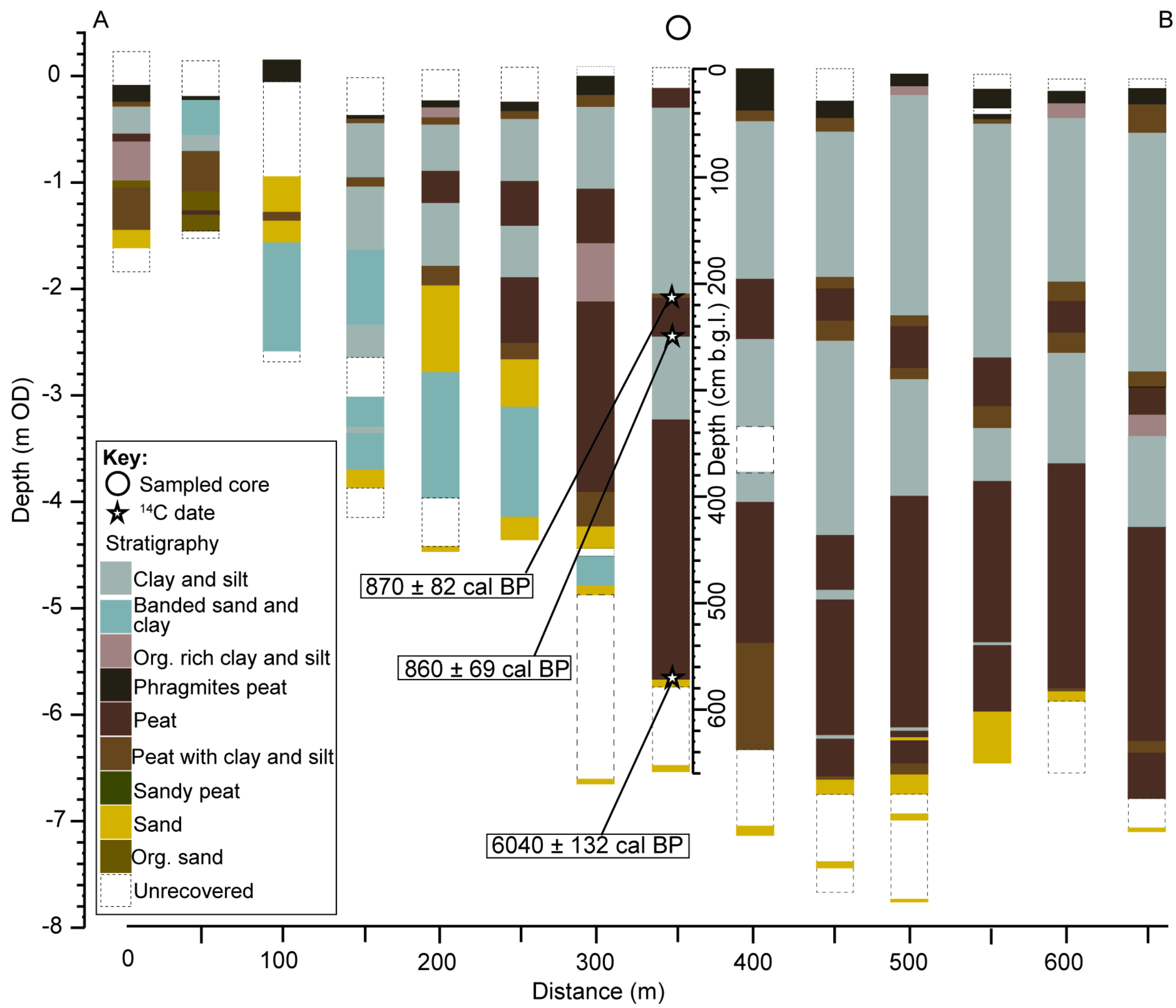


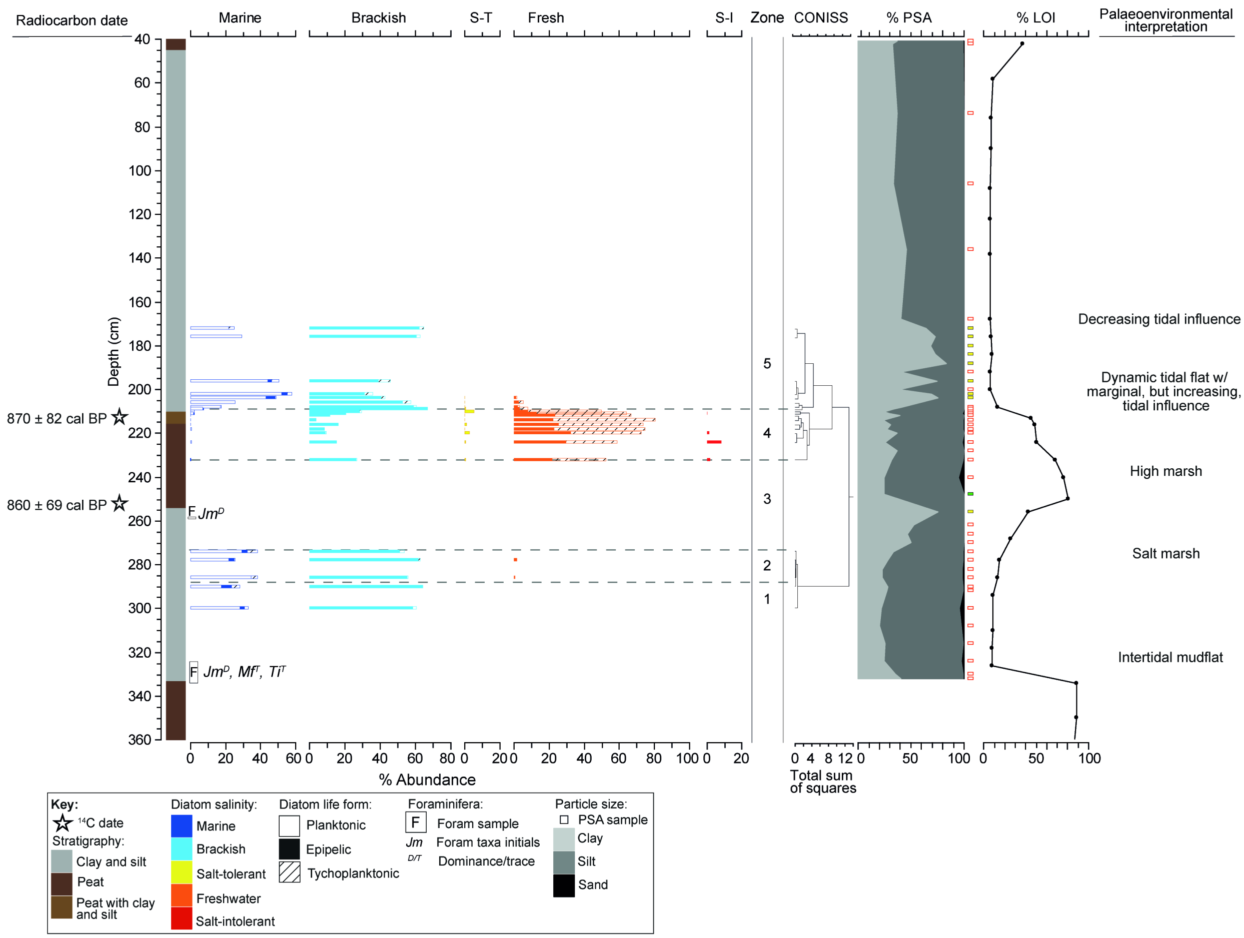
A
B
0
-1
-2
-3
Depth (m OD)
0
100
200
Depth (cm b.g.l.)
2530 ± 172
cal BP
2870 ± 87
cal BP
0
25
50
75
Distance (m)
Key:
Sampled core
14C date
Stratigraphy
Clay and silt
Org. rich clay and silt
Peat
Peat with clay and silt
Sandy peat
Sand
Org. sand
Unrecovered



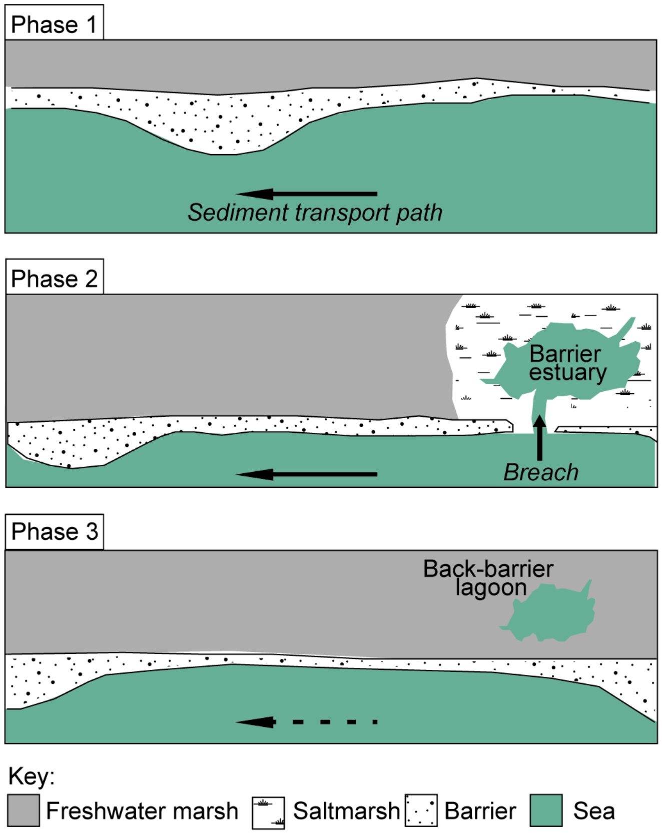
Radiocarbon date
Marine
Brackish
Fresh
Zone
CONISS
% PSA
% LOI
Palaeoenvironmental interpretation
Depth (cm)
2530 ± 172 cal BP
2870 ± 87 cal BP
% Abundance
Total sum of squares
Intertidal-subtidal mudflat
Increasing tidal influence
Intertidal to lower supratidal mudflats and creeks
Key:
14C date
Stratigraphy
Clay and silt
Peat
Peat with clay and silt
Sandy peat
Diatom salinity:
Marine
Brackish
Freshwater
Diatom life form:
Planktonic
Epipelic
Tychoplanktonic
Aerophilous
Particle size:
PSA sample
Clay
Silt
Sand


10
5
1
Standard deviation (ϕ)
1
5
10
Mean (ϕ)
Closed basin
Channel and
storm episodes
Open to filled
estuary
Key:
Open to filled estuary:
Oldtown Marsh
Great Dingle Hill
Closed Basin:
Oldtown Marsh


A
B
0
-1
-2
-3
-4
-5
-6
-7
-8
Depth (m OD)
0
100
200
300
400
500
600
Depth (cm b.g.l.)
0
100
200
300
400
500
600
Distance (m)
870 ± 82 cal BP
860 ± 69 cal BP
6040 ± 132 cal BP
Key:
Sampled core
¹⁴C date
Stratigraphy
Clay and silt
Banded sand and clay
Org. rich clay and silt
Phragmites peat
Peat
Peat with clay and silt
Sandy peat
Sand
Org. sand
Unrecovered



Radiocarbon date
Marine
Brackish
S-T
Fresh
S-I
Zone
CONISS
% PSA
% LOI
Palaeoenvironmental interpretation
Depth (cm)
870 ± 82 cal BP
860 ± 69 cal BP
Decreasing tidal influence
Dynamic tidal flat w/ marginal, but increasing, tidal influence
High marsh
Salt marsh
Intertidal mudflat
% Abundance
Total sum of squares
Key:
14C date
Stratigraphy:
Clay and silt
Peat
Peat with clay and silt
Diatom salinity:
Marine
Brackish
Salt-tolerant
Freshwater
Salt-intolerant
Diatom life form:
Planktonic
Epipelic
Tychoplanktonic
Foraminifera:
Foram sample
Foram taxa initials
Dominance/trace
Particle size:
PSA sample
Clay
Silt
Sand


Phase 1
Sediment transport path
Phase 2
Barrier estuary
Breach
Phase 3
Back-barrier lagoon
Key:
Freshwater marsh
Saltmarsh
Barrier
Sea