CHAPTER 3

An Overview of Holocene Coastal Change From Berwick-upon-Tweed to Whitby

By Natasha Barlow and Ian Shennan[1]

3.1 Introduction

The coast of North East England contains a diverse range of environments, providing suitable resources and locations for human occupation since the retreat of the last British ice sheet, more than 16000 years ago. It is important to consider relative sea level (RSL) change and coastal evolution of the North East coast to understand how changes in the palaeocoastline affected coastal communities since the Late Upper Palaeolithic. The British Isles ice sheet stored <1 m equivalent sea level at the Last Glacial Maximum but post-glacial isostatic adjustment processes produced vastly contrasting relative sea-level changes at different locations around the coastlines of the UK. The effects of these processes change considerably along the coast of NE England.

The plan of the report is therefore as follows. In Section 3.2 we review the mechanisms of Holocene RSL change and the archives of past sea level change to provide a framework to consider the data collected in the NE. Section 3.3 reviews the solid and drift geology and geomorphological processes as important parameters in understanding the temporal and spatial patterns of Holocene coastal change. Section 3.4 provides detailed examination of Holocene RSL change and coastal evolution from Berwick to Whitby, divided into the individual sections of the Shoreline Management Plan (SMP) Cells 1a-1d.

Table 3.1 SMP Cells for the NERCZA study area

SMP Cell	Northern Extent	Southern Extent
1a	Berwick-upon-Tweed	River Tyne
1b	River Tyne	Seaham
1c	Seaham	Saltburn
1d	Saltburn	Whitby

Due to the nature of the environmental records of Holocene RSL change, there are areas, particularly on stretches of high-energy coast, in which knowledge of past coastal change is limited. To provide a regional-scale context of the evolution of the coast of NE England Section 3.5 contains summaries of modelled results of the palaeogeography of the North Sea. In Section 3.6 we make recommendations for possible future research and summarise our main conclusions in Section 3.7. All ages quoted are in calendar years before 0 BC (yrs BC) unless otherwise indicated (where ages are stated as years before present (yrs BP), present is defined as AD 1950).

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3.2 Holocene Relative Sea Level Changes

In its simplest form, relative sea-level changes are a function of fluctuations in both ocean and crustal elevations. For each geographical location (φ), the change in relative sea level RSL (τ,φ) at time (τ) can be expressed schematically (Shennan and Horton, 2002) as:

> RSL (τ,φ) = Eustatic function (τ) + Isostatic function (τ,φ) + Tectonic function (τ,φ) + Local factors (τ,φ)

This is a complex relationship as most variables vary in both time and space (fig.3.1). The solely time-dependent eustatic function over the last 16,000 years is the change in global volume of water in the oceans due to meltwater discharge from land-based ice sheets and glaciers. The isostatic function is the rebound process including both ice (glacio-isostatic) and water (hydro-isostatic) load contributions. Any tectonic effect is usually considered negligible on the millennial timescale in most studies of Great Britain to date (c.f. Kiden, 1995). Local factors include tidal regime, meteorological and hydrological factors, such as changes in air pressure and river discharge, and sediment compaction. All of these may change through time and may potentially alter how RSL is recorded at each site.

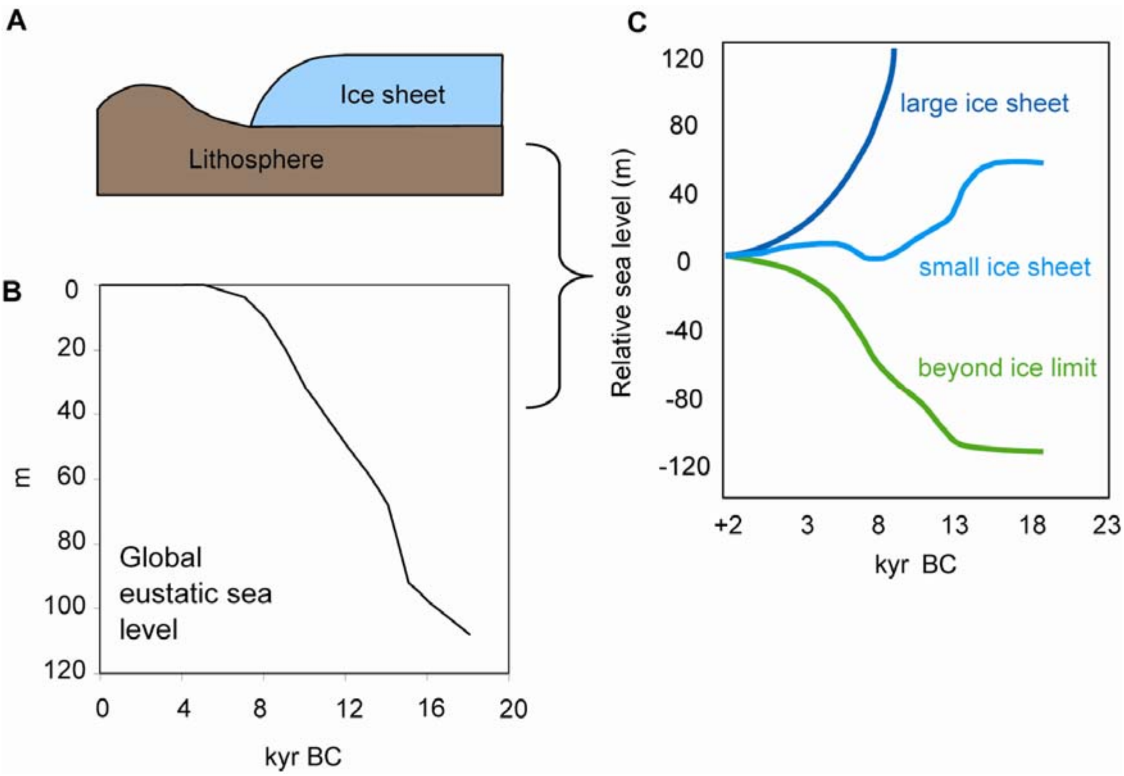


Figure 3.1 During the last glacial maximum, ~22,000 years ago, ice from Scandinavia and the British Isles extended beyond the present coastline onto the continental shelf. Increased mass of ice caused deformation of the Earth's crust (fig. 3.1A). As global climate warmed, great ice sheets then present across much of North America, Northern Europe, parts of Asia and South America and Antarctica started to melt, causing global, or eustatic, sea-level rise (fig. 3.1B). Patterns of sea-level rise vary from region to region in response to changing distributions of ice and water. Termed relative sea-level change for any particular location on the Earth's surface, the pattern depends on distance from the ice

sheet, size of nearby ice sheets and glaciers, their rates of retreat and the structure of the Earth's crust in the region (fig. 3.1C).

Environmental records of Holocene RSL change and coastal evolution have not been destroyed by the series of glacial and interglacial cycles that characterised the Pleistocene and hence can provide a quite detailed record of RSL change. Prior to ~9,050 yr BC there are few records of RSL change as the coastline was offshore from its present position following deglaciation after the Last Glacial Maximum (LGM) ~18-20 kyr BC, with time-transgressive deglaciation following (Evans *et al.*, 2005). The global eustatic sea level curve is largely derived from coral records at locations far from the former ice sheets of the LGM, following model corrections for tectonic and hydo-isostatic effects (Bassett *et al.*, 2005), for example Barbados (Fairbanks, 1989); Huon Peninsula, Papua New Guinea (Chappell and Polach, 1991) and Sunda Shelf (Hanebuth *et al.*, 2000). These records indicate that since the LGM global eustatic sea level has risen 120-125m reaching near present levels ~4050 years BC during the mid Holocene highstand. Since 2050 yr BC there has been minimal polar deglaciation resulting in limited global eustatic sea level change (Peltier, 2002).

Environmental records also capture the effects of the isostatic and local variables of RSL change. Along the coast of NE England lithology, coastal geomorphology and biological proxies provide elevation and age information allowing reconstruction of local and regional RSL histories. In particular, lithology and micropalaeontological evidence at the contact between intercalated marine and terrestrial sediments at low energy coasts can provide sea level index (SLI) points; indicating the tendency and elevation of sea level change at a given time (Shennan et al., 1983). Over 12,000 SLI points now exist to constrain RSL since the LGM in Great Britain (Shennan and Horton, 2002). Biostratigraphy may also record more subtle changes, for example a transition in the pollen record from a salt marsh assemblage to a freshwater vegetation community (Innes and Frank, 1988). Combined with radiocarbon dating such records can provide limiting dates where the palaeoenvironment indicated by the biostratigraphy is not clearly related to a fossil tide level; at which point sea level must have been at or below that record (Shennan *et al.*, 2000a). Such information helps to constrain SLI points. Combining the environmental evidence of past RSL change with geophysical modelling allows predictions of isostatically-induced sea level changes, improving understanding of the spatial and temporal patterns of RSL change (Shennan and Horton, 2002). In addition, Shennan *et al.* (2000b) combined geophysical, field and bathymetric data to produce reconstructions of Holocene palaeogeography of the North Sea which has revealed a marine transgression of the continental shelf.

In general, the focus of much RSL research is on the vertical change in sea level. However, models can improve understanding of the horizontal change. Due to the increased influence of anthropogenic activity upon the land and limitations of radiocarbon dating, it becomes difficult to establish detailed RSL history from 1000 yr BC to present when tidal records become available. Along the NE coast, two tide gauges, at North Shields and Whitby, provide information of changes in sea level from 1946 and 1980 to present respectively (NTSLF, 2007).

It is therefore possible to establish a detailed picture of Holocene coastal evolution and RSL change of NE England using a wide range of available field evidence combined with appropriate models. These palaeoenvironmental reconstructions are important to understand the relationship with, and impact of, coastal evolution on the coastal communities of North East England since the Late Upper Palaeolithic.

3.3 Geology of the NE Coast

To provide the context for the post-LGM coastal changes of NE England we first consider the coastal solid and drift geology from Berwick-upon-Tweed to Whitby. Extensive Carboniferous, Permian, Triassic and Jurassic sequences lie upon folded basement rocks of Lower Palaeozoic age and Old Red Sandstone (Johnson, 1995). Unconsolidated Quaternary drift sediments occur along much of the coast.

3.3.1. Solid Geology

The underlying solid geology varies considerably along the coast (Figure 3.2). The Northumberland coastline is characterised by rocks of Carboniferous age. Older Carboniferous limestone dominates the coast from Berwick-upon-Tweed to Howick. Younger Carboniferous millstone grit outcrops at locations such as Cheswick, and igneous intrusive basalt deposits are found at Budle (BGS, 2007). South of Howick millstone grit defines the solid geology to High Buston. From High Buston to the Tyne the younger Carboniferous Westphalian Coal Measures, were laid down in a continuous delta (Johnson, 1995), though in places are interrupted by igneous dykes of either Jurassic or Carboniferous age, for example at Seaton.

South of the Tyne and along the County Durham coast to Hartlepool (SMP 1b and 1c), Permian marine magnesian limestone and Roker dolomite form many of the coastal cliffs, with limestone of the Late Permian Seaham Formation at Crimdon. South of Hartlepool to the Tees Estuary at Cowpen, Late Permian and Triassic Sherwood Sandstone occupies the central area of SMP 1c (BGS, 2007). The coarse material of the solid geology of the north fines out at the Tees Estuary and is replaced by Triassic Mercia Mudstone, dominated by red 'marl' (Swinnerton and Kent, 1976).

The southern extent of SMP 1c and SMP 1d from Saltburn to Whitby comprises the Jurassic rocks that form the North Yorkshire Moors. Lower Jurassic Lias deposited under marine conditions dominates the coastal geology, which south of the Tees to Saltburn consists of Lower Lias Redcar Mudstone, exposed in the intertidal zone at West Scar, off Redcar. From Saltburn to Runswick Middle Lias sandstones, Cleveland Ironstone and oolite interbed. South of Runswick to Whitby, the sandstones are replaced by Upper Lias Shales, containing Jet Rock, which lie alongside Jurassic oolitic beds (Swinnerton and Kent, 1976).

3.3.2. Drift Geology

Glacial till and diamicton deposited by the ice that occupied the NE at many times through the Quaternary, overlies much of the solid geology discussed above. Throughout SMP cells 1a and 1b (Berwick-upon-Tweed to Seaham) the deposits are generally more than 8m thick, with distinct units representing several late Pleistocene glaciations. A lower till at Warren House Gill, County Durham is dated to at least marine isotope stage (MIS) 6 (Catt, 2007), with Devensian (MIS 2) glacial material widely spread along the coast, for example at Blackhall Rocks (Bridgland, 1999). At Shippersea Bay, Easington, an interglacial raised gravel beach lies upon the magnesian limestone cliffs at ~32m above present sea level, representing a RSL high-stand during MIS 7 (Bowen *et al.*, 1991). At various locations, for example Bamburgh, Hauxley, Druridge Bay and Whitley

Figure 3.2 Solid geology of the North East coast with main locations discussed in text marked. Solid geology definitions based upon BGS data (BGS, 2007).

Bay, Holocene wind blown sand fronts the cliffs. Intertidal alluvium and river terrace deposits dissect the glacial tills on and around Holy Island and within most of the estuaries of the Northumberland coast. Numerous locations, discussed in Section 3.4, contain Holocene peat deposits.

From Horden to Saltburn the drift geology is defined by late Quaternary glacio-fluvial sands and gravels, dissected by layers of till (BGS, 2007). More recent Holocene river alluvium and peat deposits occur within the Tees Estuary. South of Saltburn to Whitby (SMP 1d) some Quaternary till occupies the embayments within the prevailing solid geology.

3.3.3. Coastal Geomorphological Processes

The NE coast is a macrotidal environment with maximum spring tides of over 4m at Amble and Blyth (NTSLF, 2007). Spring tide levels rise up estuary by around 0.2m in both the Tyne and Tees. The prevailing winds are offshore from the south west, but high speed on shore winds generate waves with long fetches over the North Sea, particularly during winter gales. Combined with tidal currents the net movement of material along the coast in suspension and beach material by longshore drift is southwards, though there are some local variations. During the early Holocene RSL rise, unconsolidated sediments, now offshore, provided a plentiful supply for onshore and longshore movement, with additional material provided by erosion of cliffs. Holocene sea level changes and high energy waves has resulted in a series of sandy bays backed by sand dunes or cliffs of glacial till between rocky headlands fronted by wave cut platforms along the Northumberland coast. The amount of alongshore material transported is relatively small, mostly confined to individual embayments. The southward movement of longshore drift has resulted in small spits deflecting the Aln, Coquet, Lyne and Wansbeck. There is local northward drift at Blyth. Prior to industrial development the tidal section of the Tyne contained intertidal sediments during the Holocene, for example at Jarrow.

There is minimal interchange of sediment between the Tyne and Wear with the magesian limestone cliffs contributing little material to the few beaches along this stretch of coast. The tidal section of the Wear has accumulated sands, silts and clays though no saltmarsh development has occurred. The more open stretches of cliffs south of the Wear to Crimdon are fronted by beaches of gravel resulting from cliff erosion, but the net movement of material between the headlands is limited. South of Crimdon coastal dunes have formed behind a sandy beach.

The protected environment of Hartlepool Bay and Tees Bay have allowed sediment accumulation and infilling, the rate of which is particularly related to rapid sea level rise and increasing tidal range during the early Holocene (Plater *et al.*, 2000). Outside of the estuaries some southward movement of material occurs. In places such as Redcar the coast cliffs are fronted by a narrow zone of gravels due to cliff errosion. Differential erosion of the varied geology south of Saltburn results in a diverse coastline of cliffs, bays and headlands (glacial deposits at or near sea level are eroded at a rate of three times that compared to shale outcrops). Little material moves between individual bays, except in sediment suspension. Throughout the late Holocene there has been a net landward migration of the open coast, and most of the North East coast is now considered as undergoing rapid erosion.

3.4 North East England Holocene Coastal and RSL Change

The summary of the RSL change and coastal evolution of NE England from Berwick-upon-Tweed to Whitby over the last 12 kyr BC is structured around the Shoreline Management Plan (SMP) cells 1a – 1d. The main locations discussed within the text are shown by the map in Figure 3.3. All SLI points for the region are summarised in Tables 3.2 and 3.3.

3.4.1 Berwick-upon-Tweed – River Tyne (SMP Cell 1a)

Shennan and Horton (2002) report 47 SLI points and 8 limiting dates from sites between Berwick-upon-Tweed and the Tyne (Table 3.2 and fig. 3.3). The Holocene RSL history of Northumberland divides it into three geographical units: north, central and south. Data for the northern sites has been collected from Beal Cast, Bridge Mill and Broomhouse Farm (Shennan *et al.*, 2000a), central sites from Annstead Burn, Elwick and Newton Links (Plater and Shennan, 1992; Shennan *et al.*, 2000a) and in the south from Alnmouth, Amble Bay, Cresswell Ponds and Warkworth (Plater and Shennan, 1992;

Shennan *et al.*, 2000a). These are accompanied by additional palaeoenvironmental data which help to build up a full picture of coastal evolution of the Northumberland coast.

Figure 3.3 Location of SLI points from raised peat deposits within SMP Cell 1a

Shennan *et al.* (2000a) present and interpret 11 SLI points from north Northumberland constraining past sea level during ca. 6.4-1.6 kyr BC. At Broomhouse Farm a series of intercalated peat and silts overlie a Devensian till. The basal peat dates to the late Devensian interstadial at ca. 11.5 kyr BC, which underlies a Younger Dryas limnic sediment. A series of dates from Beal Cast and Bridge Mill from 6450 to 4050 yr BC, record a trend of rising sea level from ca. -0.5m to >2m above present towards the mid Holocene (fig. 3.4). Sea level tendencies derived from the lithology and biostratigraphy of the intercalated peat and silts at Broomhouse Farm record alternating positive and negative tendencies of sea level during the mid Holocene. Shennan *et al.* (2000a) are unable to exactly constrain the timing of the maximum with the available environmental data, however it is clear that between ca. 5.3-1.7 kyr BC RSL fluctuated within a 1m range at 1.5 – 2.5m above present levels. Within the sequence is a sand lens relating to a high-energy event, for example due to barrier over-wash during a storm surge, dated to 5850-6050 yr BC (Horton *et al.*, 1999c; Shennan *et al.*, 2000a). Shennan *et al.* (2000a) tentatively link this sediment deposition to the tsunami attributed to the second Storegga Slide on the Norwegian continental slope (Long *et al.*, 1989; Smith *et al.*, 1985; Smith *et al.*, 2004).

SLI points from Bridge Mill and Broomhouse Farm at 2450-2850 yr BC (RSL ca. 2.10

±0.20m above present) and 3750-4050 yr BC (RSL ca. 1.19 ±0.20m above present) record a negative sea level tendency. No SLI point exists for the late Holocene; though model results suggest a continued fall of late Holocene RSL to present levels, due to local isostatic uplift (Shennan and Horton, 2002). The best estimate of the relative land uplift over the last 4000 yrs is 0.71 mm yr^{-1} within northern Northumberland.

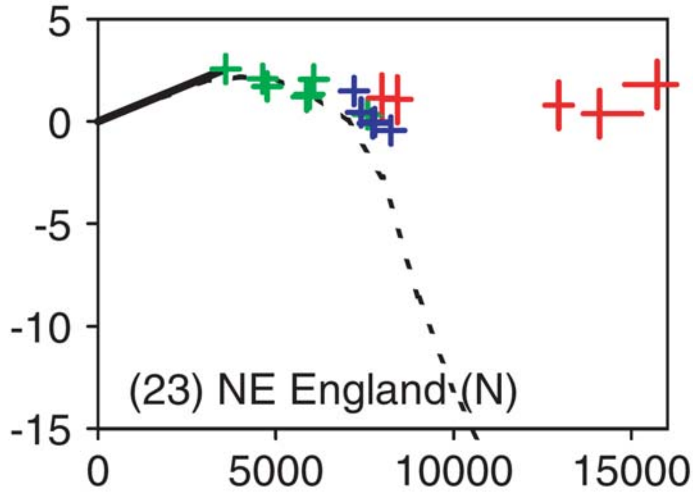


Figure 3.4 Sea level index points for Northumberland (north) sites as calibrated age (yr BP) against change in sea-level relative to present (m) as reported in Shennan and Horton (2002). The best estimate of late Holocene sea level trend plotted as a solid line with the dashed line showing predicted modelled RSL change. + Basal index points; + Intercalated index points; + Limiting dates

Within the shoreline regression of the last 1000 yrs, Wilson *et al.* (2001) identify the onset of dune development in north Northumberland from cores taken at Cheswick, Holy Island and Ross Links. Dating of aeolian sediment suggests primary dune building occurred during the climatic cooling termed the 'Little Ice Age', ca. 1300-1900 A.D. (Grove, 2004) when the falling RSL reached within 1m of present levels in the area. Wilson *et al.* (2001) suggest that the absence of dune systems prior to this period may have been a consequence of coastal configuration, the rate of shoreline regression and availability of sediment.

Less data are available from the central Northumberland sites; as summarised in the sea level curve shown in Figure 3.5. Plater and Shennan (1992) use diatoms through a complex series of silts and a peat layer at Elwick to infer a period of continual increase in marine influence. Peat accumulation on the underlying clays is dated to 5850-6150 yr BC, which, due to RSL rise, was periodically tidally inundated to a point of mudflat deposition at 5650-5950 yr BC (Shennan *et al.*, 2000a). Three additional SLI points from ca. 6350-5850 yr BC from Annstead Burn capture the early Holocene RSL rise from ca. 1.5m below present. The Annstead Burn sequence also contains a sand deposit dated to ca. 6050-6350 yr BC, generally considered a few centuries older than the timing of the Storegga Slide. Shennan *et al.* (2000a) suggests it represents a high-energy event that deposited coarse-grained material that was subsequently overlain with intertidal clays as the embayment infilled, possible due to the establishment of a dune system.

Wilson *et al.* (2001) record mid Holocene sand deposition by a series of coarse grained layers at St. Adians dunes. These date (ca. 3850-1850 yr BC) to a period of deposition prior to the mid Holocene highstand. This is similar to the Holocene intertidal sedimentation recorded at Brockmill, Holy Island Bay (Plater and Shennan, 1992). During the late Holocene, the primary phase of dune emplacement in the central area occurred from ca. 1650-1450 yr BC with the onset of RSL regression, and increased dune development during the Little Ice Age (Wilson *et al.*, 2001). Overall, the SLI points from this small central data set plot just below those from the northern sites, with a mid-Holocene maximum (ca. 2250-1850 yr BC) represented by one point from Newton Links at 0.5m above present (Shennan *et al.*, 2000a). Modelled best fit estimates from the central area suggest 0.11 mm yr^{-1} of land uplift over the past 4000 years (Shennan and Horton, 2002).

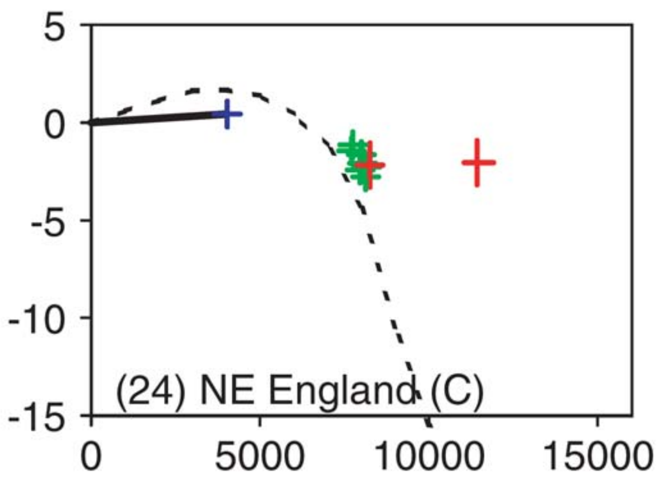


Figure 3.5 Sea level index points for Northumberland (central) sites as calibrated age (yr BP) against change in sea-level relative to present (m) as reported in Shennan and Horton (2002). The best estimate of late Holocene sea level trend plotted as a solid line with the dashed line showing predicted modelled RSL change. + Basal index points; + Intercalated index points; + Limiting dates

From Alnmouth to Cresswell 26 Holocene SLI points exist from a series of intercalated peats and inorganic deposits (Shennan *et al.*, 2000a) producing the sea level curve in Figure 3.6. The stratigraphy of the Holocene sediments at Alnmouth is highly complex with a series of peat layers whose deposition has been complicated by the underlying topography and erosion. The peats are largely dividable into an upper and lower suite dissected by silts and clays (Horton *et al.*, 1999b; Horton *et al.*, 1999c; Shennan *et al.*, 2000a). The oldest SLI point from Alnmouth (6350-7050 yr BC) records a period of rising water table levels with RSL ca. 4m below present and approaching estuarine conditions (Shennan *et al.*, 2000a). Positive sea level tendencies are also recorded at 7.8-8.0 (RSL ca. 2.01 ±0.20m below present) and 5550-5350 yr BC (RSL ca. 1.17 ±0.20m below present). Similar early Holocene SLI points from Warkworth and Cresswell capture the early Holocene RSL rise along the Northumberland coast from more than 4m below present around 6550 yr BC (Horton *et al.*, 1999b; Shennan *et al.*, 2000a).

At Howick, Boomer *et al.* (2007) record the presence of a coarse clastic unit which they dated to 6400 yr BC, similar to a comparable deposit at Annstead Burn. Boomer *et al.* (2007) do tentatively link this deposit to the tsunami associated with the Storegga Slide, unlike Shennan *et al.* (2000a) at Annstead Burn. Regardless, it is clear at ca. 6 kyr BC one or more high-energy events occurred along the coast of Northumberland depositing coarse-grained material. At present, the cause of this/these event/s remains uncertain.

Into the mid Holocene, dates on the lower Alnmouth peat, which exists in the southern seaward part of the Alnmouth site, suggests formation between 5050-4050 yr BC. The thicker, upper peat from the central area of Plater and Shennan's (1992) north-south transect dates from 3050 yr to 1550 yr BC. Biostratigraphic analysis shows this peat-silt/clay sequence to represent fluctuations between freshwater and intertidal conditions during the mid Holocene. Amble Burn presents a similar silt-peat regressive contact dated to 5550-5850 yr BC when RSL was ca. 1.91 ±0.20m below present. Around Druridge Bay, the Creswell Pond *(*Horton *et al., 1999c;* Shennan *et al.*, 2000a) and Low Hauxley (Innes and Frank, 1988) sequences also record a period of mid-Holocene peat formation. Marine mudflats at Cresswell Ponds laid down at 5250-5550 yr BC, when RSL was ca. 2.14 ±0.20m below present, give way to transitional saltmarsh and subsequently to an organic freshwater environment. Lithological and micropalaeontological evidence from Howick also records a build up of freshwater organic material as the local sedimentation rate exceeded the rise in mid Holocene RSL (Boomer *et al.*, 2007).

A series of transgressive SLI points record increased tidal inundation with RSL up to 1m below present at 1750-1850 yr BC, due to probable dune breaching, resulting in a series of five thin peat layers intersected by sand (Horton *et al.*, 1999c; Shennan *et al.*, 2000a). Late Holocene dune instability and redistribution is also recorded at Low Hauxley (Innes and Frank, 1988). The lithological and biological data from the southern sites shows a mid Holocene highstand to little above present, which is further constrained by a limiting date from Cresswell recording RSL at or below 1.72 ±1.13m above present at 1650-1950 yr BC (Shennan *et al.*, 2000a). During the gradual late Holocene RSL regression towards present levels, coastal dune accumulation began between 750 yr BC – AD 650, with the main periods of development associated with cooler periods of the last 3000 years (Wilson *et al.*, 2001).

The spatial variation in Northumberland Holocene RSL and coastal evolution is a consequence of differential LGM glacio-isostatic loading, resulting in decreasing mid and late Holocene uplift from north to south. The rate of isostatic uplift for southern Northumberland given by Shennan and Horton (2002) is -0.09 mm yr^{-1} with a best fit estimate, taking into account sediment compaction, of 0.17 mm yr^{-1}. The Holocene RSL and coastal evolution of the south Northumberland sites is far more constrained by global eustatic sea level change than isostatic adjustment. In addition, it becomes clear that though the general trend of Holocene RSL change along the coast of Northumberland is the similar, site-specific process such as sedimentation rates, coastal geomorphology and coastal configuration have a substantial impact on local RSL change and coastal evolution.

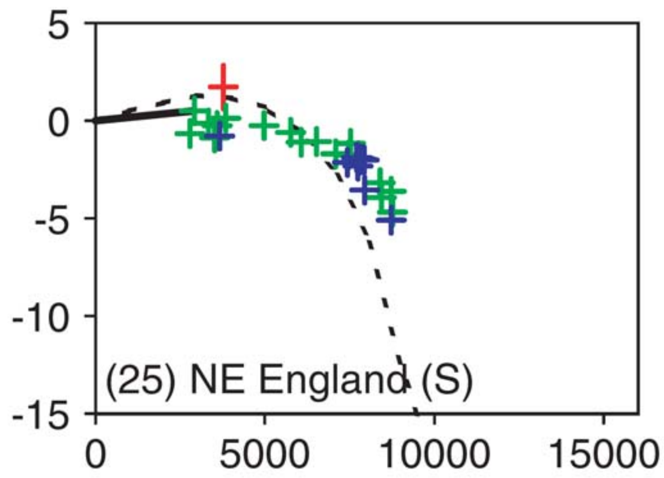


Figure 3.6 Sea level index points for Northumberland (south) sites as calibrated age (yr BP) against change in sea-level relative to present (m) as reported in Shennan and Horton (2002). The best estimate of late Holocene sea level trend plotted as a solid line with the dashed line showing predicted modelled RSL change. + Basal index points; + Intercalated index points; + Limiting dates

3.4.2 River Tyne – Seaham (SMP Cell 1b)

Very few low energy sedimentary environments suitable for the preservation of an archive of Holocene sea level change exist within the limestone and dolomite cliffs and rock platforms between the Tyne and Seaham. Therefore, very little RSL research has occurred along this stretch of coast. One offshore record, approximately 30 miles east of the mouth of the Wear, records the incursion of marine conditions, using dinoflagellate cyst's, during the early Holocene into this area of the North Sea as a consequence of global eustatic sea level rise (Harland and Long, 1996). It would seem sensible to assume that the rate and pattern of RSL change during the Holocene at this stretch of coast would be similar to that seen slightly further south, with a gradually decreasing rate of RSL rise towards present day levels. As sites in southern Northumberland experienced a mid Holocene RSL maximum only 0.5m above present levels, it is likely that RSL between the Tyne and Seaham did not exceed present day sea level. Based on model results from Shennan and Horton (2002), this part of the North East coast is experiencing very little, if any, late Holocene land/sea level changes due to its position upon the pivotal point between the isostatically rebounding north and the subsiding south.

Site	Laboratory code	^{14}C age ± 1σ	Change in RSL (m)	Calibrated age (yr BC)			Longitude W	Latitude N
				Maximum	Mean	Minimum		
North Northumberland sea-level index points								
Beal Cast, BC96-2	AA23823	6955 ± 75	-0.03 ± 0.21	5988	5832	5710	152284	5540139
Beal Cast, BC96-2	AA23896	6500 ± 75	0.45 ± 0.21	5608	5452	5323	152284	5540139
Beal Cast, BC96-3	AA23824	6885 ± 70	-0.11 ± 0.21	5892	5771	5636	152152	5540058
Beal Cast, BC96-3	AA23825	7420 ± 75	-0.45 ± 0.21	6419	6293	6091	152152	5540058
Bridge Mill, BM95-7A	AA24226	6285 ± 65	1.49 ± 0.21	5458	5254	5057	156132	5541285
Bridge Mill, BM95-7A	AA24225	5290 ± 60	2.05 ± 0.21	4310	4123	3977	156132	5541285
Bridge Mill, BM95-7A	AA24223	3360 ± 60	2.57 ± 0.21	1864	1648	1510	156132	5541285
Bridge Mill, BM95-7A	AA24224	4105 ± 55	2.1 ± 0.21	2872	2683	2494	156132	5541285
Broomhouse Farm, BR96-8	AA23894	5185 ± 55	1.34 ± 0.21	4220	3997	3802	156223	5541569
Broomhouse Farm, BR96-8	AA25596	6700 ± 60	0.35 ± 0.21	5716	5622	5516	156223	5541569
Broomhouse Farm, BR96-8	AA23893	5130 ± 55	1.19 ± 0.21	4039	3916	3789	156223	5541569
Broomhouse Farm, BR96-8	AA25595	4250 ± 70	1.7 ± 0.21	3019	2814	2623	156223	5541569
North Northumberland limiting dates								
Broomhouse Farm, BR96-8	AA25597	10900 ± 85	0.8 ± 1.13	11192	11008	10704	156223	5541569
Broomhouse Farm, BR96-8	AA25598	12040 ± 110	0.39 ± 1.13	13338	12152	11695	156223	5541569
Broomhouse Farm, BR96-8	AA25601	7165 ± 60	1.16 ± 1.13	6202	6029	5890	156223	5541569
Broomhouse Farm, BR96-8	AA27618	7620 ± 100	1.07 ± 1.13	6641	6464	6245	156223	5541569
Broomhouse Farm, BR97-3	AA34199	13120 ± 80	1.81 ± 1.13	14331	13785	12870	156292	5541569
Central Northumberland sea-level index points								
Annstead Burn, AN96-5	AA27228	7355 ± 90	-2.27 ± 0.21	6395	6212	6027	139050	5534165
Annstead Burn, AN96-5	AA27229	7145 ± 60	-2.44 ± 0.21	6162	6010	5846	139050	5534165
Annstead Burn, AN97-1	AA27226	7325 ± 60	-2.78 ± 0.21	6371	6173	6025	139027	5534191
Elwick 42	SRR3844	6875 ± 45	-1.47 ± 0.23	5838	5758	5665	148310	5537560
Elwick 42	SRR3845	7230 ± 45	-2.1 ± 0.23	6209	6085	6004	148310	5537560
Elwick Q05	SRR3842	6935 ± 45	-1.13 ± 0.22	5965	5803	5717	148320	5537550
Elwick Q05	SRR3843	7180 ± 45	-1.65 ± 0.22	6163	6042	5919	148320	5537550
Newton Links, NBD11	AA23498	3690 ± 60	0.44 ± 0.4	2277	2080	1894	138012	5531533
Central Northumberland limiting dates								
Annstead Burn, AN97-1	AA27227	9965 ± 85	-2.06 ± 1.13	9975	9482	9243	139027	5534191
Annstead Burn, AN97-1	AA27616	7420 ± 60	-2.18 ± 1.13	6411	6299	6100	139027	5534191
South Northumberland sea-level index points								
Alnmouth 31/32	SRR3848	6180 ± 50	-1.72 ± 0.22	5288	5135	4989	137120	5523380

Alnmouth 31/32	SRR3846	3560 ± 45	0.13 ± 0.21	2024	1903	1754	137120	5523380
Alnmouth 31/32	SRR3847	5285 ± 45	-1.1 ± 0.22	4226	4117	3986	137120	5523380
Alnmouth 33	SRR3850	6945 ± 45	-1.93 ± 0.8	5969	5813	5721	137160	5523350
Alnmouth 46	SRR4584	6935 ± 45	-2.34 ± 0.21	5965	5803	5717	137160	5523340
Alnmouth, AL94-21B	AA24220	7650 ± 55	-3.96 ± 0.21	6594	6486	6407	136416	5523484
Alnmouth, AL94-21B	AA27617	7885 ± 65	-3.62 ± 0.21	7035	6779	6593	136416	5523484
Alnmouth, AL95-1	AA24219	7110 ± 55	-2.01 ± 0.21	6071	5971	5840	137107	5523323
Alnmouth, AL95-1	AA24218	6635 ± 55	-1.17 ± 0.21	5632	5568	5480	137107	5523323
Amble Bay, AB96-2	AA23892	6870 ± 60	-1.91 ± 0.21	5862	5755	5637	133141	5519386
Cresswell Ponds, CP95-11	UB3906	3405 ± 43	-0.79 ± 0.22	1874	1707	1533	133050	5515060
Cresswell Ponds, CP95-6	UB3905	2656 ± 56	-0.69 ± 0.41	969	831	668	133060	5514330
Cresswell Ponds, CP95-8	AA24217	6525 ± 55	-2.14 ± 0.21	5611	5489	5367	133056	5514335
Cresswell Ponds, CP95-R1	AA22663	3280 ± 45	-0.91 ± 0.4	1680	1569	1449	133056	5514335
Cresswell Ponds, CR95/7	UB3904	3359 ± 40	-0.26 ± 0.22	1737	1647	1525	133060	5514330
Warkworth AW16	SRR3703	7030 ± 45	-1.99 ± 0.4	5993	5904	5799	136160	5520260
Warkworth AW16	SRR3700	4405 ± 45	-0.26 ± 0.4	3320	3032	2908	136160	5520260
Warkworth AW16	SRR3701	5010 ± 45	-0.62 ± 0.21	3943	3800	3700	136160	5520260
Warkworth AW16	SRR3699	2810 ± 45	0.5 ± 0.4	1105	962	832	136160	5520260
Warkworth AW16	SRR3702	6555 ± 45	-1.77 ± 0.21	5616	5518	5389	136160	5520260
Warkworth, WA94-2A	AA24228	3120 ± 55	-0.12 ± 0.21	1510	1392	1260	136112	5520239
Warkworth, WA94-2A	AA24227	5720 ± 60	-1.09 ± 0.21	4713	4570	4402	136112	5520239
Warkworth, WA94-2B	AA24230	7135 ± 70	-3.57 ± 0.21	6195	6000	5839	136112	5520239
Warkworth, WA94-2B	AA24229	7615 ± 70	-3.2 ± 0.21	6631	6458	6258	136112	5520239
Warkworth, WA95-3	AA24222	7880 ± 65	-5.1 ± 0.21	7037	6771	6590	136101	5520232
Warkworth, WA95-3	AA24221	7905 ± 60	-4.69 ± 0.21	7035	6807	6643	136101	5520232
South Northumberland limiting dates								
Cresswell, CR951	UB3907	3511 ± 38	1.72 ± 1.12	1936	1827	1738	132440	5514260
Tyne sea-level index points								
Cowen Road, CRB96-3A	AA23822	7795 ± 85	-5.68 ± 0.21	7027	6633	6452	140136	5457367

Table 3.2 Summary of SLI points and limiting data from Northumberland. RSL is calculated as altitude minus the reference water level. The RSL error range is calculated as the square root of the sum of square of altitudinal error, sample thickness, tide level error and indicative range.

3.4.3 Seaham – Saltburn (SMP Cell 1c)

Much of the reconstruction of Holocene RSL change within this area has occurred from the sedimentary basin surrounding the Tees; namely within the low energy environments of the Tees Estuary and Hartlepool Bay producing 30 SLI points (Table 3.3 and fig. 3.7) and the RSL curve shown in Figure 3.8. The limestone cliffs to the north and south of Hartlepool do not provide archives of past sea level. At present, there is no Holocene chronology for the main County Durham coastal dune system at Crimdon.

At Hartlepool Bay, peat beds exposed at several locations in the intertidal zone are the visible element of a series of intercalated Holocene clay, muds and organic material. A basal peat, thought to be laid down prior to 5050 yr BC provides the earliest evidence for sediment deposition during a period of rising sea level (Horton *et al.*, 1999a). Evidence for the earlier coastal history of the area is thought to have been buried by dunes or exist beyond the present day intertidal zone; though peat retrieved from trawlers beyond the low tide mark suggest a freshwater/wetland environment in Hartlepool Bay during the early Holocene (Waughman *et al.*, 2005).

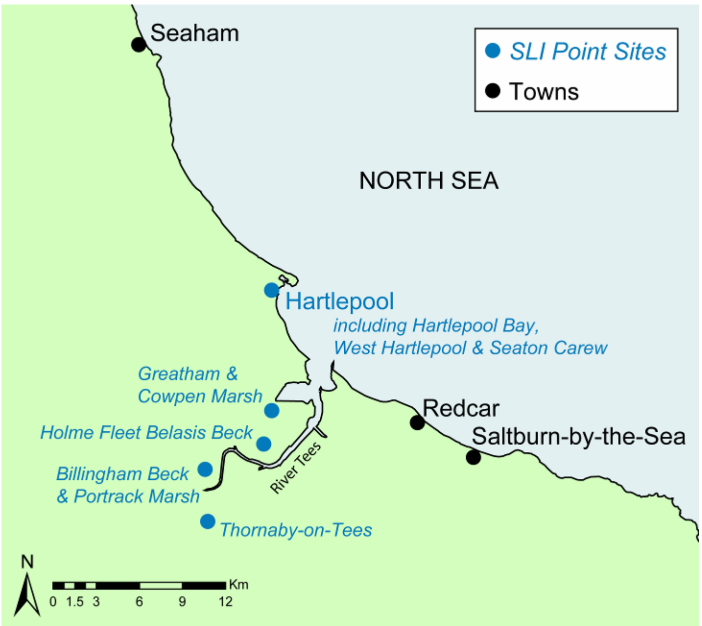


Figure 3.7: Location of SLI points from raised peat deposits within SMP Cell 1b

Transgressive overlaps record marine inundation of the peat as RSL rose towards the mid Holocene. Intertidal sedimentation is recorded by a thin silt near the base of saltmarsh deposits dated to 4050-4250 yr BC (Waughman *et al.*, 2005). Sea level rise continued until ca. 3550 yr BC when the biostratigraphy analysed from a series of intercalated silts and peats records a fluctuating RSL during the mid-Holocene highstand. Tooley (1978) records a switch from alder fen to freshwater communites of bulrushes and water lilly and later saltmarsh communities from ca. 3350 yr BC at Hartlepool Bay due to rising sea level. This complex stratigraphy is a combination of RSL change and local factors such as groundwater movements and adjacent land use changes (Horton *et al.*, 1999a). Figure 3.9 summarises the periods of mid Holocene RSL transgression and regression recorded at Hartlepool.

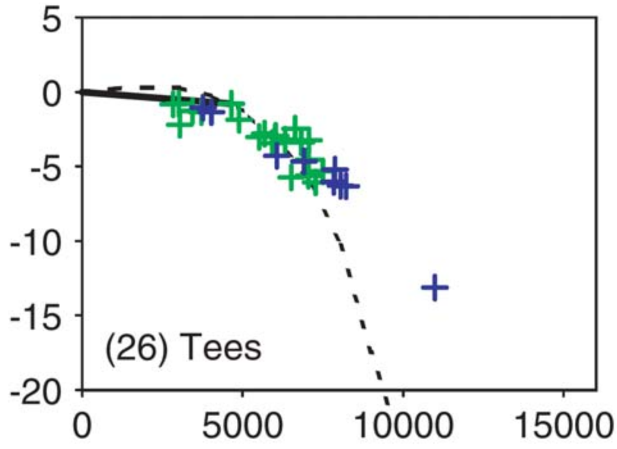


Figure 3.8 Sea level index points for Tees sites as calibrated age (yr BP) against change in sea-level relative to present (m) as reported in Shennan and Horton (2002). The best estimate of late Holocene sea level trend plotted as a solid line with the dashed line showing predicted modelled RSL change. + Basal index points; + Intercalated index points; + Limiting dates

In a similar manner to sequences along the Northumberland coast, Hartlepool Bay also records evidence of coarse-grained sediment deposited due to two high-energy events during the Holocene at ca. 4250 yr BC and ca. 2950 yr BC (Waughman *et al.*, 2005). It is possible that the later event resulted in a recorded negative tendency of sea level in the following centuries as the increased marine influence that accompanied this sediment deposition resulted in the formation of an intertidal environment. The evidence for RSL change during the last 2000 years is limited. A series of sand and organic deposits at Carr House Sidings would suggest three low amplitude fluctuations of tidal influence divided by two terrestrial phases since ca. AD 50 (Waughman *et al.*, 2005). The suggested period of reduced marine influence during the later phases of the Holocene may be a consequence of the establishment of dunes in a similar manner to those in Northumberland (Wilson *et al.*, 2001) by ca. AD 950 which formed during periods of static or regressive sea level.

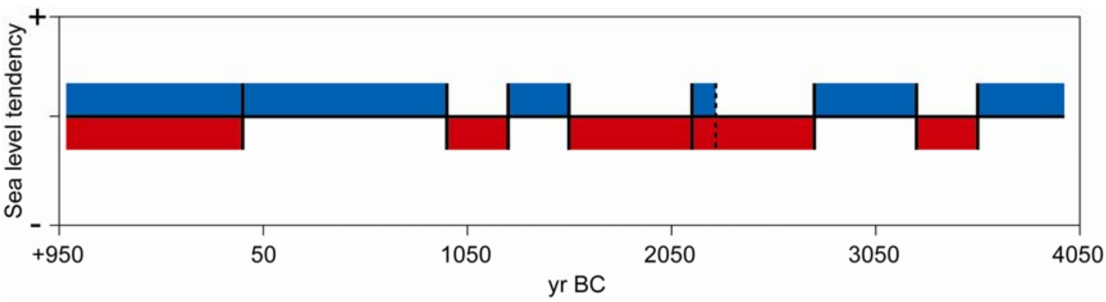


Figure 3.9 Diagrammatic representation of the fluctuations in RSL at Hartlepool Bay during the mid Holocene based on recorded tendencies of sea level moment by SLI points.

The sedimentary record in the Tees Estuary displays a very similar pattern of Holocene RSL change. Plater *et al.* (2000) describe a series of late Devensian glacio-fluvial sands and gravels and laminated silts and clays considered to be a consequence of a large ice-damned glacial lake in the Lower Tees Basin that formed during the retreat of the British

Ice Sheet. Collapse of this pro-glacial lake and establishment of the Tees channel resulted in the formation of the Tees Estuary at the end of the Pleistocene. During the late Pleistocene into the early Holocene, a resistant clay island existed in the lower Tees Estuary, which the post LGM eustatic sea level rise did not inundate until ca. 5350 yr BC (Plater *et al.*, 2000). Early Holocene (ca. 6050-8050 yr BC) sediments of sands and gravels, with some organic deposits, record a period of early Holocene sea level rise in the channels of the newly formed Tees Estuary representing both terrestrial and marine influence in the area (Plater *et al.*, 2000). Shennan (1983) records a SLI point at Thornaby-on-Tees suggesting early Holocene RSL (8450-9050 yr B) to be ~13m below present levels. From ca. 6050-550 yr BC a decelerating rate of rising sea level dominated sediment deposition in the Tees Estuary (Plater and Poolton, 1992). Shennan *et al.* (2000b) proposed a shift in tidal asymmetry in the mid Holocene that may have resulted in increased sediment accumulation between 5850-4050 yr BC. The spring tidal range increased from approximately 63% at ca. 6050 yr BC to 90% of its present magnitude by ca. 4050 yr BC. Within the outer estuary are a series of intercalated peat and tidal mud flat silts and clays from the mid to late Holocene (Horton *et al.*, 1999a). Deposited within these sediments are a series of sand layers where marine sand deposition replaced fine-grained tidal sedimentation between ca. 4350-1550 yr BC (Plater *et al.*, 2000). Terrestrial plant remains overlie tidal silts and sands as the rate of marine inundation decreased through the Holocene resulting in peat formation between 3950-4250 yr BC to 1650-1850 yr BC at Cowpen Marsh (Plater *et al.*, 2000). Brackish and fresh water lagoons existed at locations further inland, such as Billingham Beck, the location of the tidal limit from ca. 5550 yr BC (Plater *et al.*, 2000). Plater and Poolton (1992) record a major short-term change in sedimentation accompanied by a shift to marine diatoms at Cowpen Marsh thought to be a consequence of a storm surge at ca. 3150 yr BC.

From ca. 1050 yr BC the rate of sediment accumulation in the estuary increased. At Saltholme and Portrack Marsh Plater *et al.* (2000) record a transition from saltmarsh to tidal flats and more open marine influence at ca. 850 yr BC. Marine inundation also increased from ca. 1.7 kyr BC (Shennan, 1992) at Cowpen Marsh, previously terrestrially dominated, resulting in brackish to marine conditions (Plater *et al.*, 2000). Plater *et al.* (2000) also suggest that increased sedimentation in the late Holocene is a consequence of vegetation clearance and land use in the Tees Basin. The RSL curve for the Tees is constrained by 30 SLI points (Table 3.3) and at no point within the Holocene was the Tees RSL above present day levels (Shennan *et al.*, 2000c). During the mid Holocene RSL rose from ca. 5m to 1m below present (fig. 3.8). Model results suggest that during the late Holocene, the Tees has been subsiding at a rate of 0.38 mm yr^{-1} over the past 4000 years; with a best estimate of 0.17 mm yr^{-1} (Shennan and Horton, 2002).

3.4.4 Saltburn –Whitby (SMP Cell 1d)

Saltburn to Whity is dominated by Jurassic cliffs topped by Quaternary till, dissected by late Holocene sand deposits in small embayments, which, like the County Durham coast, largely do not preserve a record of Holocene RSL change. Shennan and Horton (2002) do not report any SLI points for the North Yorkshire coast. Considering the evidence from further north, as discussed above and SLI points reported in the Humber, it is likely that RSL rose rapidly in this area during the Holocene from approximately 15-20m below present at the Pleistocene-Holocene boundary and never exceeded present day levels in the late Holocene. An estimate of relative land subsidence over the last 4000 years in this coastal zone, based upon Shennan and Horton's (2002) modelled results of late Holocene relative land/sea level changes in Great Britain (fig. 3.10), is 0.2-0.5m yr^{-1}.

Site	Laboratory code	^{14}C age ± 1σ	Change in RSL (m)	Calibrated age (yr BC)			Longitude W	Latitude N
				Maximum	Mean	Minimum		
Tees sea-level index points								
Billingham Beck, BBC3	AA27200	7035 ± 75	-6.04 ± 0.21	6018	5903	5739	117559	5435341
Billingham Beck, BBC3	AA27201	7405 ± 70	-6.34 ± 0.21	6406	6277	6086	117559	5435341
Billingham Beck, BBC3	AA27199	6160 ± 70	-4.54 ± 0.21	5292	5107	4858	117559	5435341
Billingham Beck, BBC3	AA27198	6615 ± 70	-5.31 ± 0.21	5663	5557	5392	117559	5435341
Billingham Beck, BBC6	AA27202	6350 ± 95	-6.08 ± 0.22	5480	5327	5061	117506	5435179
Cowpen Marsh 01	SRR3706	7065 ± 45	-5.22 ± 0.22	6012	5933	5814	112580	5436510
Cowpen Marsh 01	SRR3705	5250 ± 45	-3.02 ± 0.21	4221	4068	3971	112580	5436510
Cowpen Marsh 01	SRR3704	3450 ± 45	-1.36 ± 0.21	1883	1767	1635	112580	5436510
Greatham Tioxide pipeline	HV18300	5830 ± 95	-2.45 ± 0.22	4905	4684	4459	112500	5437400
Greatham Tioxide pipeline	HV18299	4310 ± 70	-1.87 ± 0.22	3301	2945	2674	112500	5437400
Hartlepool Bay-4	HV18061	3685 ± 75	-1.36 ± 0.22	2290	2075	1879	111480	5440390
Hartlepool Bay-4	HV18062	3500 ± 75	-1.06 ± 0.21	2024	1825	1630	111480	5440390
Hartlepool Bay-4	HV18064	2865 ± 75	-0.78 ± 0.21	1258	1049	838	111480	5440390
Hartlepool Bay-4	HV18063	3210 ± 80	-1.28 ± 0.21	1684	1489	1306	111480	5440390
Holme Fleet Belasis Beck HFBB5	AA27203	7240 ± 90	-6.3 ± 0.21	6334	6105	5898	114010	5436196
Holme Fleet Belasis Beck HFBB11	AA27211	5165 ± 75	-3.43 ± 0.4	4220	3971	3784	114152	5436196
Holme Fleet Belasis Beck HFBB11	AA27210	2895 ± 75	-2.21 ± 0.21	1311	1091	895	114152	5436196
Portrack Marsh PMC5	AA27205	5710 ± 140	-5.74 ± 0.21	4900	4567	4254	116505	5434064
Portrack Marsh PMC5	AA27197	6160 ± 70	-5.62 ± 0.21	5292	5107	4858	116505	5434064
Portrack Marsh PMC5	AA27196	2710 ± 75	-0.84 ± 0.21	1043	881	766	116505	5434064
Seaton Carew Funfair	HV18298	4130 ± 95	-0.8 ± 0.25	2893	2705	2470	111070	5439250
Thornaby	HAR3711	9680 ± 110	-13.11 ± 0.24	9288	9035	8739	116460	5433360
West Hartlepool 11A	HAR3714	6050 ± 90	-4.68 ± 0.25	5226	4955	4722	111480	5440500
West Hartlepool 19	Q2663	4945 ± 50	-2.8 ± 0.24	3911	3730	3642	111320	5440290
West Hartlepool 19	Q2661	5975 ± 120	-3.41 ± 0.25	5208	4870	4551	111320	5440290
West Hartlepool 19	Q2660	6180 ± 100	-3.26 ± 0.25	5333	5121	4811	111320	5440290
West Hartlepool 19	Q2664	4770 ± 50	-3.02 ± 0.24	3649	3566	3377	111320	5440290
West Hartlepool 19	Q2662	5530 ± 90	-3.23 ± 0.24	4553	4379	4053	111320	5440290
West Hartlepool 2	HV3459	5240 ± 70	-2.97 ± 0.25	4304	4072	3823	111260	5440280
West Hartlepool 3	HV4712	5285 ± 120	-4.28 ± 0.24	4348	4120	3801	111490	5440500

Table 3.3 Summary of SLI points and limiting data from the Tees. RSL is calculated as altitude minus the reference water level. The RSL error range is calculated as the square root of the sum of square of altitudinal error, sample thickness, tide level error and indicative range.

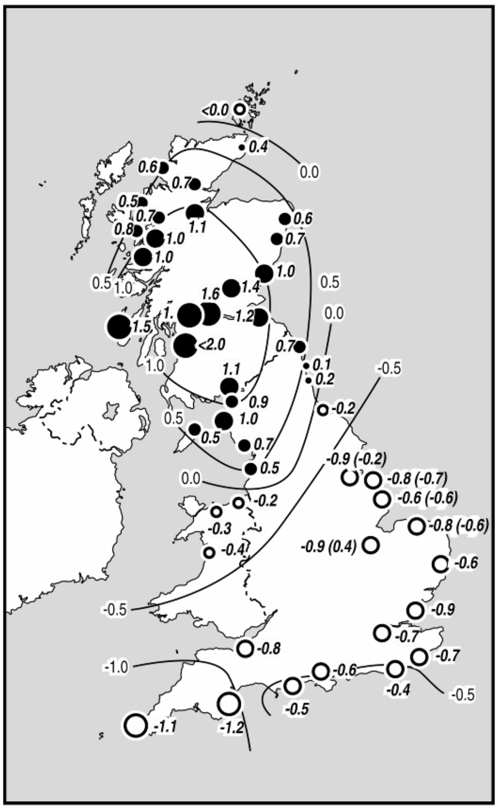


Figure 3.10 Late Holocene relative land-/ sea-level changes (mm yr^{-1}) in Great Britain from Shennan and Horton (2002). Positive values indicate relative land uplift or sea-level fall, negative values are relative land subsidence or sea-level rise. Figures in parentheses are the trends that take into account modelled changes in tidal range during the Holocene. Contours are drawn by eye as a summary sketch of the spatial pattern of change

3.5 Holocene palaeogeography of the North Sea

There is a close link between the Holocene history of the NE coast and the post-LGM transgression of the continental shelf in the North Sea. At present the only reconstruction of the Holocene palaeocoastline of the North East is from Shennan *et al.* (2000b) models of the North Sea, which we present within this section. Their models combine SLI points from the eastern coast of England and information from offshore cores with geophysical models incorporating ice-sheet reconstructions, earth rheology, eustasy and hydro- and glacio-isostasy, and estimations of previous tidal regimes to develop and test reconstructions of the palaeogeography of the North Sea. This then provides estimates of the location of the palaeocoastline through the Holocene as shown in Figure 3.11. The model ages are reported as median calibrated years BC.

3.5.1 9572 yr BC palaeogeography

At the start of the Holocene the North Sea coastline comprises the area of the Norwegian Trough and a western embayment extending south to the latitude of Flamborough Head (fig.3.11). The coastline is only a little east of the present coast of North East England. In most of Scotland there is the prediction of intertidal sedimentation inland of the present coast.

There are few observations of this age to test this reconstruction. The sea-level index point dated 11162-11012 yr BC from core 53/+00/889 off Flamborough Head (Shennan *et al.*, 2000b) indicates that the western embayment (fig. 3.11) was inundated well before 8050 yr BC. Marine shell material from the Geordie Trough, off NE England, dated at 8748-8356 yr BC (Harland and Long, 1996), also accord with this reconstruction. Freshwater peats from the Well Bank, ENE of Norfolk, with Late Devensian pollen assemblages, dated to 11320-11179 yr BC in core 53/+02/1495 (Shennan *et al.*, 2000b), and from deep river channels in the Fenland (Waller, 1994), simply concur with the prediction of those areas being inland of any tidal influence.

3.5.2 8162 yr BC palaeogeography

By this time the western embayment had extended south, to off Spurn Point, and then east to produce a shallow estuary to the south of the Dogger Bank (fig. 3.11). This reconstruction is similar to that proposed by Jelgersma (1979). The earliest sea-level index point from the river Tees (Table 3.3) agrees with the prediction that the coastline of North East England lay very close to the present, with tidal waters extending into the estuary. The five index points from the Well Bank, off Norfolk (cores 53/+02/1398, 1399, 1400, 1496, 1947) (Shennan *et al.*, 2000b), dated between 8452 and 7974 yr BC lie at the head of the bay that extends north of the Strait of Dover. Core 53/+01/1567 records the extension of the bay to the northwest at 7963-7979 yr BC as sea level continues to rise.

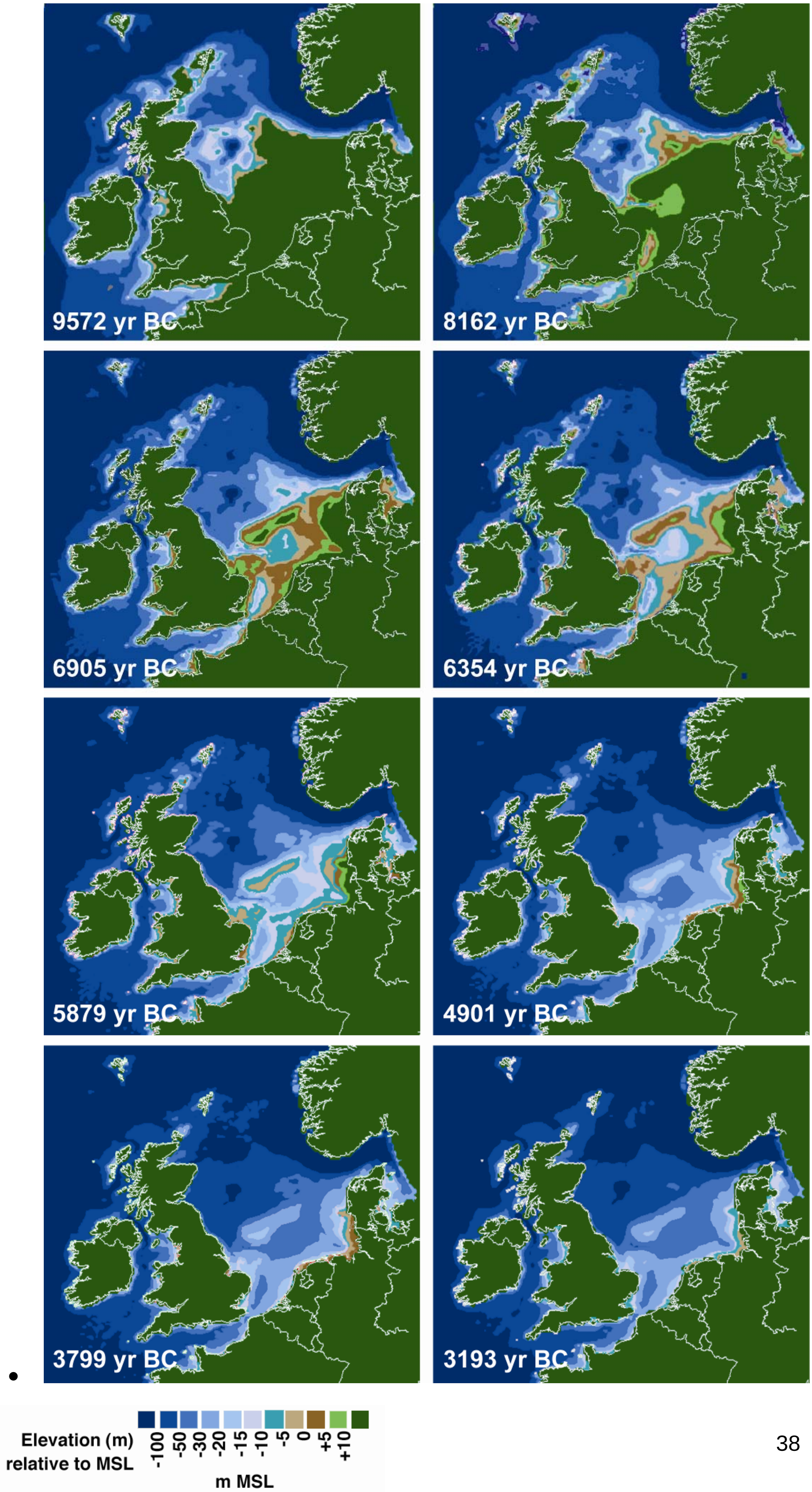
3.5.3 6905 yr BC palaeogeography

The reconstruction indicates that the North Sea was now connected to the English Channel via a narrow strait ENE of Norfolk and west of Texel (fig. 3.11). The Dogger Bank becomes cut off from the European mainland during high tides. It seems likely that the tidal regime around this time in the southern North Sea could be rapidly changing as the different tidal channels developed. The sea-level index point from the north side of the Dogger Bank, dated 7238-7057 yr BC in core 55/+02/213VE, (Shennan *et al.*, 2000b) shows good agreement with the model predictions, as do the observations from Northumberland–South and the River Tyne (Table 3.2). The model suggests that the first incursion of tidal water to the north Norfolk coast is from the east, from the deeper water eventually connecting to the English Channel. To the north there is still land above highest tides. The samples (Shennan *et al.*, 2000b) from cores 53/+01/1530 and 52/+01/2699, 7034-6824 yr BC and 6500-6379 yr BC respectively, and that from Warham Marshes in north Norfolk, 6465-6256 yr BC (Shennan et al., 2000b), record the continuing transgression over the next 500 years.

3.5.4 6354 yr BC palaeogeography

The model predicts that by 6354 yr BC all the estuaries of the east coast could have some

Figure 3.11 Palaeogeographical reconstructions of North West Europe from Shennan et al. (2002b). Elevations (meters) relative to Mean Sea Level (MSL); depths below MSL are given as negative. Ages given as median calibrated years BC.


9572 yr BC
8162 yr BC
6905 yr BC
6354 yr BC
5879 yr BC
4901 yr BC
3799 yr BC
3193 yr BC
Elevation (m)
relative to MSL
-100
-50
-30
-20
-15
-10
-5
0
+5
+10
m MSL

•

tidal influence from high tides. The ages of the first sea-level index points for the Humber estuary, Lincolnshire Marshes, Fenland and Norfolk Broads (Shennan *et al.*, 2000b) are from well-developed salt marsh peats rather than indicators of the first saline water into an estuary and their younger ages are not at odds with the model. There are extensive intertidal flats from Flamborough Head to north Norfolk. The channel separating north Norfolk from mainland Europe is only 5 to 10m deep at mid-tide and the channel between the Dogger Bank and mainland Europe was less than 5m below MSL in parts (fig. 3.11).

3.5.5 5879 yr BC palaeogeography

Wide intertidal areas are still predicted for the areas off the Humber estuary, Lincolnshire Marshes, Fenland and north Norfolk (fig. 3.11), which agree with the sea-level index points based on saltmarsh peats for these areas (Shennan *et al.*, 2000b). The Dogger Bank is only exposed at low tide.

3.5.6 4601 yr BC palaeogeography

By this time the Dogger Bank is submerged at all stages of the tide and the western margins of the North Sea are close to or inland of the present coastline (fig. 3.11), as indicated by the many index points available (Shennan *et al.*, 2000b).

3.5.7 3799, 3193 and 1228 yr BC palaeogeographies

From ~4000 yr BC to the present, relative sea level increases gradually in the western North Sea south of the River Tyne, but rises to above present to the north to a maximum after ~3500 yr BC (Shennan *et al.*, 2000c). Such changes in water depth and coastline configuration do not show clearly at the resolution of the reconstructions illustrated (fig. 3.11) and reference should be made to the local histories made in Section 3.4.

3.5.8 Tidal changes during the Holocene

The approach to tidal modelling adopted by Shennan *et al.* (2000b) is very similar to previous studies whereby models developed for the present (Flather, 1976), predict tides for past bathymetries and coastline configurations (e.g. Austin, 1991; Hinton, 1992). The major differences in comparison to previous studies is the use of bathymetries and coastlines based on modelling of differential isostatic rebound and including up to twenty-six tidal harmonics, rather than one or six (Austin, 1991; Hinton, 1992; Hinton, 1995; Hinton, 1996).

The models predict an increase in tidal range for the western North Sea during the Holocene. This coincides with the time of major changes in palaeogeography (fig. 3.11). At 6050 yr BC the coastline only lay near to the present coast of Yorkshire, north of Flamborough Head, with a tidal channel extending south towards the present Wash (fig. 3.11). Off Flamborough Head high tide level was *c.* 1.6m above mean tide level at 6050 yr BC, rising to 1.9m at 5050 yr BC, 2.1m at 4050 yr BC and only a little higher at 3050 yr BC. Holocene changes in high tide level for Northumberland-South and the Tees Estuary both record an increase in high tide level, and tidal range, through the Holocene. For example, the MHWST for Northumberland-South increases from 0.91m above RSL at 6050 yr BC to 1.88 m above RSL at AD 950. These model results allow a fuller regional picture of the RSL and coastal changes that occurred during the Holocene in NE England.

3.6 Potential for further work

The wide range of data presented above has allowed the reconstruction of Holocene coastal evolution and RSL change along the NE coast. There are areas however, where further work would improve understanding of local and regional horizontal changes in the palaeocoastline. The contemporary geology of the NE coast is well documented by the British Geological Survey (2007). To be able to provide a more comprehensive map of local and regional palaeocoastline position beyond that produced by Shennan *et al.* (2000b), requires a series of Holocene geomorphology maps to be produced as to how the geology has altered over time in response to RSL changes.

A limitation of palaeoenvironmental data is its limited use in the late Holocene when intensive anthropogenic activity on the landscape disturbs the environmental record. Further work is required to combine historical records of coastline configuration and environmental change with evidence derived from the landscape to provide additional RSL data for the late Holocene period before instrumental monitoring comes into use. Combining both these geological and historical records will improve estimates of palaeogeography of the NE coast.

Increasing the spatial and temporal resolution of vertical and horizontal changes of the coast will also have implications for the modelling of coastal change. Shennan *et al* (2000b) acknowledge that there is little justification in increasing the sophistication of models if there are no data to test their output. Additionally, detailed palaeogeography will aid future modelling work where the next steps are to investigate sediment movement, particularly with regard to tidal changes through estuarine environments and bays such as those at Druridge and Hartlepool. Shennan *et al.* (2003) have already demonstrated such possible improvements by using an integrated approach to higher resolution coastal modelling in the Humber Estuary.

3.7 Conclusions

During the Holocene the NE coast experienced varied RSL. From the late Upper Palaeolithic to the mid Holocene all areas of the coast was subjected to marine transgression due to global eustatic sea level rise as a consequence of the melting of the ice sheets of the LGM. Shennan *et al.*'s (2000b) model results of the palaeogeographical changes of the North Sea show the degree of horizontal coastal movement since 9050 yr BC to be limited compared to elsewhere along the east coast of Great Britain, though still in the order of several kilometers. The vertical changes have been quite large with sea level rising from *c.*20m below present levels at the start of the Holocene. During the mid Holocene sites along the north Northumberland coast experienced sea level up to 2.5m above present day levels. From north to south the highstand level reduced with RSL not surpassing present day levels south of the Tees. In addition, the environmental and modelled data suggests that the mid Holocene high occurred later along the southern NE coast. In the late Holocene, RSL changes are dominated by the spatially varied response to isostatic adjustment with areas north of the Tyne uplifting and to the south subsiding. The late Holocene also offered the primary period of dune development, particularly during periods of climatic cooling and static or falling sea levels. It is clear that during the Holocene there were several high-energy coastal events depositing coarse-grained material at several locations. The differential geology from Berwick to Whitby results in a varied response to these Holocene sea level changes with the contemporary coast consequently dominated by varied environments including cliffs, rock platforms, bays, salt marshes or dune systems. Overall, the Holocene coastal history of the NE coast is characterised by a terrestrial regression forcing coastal communities further inland over time.