Marine Estate Research Report

Historical changes in the seabed of the greater Thames estuary

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The Crown Estate – Caird Fellowship Research Project

Final Report – July 2008

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Published by The Crown Estate on behalf of the Marine Estate

The basis of this report was work undertaken by Helene Burningham, as The Crown Estate- Caird research Fellow in 2007, under the joint scheme between The Crown Estate and the National Maritime Museum (NMM) Greenwich. Assistance with the research was also provided by Dr Jonathan Potts, formerly at NMM but now at the University of Portsmouth.

This report is available from The Crown Estate website at www.thecrownestate.co.uk

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Suggested Citation

Burningham, H. and French, J. 'Historical changes in the seabed of the greater Thames estuary'.

The Crown Estate, 54 pages

ISBN: 978-1-906410-04-9

First published 2008

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i. Executive Summary

This report presents summary results from The Crown Estate – Caird Fellowship research project at the National Maritime Museum to investigate the geomorphic history of the seabed and associated features within the greater Thames estuary within a region of over 5000km^2 bounded by Aldeburgh (Suffolk), Southend-on-Sea (Essex) and Margate (Kent). Bathymetric charts published over the last 400 years have been analysed to derive changes in seabed depth, with particular reference to three main classes of bank and ridge: Type 1 (open shelf ridges) to the east, Type 2A (wide estuary mouth ridges) within the Thames estuary and Type 3A (headland-associated banner banks) to the north.

Differences in datum between charts present a problem since there is no consistency in the absolute vertical datum. Accordingly, depths were converted to a common datum (Ordnance Datum Newlyn) using a spatially-varied conversion factor that takes account of the complex tidal regime of the greater Thames estuary. Historical change in chart datum due to sea-level rise is estimated at 1.9-2.4 mm yr^{-1}, and it is suggested that seabed features that do not exhibit vertical accretion greater than or equal to this rate are unlikely to be keeping pace with historical sea-level rise. As a basis for a preliminary investigation of temporal trends, linear regression was performed on the entire bathymetric dataset. Results were filtered to identify those features exhibiting a significant linear trend, and those where segmented linear trends were apparent (in which case stepwise regression was performed).

Historical changes in seabed elevation, derived from the analysis of published charts, are spatially and temporally variable. There is evidence of progressive long-term vertical accretion and degradation, in addition to stepped or cyclic variability. In many cases the changes observed are associated with shifts in bank and channel configuration. This is particularly true of *estuary mouth banks* within the central Thames estuary. Here, features in close proximity exhibit opposing trends where channels and banks migrate and go through processes of constriction, attachment and detachment. The seabed around the southern extents of these estuary mouth banks is deepening whereas that to the north appears to be shoaling. The northward extension of Sunk and Long Sand Heads does suggest a general northeasterly shift in these entire features, which would explain the general deepening/shoaling trends observed. Kentish Knock however, is systematically accreting and configuration changes suggest the feature is at the very least sustaining its footprint.

The Suffolk shoreface (Harwich to Orfordness) appears to show an overall deepening over the history reported here. The depositional features, which are mainly *headland associated* banks, do not display a clear trend, and there is evidence to suggest that a more significant change is occurring in their lateral extent and orientation with respect to the shoreline. Aldeburgh Napes appears to be disconnected from sediment supply and is gradually being denuded, whilst the Onion-Aldeburgh Ridge system displays a possible sediment source-supply coupling.

The general history of the offshore *shelf ridges* is not consistent, and there is no evidence that the Gabbards have changed over their documented history. The Galloper and the unnamed bank to the north suggest a positive trend, but the narrowness or spatial inconsistency of these features suggests that this may simply be a factor relating to changes in survey resolution.

ii. Glossary

Chart datum (CD)

Chart datum is the level to which depths and intertidal heights on bathymetric charts are referred. It is usually defined in terms of a specific low tide level (such as LAT or MLWS). The geodetic level of CD is therefore tide-regime (and therefore location) dependent.

Headland-associated banner banks

Bathymetric higsh on the shoreface found where a resistant headland causes acute changes in shoreline orientation. The bank features are formed by converging littoral transport pathways. Defined as Type 3A features in the banks and ridges classification of Dyer & Huntley (1999).

LAT

Lowest Astronomical Tide is the lowest predicted water level at a location, under average meteorological conditions. This varies with tidal regime and therefore location.

Linear regression

Analysis of a linear (straight line) relationship between two variables, based on a least-squares fit, and defined by coefficients that describe the intercept and slope of the line. Various statistics define the model (regression) output, including goodness of fit (r^2: the proportion of variability in the data that can be described by the model) and confidence (p-value: probability that the coefficients describing the model are not based on chance).

MLWS

Mean Low Water Springs is the average low water level occurring during spring tides. This varies with tidal regime and therefore location.

Open shelf ridges

Bathymetric highs on the shoreface not associated with estuary mouth tidal currents or littoral sediment transport. These features may form and grow as a result of excess sand supply, or may be maintained in size by equilibrium along a sediment transport pathway, or they may simply be the remains of a relic deposit. Defined as Type 1 features in the banks and ridges classification of Dyer & Huntley (1999).

Ordnance datum (OD)

Height reference point defined by mean sea level as measured at Newlyn in Cornwall between 1915 and 1921. OD is a consistent height datum across the UK. Topography on Ordnance Survey maps are referenced to OD.

Trend surface (ArcGIS Spatial Analyst)

An interpolation function in ArcGIS Spatial Analyst that fits a low-order polynomial surface to the input sample points. Used in a GIS, this enables the spatial modelling of a particular variable. The same result is obtained from a multiple linear regression between x, y (spatial component) coordinates and a third variable.

Wide estuary mouth ridges

Bathymetric highs on the shoreface formed form as a result of the mutual evasion of ebb and flood tidal currents causing bed load convergence. These banks develop in the convergent setting between respective ebb and flood channels. Defined as Type 2A features in the banks and ridges classification of Dyer & Huntley (1999).

1. Introduction

This report disseminates initial results from The Crown Estate – Caird research project at the National Maritime Museum to investigate the geomorphic history of the seabed and associated features within the greater Thames estuary (Figure 1), covering an area of over 5000km^2 between Aldeburgh (Suffolk), Southend-on-Sea (Essex) and Margate (Kent). The report presents the historical changes in seabed feature depths over the last 400 years, as derived from analysis of published bathymetric charts.

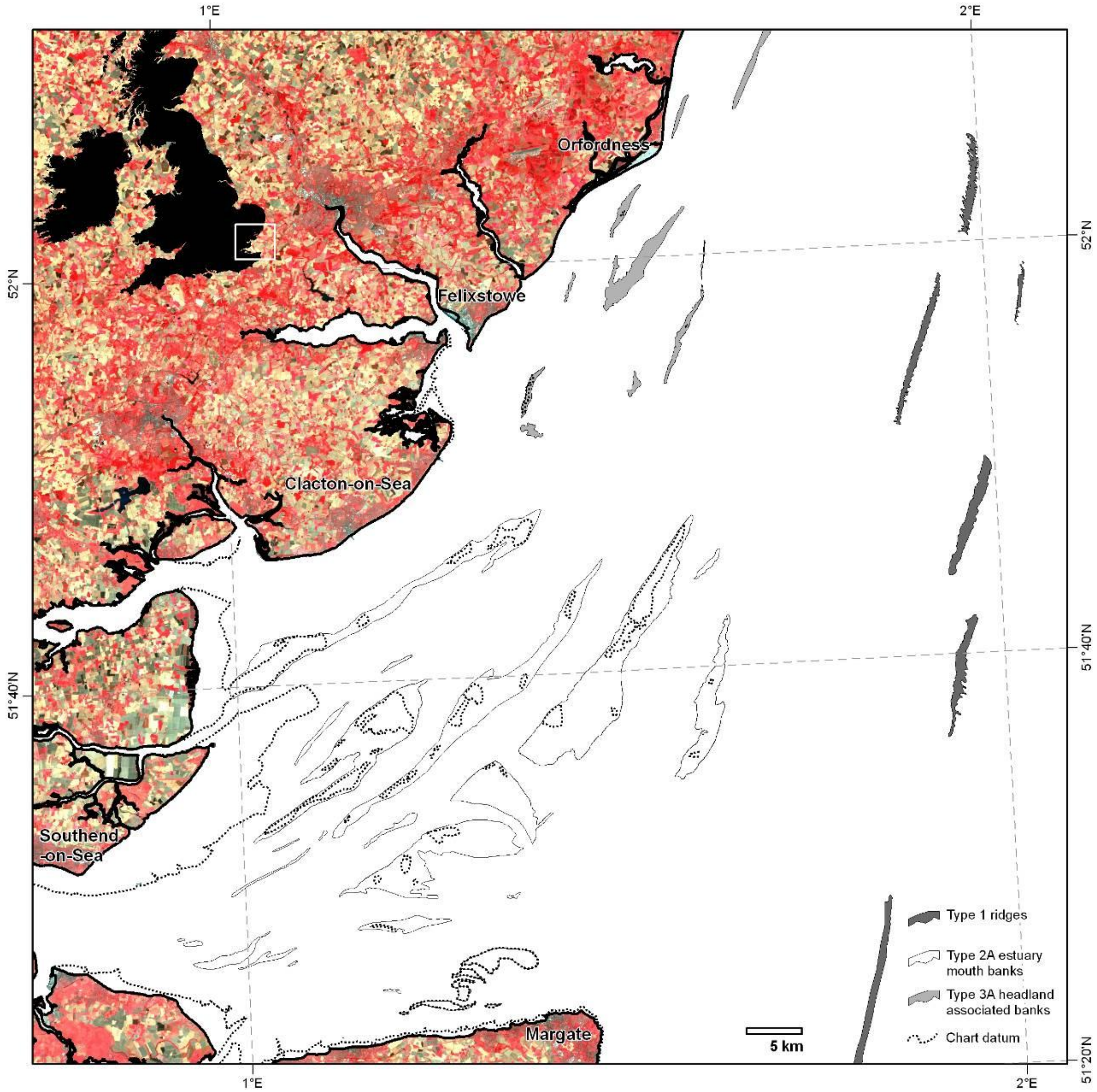

Figure 1 The greater Thames estuary study area, showing the main bank features. Bank and ridge typology based on Dyer & Huntley (1999).

The seabed features within the greater Thames estuary cover the three main classes of banks and ridges defined by Dyer & Huntley (1999): Type 1 (open shelf ridges) to the east, Type 2A (wide estuary mouth ridges) within the Thames estuary and Type 3A (headland-associated banner banks) to the north. Other features include sub-tidal reefs formed from resistant layers in the underlying London Clay, inlet-associated sediment shoals, between-bank channels (‘deeps’) and cross-bank channels (‘swashways’ or ‘spitways’). Historically, the gross framework and arrangement of these features has changed very little. There is some consensus in the scientific literature that some banks and ridges are associated with geological inheritance, but that contemporary tidal and wave driven sediment transport is responsible for most of the contemporary features.

2. Data and technical approach

2.1. Data sources

More than 170 charts, atlases and pilots covering the greater Thames estuary were examined, ranging from present UK Hydrographic Office Admiralty Charts to the 17th century sea atlases of Blaeu, Seller, Thornton and Greenville Collins. A full list of charts consulted is provided in Appendix 1a (independent surveyors and chart makers) and 1b (Admiralty charts).

Seabed features (banks and channels) were examined across the region. A total of 162 features were identified across the charts, some of which were present on most charts, whilst others only present on early or most recent charts. There has been a relatively consistent suite of bank and channel names over the last 400 years, and identifying individual features was unproblematic (Table 1). Appendix 2 provides a list of all features considered, and notes the depth measure that was obtained from the charts.

Table 1 Changes in naming conventions of selected passes and banks.

	Goldmer Gat[1]		Hallidays Rock Flats[2]		Aldeburgh Napes[3]		Bawdsey Bank[4]
1671	Goldermore Gatt	**1786**	Holidays	**1635**	Aelburger Knock	**1671**	Baldze Sand
1682	Goldermores Gatt	**1797**	Holydays	**1693**	Alborough Knaps	**1693**	Baudsey Sand
1693	Goldermores Gat	**1830**	Hollidays	**1693**	Alborough Knapes	**1693**	Bawdsey Sand
1693	Goldermors Gat	**1858**	Halliday Banks	**1786**	Aldborough Knap	**1738**	Baudzey
1738	Gouldermor	**1885**	Halliday Rock Flats	**1797**	Aldborough Knaps	**1786**	Baudsey
1786	Goldermores Gat			**1824**	Aldborough Napes	**1797**	Baldsey Sand
1797	Goldermans Gatway			**1918**	Aldeburgh Napes	**1797**	Baudsey Sand
1797	Passe de Goldermores					**1805**	Baudsey
1805	Goldmeres Gat					**1824**	Bawdsey Sand
1824	Goldmers Gatway					**1830**	Baudsey
1830	Goldmer's Gatway					**1847**	Bawdsey Bank
1847	Goldmer Gat						

[1]Goldmer Gat is a pass between Gunfleet Head and West Rocks
[2]Halliday Rock Flats covers the intertidal region south of Harwich, near the entrance to Hamford Water
[3]Aldeburgh Napes is a sand bank that lies about 6.5km offshore from Aldeburgh
[4]Bawdsey Bank is located 8.5km offshore from Shingle Street/Orford Haven

Maximum and minimum depths are the most comparable measures between historic charts, particularly where issues of geographic scale and positioning preclude direct spatial overlay of pre-1800 charts. Many of the early charts and atlases comprise very little bathymetric data, but at the very least provide some indication of minimum depths over banks and within cross-bank channels, and confirmation of continuous deep water suitable for safe navigation. As such, banks, shoals and cross-bank channels were assessed in terms of their minimum depths and between-bank channels in terms of their maximum depths. This enabled identification of the following behaviour: accretion (vertical growth of banks), breakdown (vertical denudation of banks), shoaling (of channels) and entrenching (vertical accretion of banks and deepening of between-bank channels). Soundings were given in fathoms, feet or metres: all were converted to metres.

Intertidal information is generally limited on pre-1900 charts and almost non-existent on pre-1800 charts. A number of features across the greater Thames estuary have a significant intertidal structure, and this is not reflected in the early charts. In many situations, the information is limited to a simple note that a feature was ‘dry’. This means that direct comparison with more recent ‘real’ intertidal heights is not possible, although a qualitative recognition of changes between inter- and sub-tidal states is possible.

2.2. Datum considerations

The chart datum provided on each published bathymetric chart provides the datum to which the soundings are referenced. In the dataset considered here, Admiralty surveys since 1968 have used Lowest Astronomical Tide (LAT) as chart datum. Prior to this, the level 1’ below MLWS (Mean Low Water Springs) was the most commonly cited measure of chart datum. In addition to these dominant measures, MLWS, MLW (Mean Low Water) and 8” below MLWS were also defined as variants of chart datum. Some earlier charts provide no information relating to the level of chart datum. The appended nature of charting ensured that chart datum could be inferred from earlier surveys where it was clear that data from an earlier survey had been integrated into the later survey. Where an overlap was not evident, it was assumed that the datum of the previous publication had been used.

These differences in datum between charts presents a problem when temporal comparisons are required since there is no consistency in the absolute vertical datum. It was therefore necessary to convert depths to a common datum, in this case Ordnance Datum (Newlyn). The relationship between chart datum and Ordnance Datum (OD) varies geographically, depending on tidal regime, and is a particularly important consideration when moving across a large region like the greater Thames estuary (Figure 2). A simple conversion factor is therefore not appropriate, and it was necessary to develop a spatially-variable conversion factor so that all features across the region could be converted in a consistent and systematic way. This was achieved through a trend surface model. Predicted tidal levels for LAT, MLWS and MLW were collated for all tidal reference stations within the greater Thames estuary (Hydrographic Office, 2000), and levels for 1’ and 8” below MLWS were calculated. These measures were then converted to the common datum of OD Newlyn. Trend surfaces were generated using the Spatial Analyst toolbox in ArcGIS 9.2 to produce a regional model of each chart datum (Figure 3). The conversion factor associated with the specific location of each seabed feature considered was then extracted from the 5 trend surfaces to produce a feature-specific datum-conversion for each version of chart datum. This allowed all feature depths obtained from all charts to be converted to metres relative to the common datum of OD.

For recent charts, chart datum is also attached to specific ports within the boundaries of the charted region. Where a chart comprises soundings from several surveys, information relating to the extent of each survey is provided on the chart, and the relevant port can be acquired on consultation with the original soundings. Had this level of detail been consistent across charts, it would certainly be more accurate to use the port-specific chart datum to OD conversion for each survey. However, this information is rarely given prior to the mid 20th century, and the consistent and systematic conversion process afforded through trend surface modelling was considered to be the best approach.

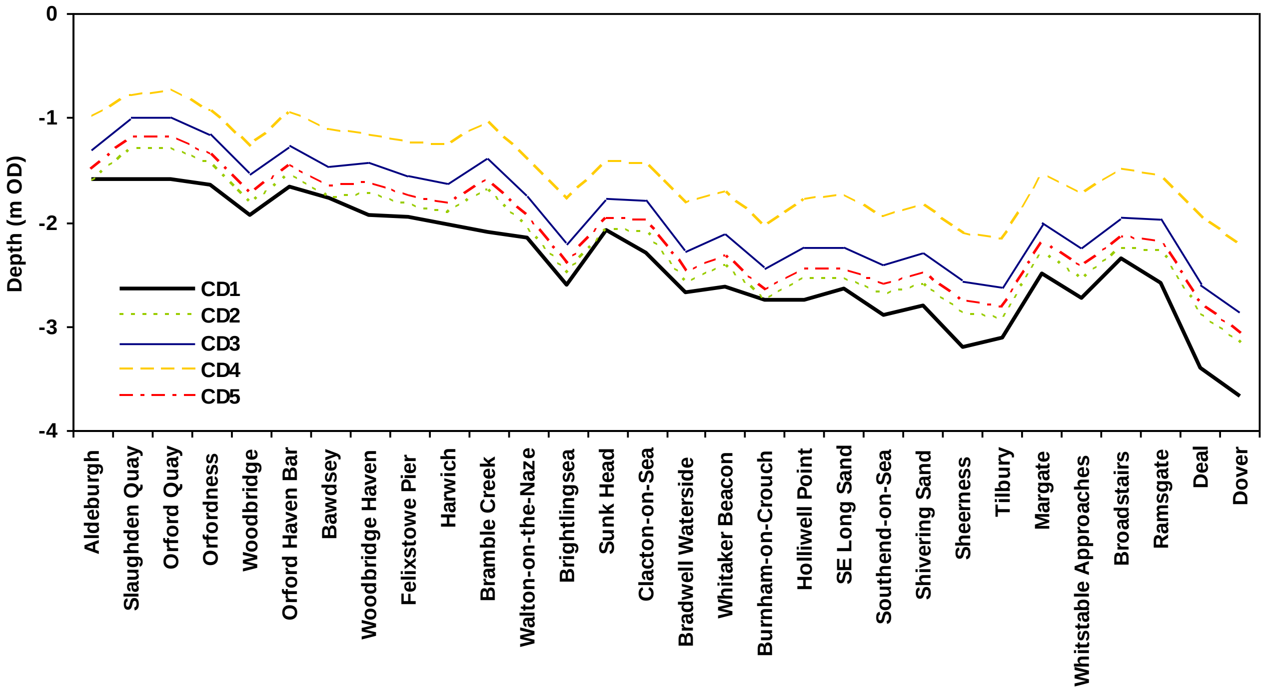

Chart datum	Level
CD1	LAT
CD2	1' below MLWS
CD3	MLWS
CD4	MLW
CD5	8" below MLWS

[LAT: Lowest Astronomical Tides; MLWS: Mean Low Water Springs; MLW: Mean Low Water]

Figure 2 Spatial variation in chart datum across the greater Thames estuary. The 5 levels relate to the definitions of chart datum identified on the 400 year chart series. Measures are derived from Admiralty tide tables (Hydrographic Office, 2000).

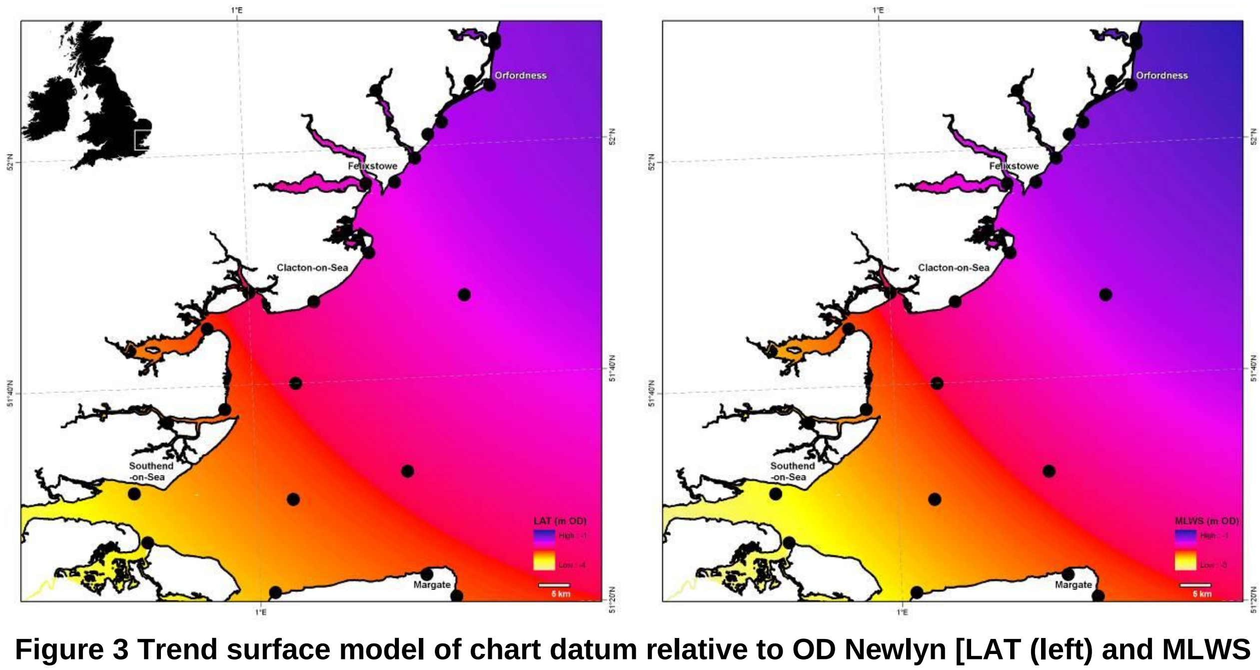

Figure 3 Trend surface model of chart datum relative to OD Newlyn [LAT (left) and MLWS (right)]. Black dots provide the location of the tidal reference stations used to generate the trend surface (Hydrographic Office, 2000).

The feature depths are hence measured relative to approximate mean sea-level (Newlyn OD). The data have not been corrected for any possible changes in relative sea level or tidal regime over the last 400 years. There are various estimates of historical relative sea-level change within this region (Table 2) which suggest on average that relative sea level has been rising by about 2.4 mm yr^{-1} over the last century. Furthermore tidal range has possibly been increasing since the mid-1800s (Amin, 1983; cited in van der Wal & Pye, 2004), with an increase of 1.04$\pm$1.22 mm yr^{-1} (1934-1966) at Southend (Woodworth *et al*., 1991). The historical change in chart datum for the greater Thames estuary could be estimated at 1.9-2.4 mm yr^{-1}, assuming that half the increase in tidal range occurs at the low water level. It is not possible to apply a meaningful correction to depth data to account for these shifts in water levels due to the lack of detail of the geographical variation and insufficient knowledge of the pre-1900 trends. However, it seems reasonable to infer that seabed features that do not exhibit a positive trend of 1.9-2.4 mm yr^{-1} are unlikely to be keeping pace with the historical rise in water level.

Table 2 Estimates of historic trends in sea-level, relevant to this study.

Source	Region	Historic sea-level trends	
Environment Agency	UK (historic)	2.2mm yr^{-1}	RSL rise
Rossiter (1972)*	Felixstowe (1918-1950)	1.6±0.3 mm yr^{-1}	RSL rise
	Southend (1929-1962)	3.4±0.4 mm yr^{-1}	
Woodworth *et al*. (1999)*	Southend (1933-1983)	1.22±0.24 mm yr^{-1}	MSL rise
	Tilbury (1961-1983)	1.58±0.91 mm yr^{-1}	
	Sheerness (1901-1996)	2.14±0.15 mm yr^{-1}	
French & Burningham (2003)	Lowestoft (1964-2001)	2.4 mm yr^{-1}	MSL rise

* cited in van der Wal & Pye (2004)

2.3 Error margin

The problems associated with the use of historical bathymetric charts, and in particular the errors associated with any quantification of change, have been previously reported (van der Wal & Pye, 2003) and there is no need to repeat the detail here. As this study is only concerned with minimum and maximum depths, there is no need to consider spatial errors. However, the combination of poorly defined datums, variable sounding methods, sea-level and tidal regime changes and an unsophisticated trend surface conversion approach, will undoubtedly lead to significant errors in the final 'depths' reported here. Early charts provided soundings to the nearest fathom (1.8m) for depths of 11 fathoms (20.1m) or more, and to the nearest foot (0.3m) for shallower depths. Recent surveys have a vertical resolution of 0.1m. In an analysis of bathymetric change in the Ribble estuary, van der Wal & Pye (2003) suggested that calculated changes within the confidence interval of $\pm$0.58 m could not be classed as significant. This confidence interval encompasses changes in method (e.g. from lead lines to sounding) and units (e.g. metrication) also pertinent to the historical sources considered here, and therefore their analysis of error is an appropriate reference for the work conducted here.

A further source of error is the attachment of specific dates to depths. It is clear throughout these results that soundings may be copied through to charts several years after the survey they are specifically associated with. As it is not clear which soundings are copied and which are 'real', all data are included in this analysis. Over short time-scales, this is produces apparent rapid or episodic changes which are unlikely to be representative of the real character of morphological change. Considering the changes over longer time-scales ensures that the broader behaviour is the primary focus, and that the stepped changes are effectively averaged out.

2.4 Temporal trends

Initial exploration of the data was achieved through qualitative time-series examination of feature depths. Intertidal features that do not have specific height/depth measures (i.e. those defined as ‘dry’ only) were replaced by a measure of chart datum for that specific location (i.e. that the feature at the very least reached chart datum at that time). This allows this information to be included on time-series plots of changing depth over time.

Temporal trends were examined quantitatively through linear regression. For this part of the analysis, the ‘dry’ measures were excluded from the analysis, and only ‘real’ depth/height measures were used. Linear regression was performed on the full time-series and shorter subsets (down to 20 year windows) to allow the objective identification of ‘best’ linear trends within the data, based on a significance threshold defined here as $r^2>0.5$ at the 99% ($p<0.01$) confidence interval. This also ensured that changes in direction and magnitude of trends within the full time-series could be identified. This analytical process was achieved in Matlab through the development of a regression and filtering routine.

For most features, only one significant trend was established (Appendix 3), although not always representing the full time-series. For a small number of features, two or more significant linear trends could be defined which had clear temporal boundaries (Appendix 4). This is a form of segmented or piecewise regression, where the boundaries are termed breakpoints.

The authors are keen to note that linear trends are not always the most appropriate or most significant form describing an association. In this study however, the use of polynomial trends were considered inappropriate (due the behaviour of the extremes of these functions) and preliminary use of logarithmic or exponential trends did not significantly improve the goodness of fit. Nonlinear regression models (e.g. Ferguson *et al*., 2008) were also considered, but these rely on a greater consistency in temporal interval, and the output statistics do not necessarily provide a better definition of trend.

3. Historical changes in seabed features

The greater Thames estuary was divided into 9 regions within which the historical behaviour of associated features was explored (Figure 4). Each region is considered individually.

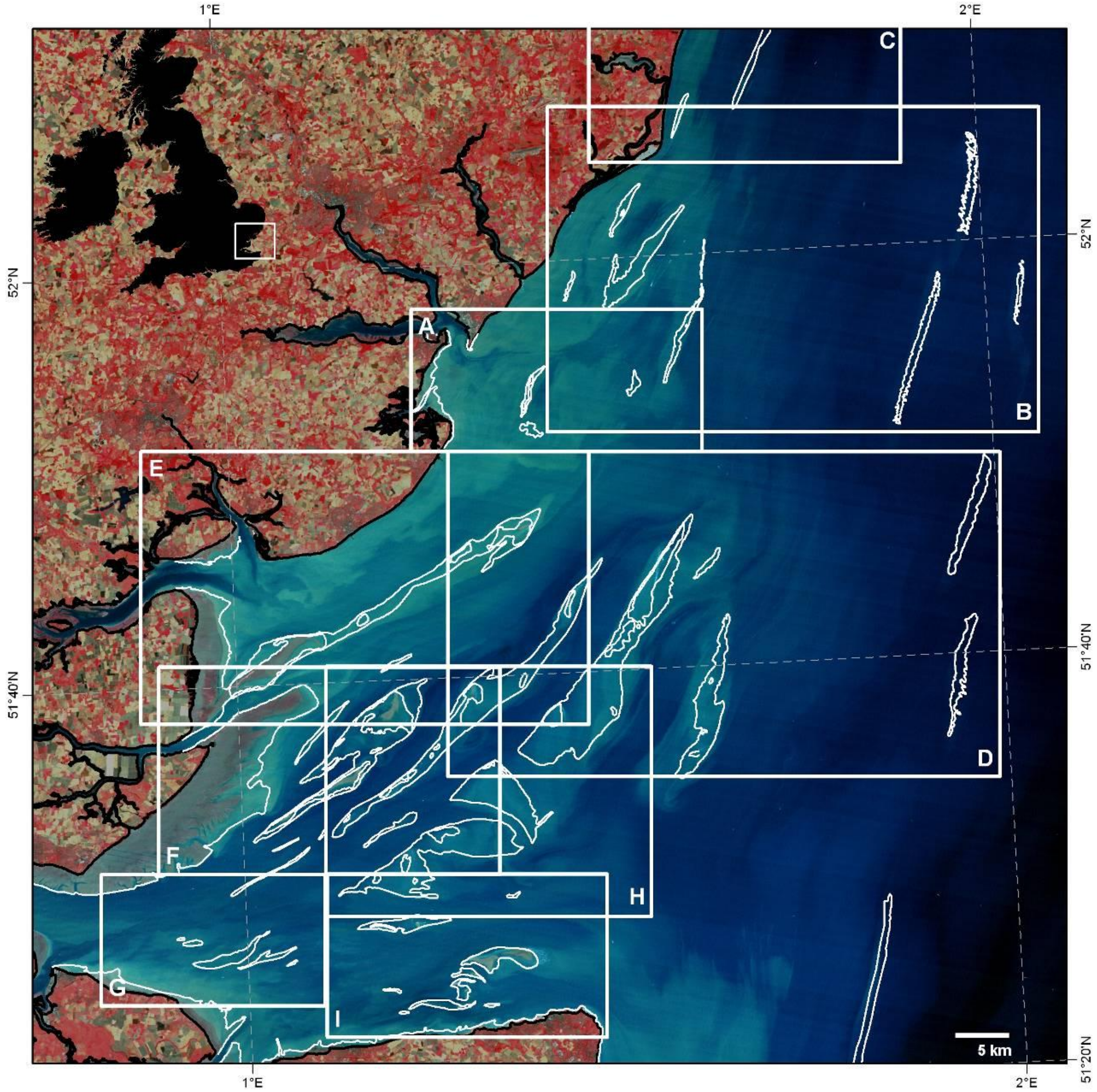

Figure 4 Delineation of the nine regions.

3.1 Area A

Area A relates to the Harwich Haven region (Figure 5) which comprises a number of shallow reefs associated with a resistant bed within the basal London Clay (HR Wallingford, 2002) and, historically, shoals associated with the Stour-Orwell inlet. Harwich Deep Water Channel (HDWC) has been dredged through this region since the 1970s to provide a navigable route to Harwich and Felixstowe Docks.

The Rough Shoals is a broad reef formed in a resistant London Clay bed. It was first noted on a chart in 1780, and was subsequently defined as comprising two distinct bathymetric highs (Upper Rough to the southwest and Lower Rough to the northeast) in the early 1800s. The net change in topography here is minimal (approximately +0.6m) and there is no evidence of any significant long-term trend (Figure 6i). Lower Rough is generally shallower than Upper Rough, and there is some suggestion that Lower Rough built up during the 1800s to reach a high in the 1850-60s, with a reverse trend to an overall low in the 1940s. The magnitude of this change is >2m in total, but this may reflect the fathom-based resolution of early surveys of what appears to be a less important feature.

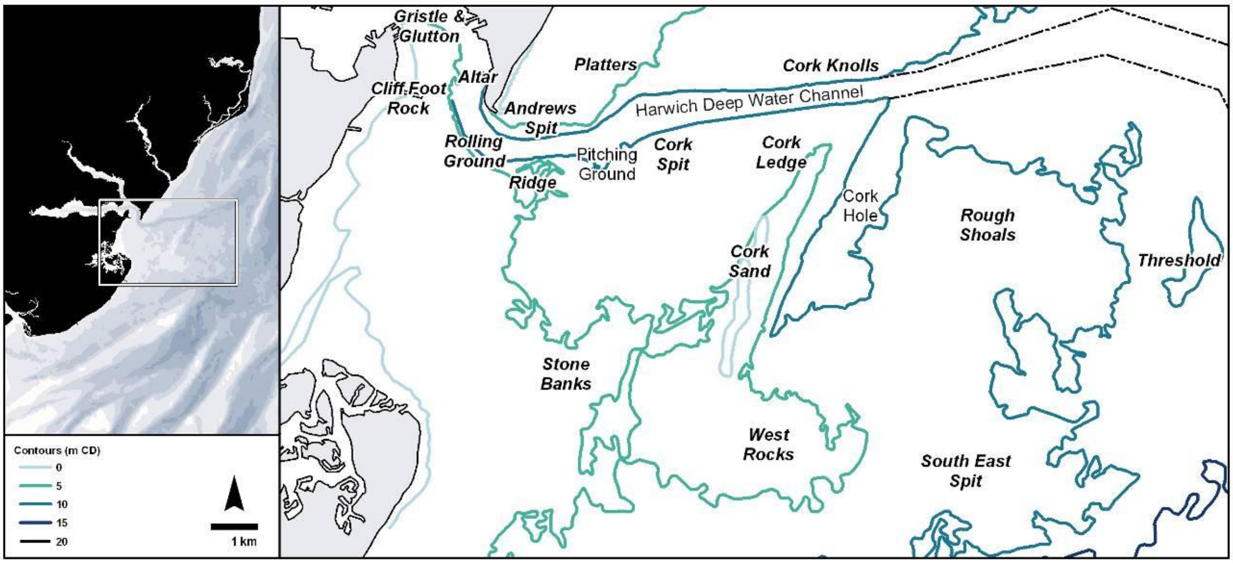

Figure 5 Guide to features present in Area A.

Bordering the current Harwich Deep Water Channel are the Cork shoals and reefs (Figure 6ii). Cork Sand was first present, but not named, on the 1635 Blaeu chart. It was subsequently named and noted as 'dry' on the 1671 Seller chart. It is an intertidal depositional feature and topographic detail was only introduced in the mid- to late-1800s. Despite this, the feature has a long history of being defined as 'dry' and it is therefore clear that Cork Sand has maintained an intertidal presence throughout its' history. The contemporary Cork Spit is the remnant of a historically broader, but small bathymetric high immediately to the east of Harwich Haven. Its area has been approximately halved with the dredging of HDWC, and there is some suggestion of deepening over Cork Spit between the 1960s and 1990s. Cork Knolls and Cork Ledge exhibit clearer temporal trends. Cork Knolls is a weakly defined bathymetric high on the north bank of the HDWC. Despite this, it has been recognised since the 1817 Norie chart, and the history suggests a more-or-less continuous and significant deepening at a rate of 13 mm yr^{-1} between 1817 and the mid-1900s (Appendix 3). Cork Ledge lies between Cork Spit and Cork Sand, south of HDWC and appears to be formed in London Clay. The history of this feature is not consistent, and the pre-1800 surveys suggest depths greater than those noted throughout its subsequent history. If these early surveys are overlooked, the post-1800 history suggests a similar deepening to Cork Knolls at a rate of 13 mm yr^{-1} (Appendix 3).

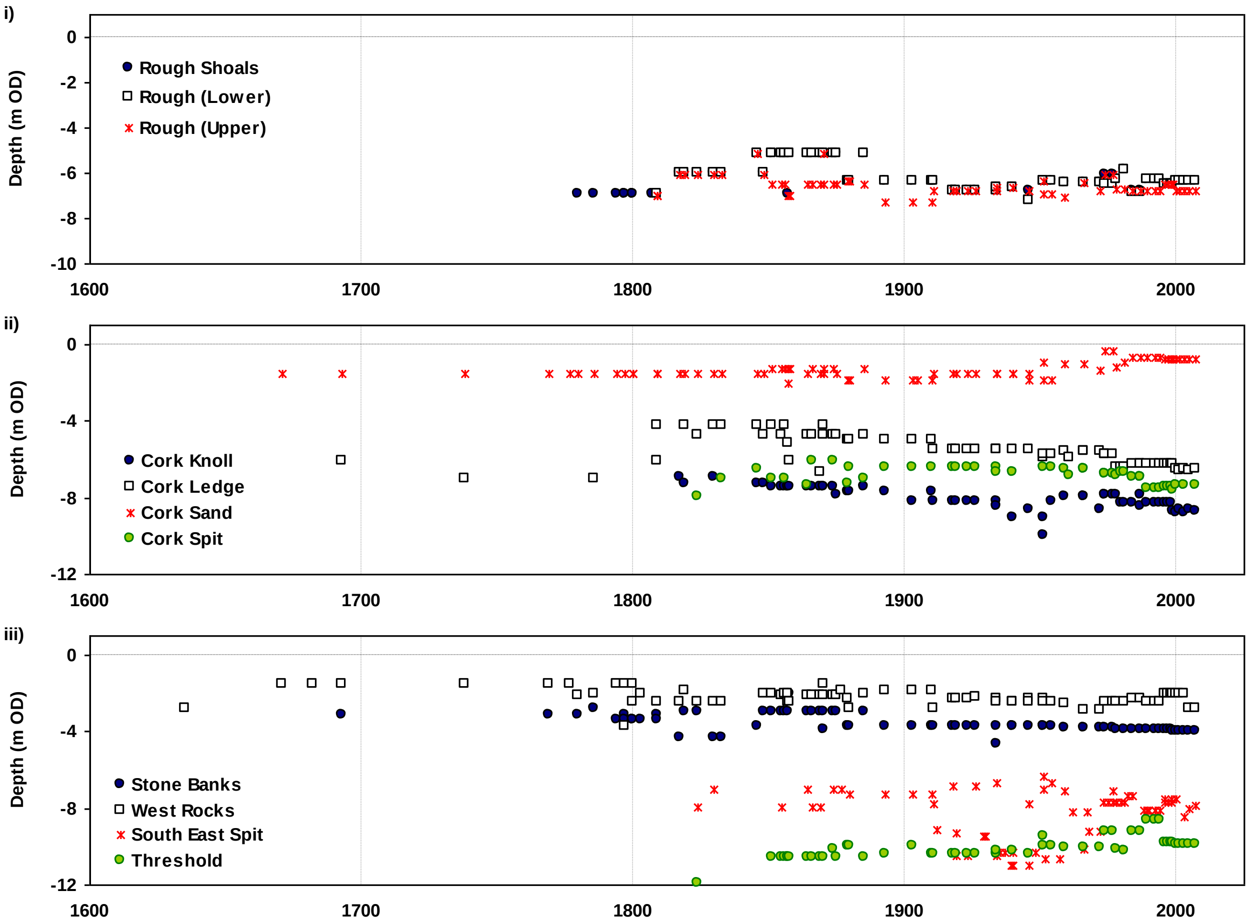

Figure 6 Changes in seabed feature depths in Area A.

Stone Banks, West Rocks, South East Spit and Threshold (Figure 6iii) are formed in the same resistant basement that defines Rough Shoals and that underlies Cork Sand. West Rocks and Stone Banks have the longest recognised history – West Rocks is one of the few named features on the 1635 Blaeu chart. Both these features show very little change over the last 400 years. Importantly, West Rocks is defined as being 'dry' on most of the pre-1800 charts, yet since 1800 the feature has depths up to a metre over it at MLWS. Stone Banks is slightly deeper, and there is some hint of a deepening through the 20th century, but this trend is not statistically significant. South East Spit is a very broad and variable feature: the mixed history presented is a consequence of its poorly defined spatial extent rather than any specific changes in bed level. Threshold is the most easterly feature associated with the London Clay platform in this region, and is separated from the southern extent of Shipwash (South Ship Head) about 3km to the west by HDWC. This feature exhibits a consistent and significant vertical growth until the late 20th century of 8.9 mm yr^{-1} (Appendix 3).

There are a number of features associated with the Stour-Orwell inlet, some of which have disappeared with the increasing port and dredging activity in the area. Glutton, Gristle and Altar are historic shoals that existed within the main inlet: as can be seen in Figure 6iv, these features have gone by the mid- 20th century. Glutton appears to follow a vertical lowering trend of 31.3 mm yr^{-1} until 1900 (Appendix 3). Analysis of the Altar record suggests that the feature was decreasing in height at a rate of 3.1 mm yr^{-1} until the 1850s, and disappeared rapidly toward the end of the 19th century. Cliff Foot Rock has persisted within this context due to its slight offset from the main channel, but has been decreasing from inter- to subtidal at a rate of 8.7 mm yr^{-1} (Appendix 3).

Rolling Ground (Figure 6v) describes an area that historically comprised a subtle, but undulating bathymetric high within the Stour-Orwell inlet, which presented problems for navigation to Harwich. Again, the development of HDWC means that this feature is no longer present, but there is a suggestion that the region shallowed at the beginning of the 19th century. Andrews Spit and Platters are features associated with the Languard-Felixstowe foreshore. Their early history suggests that these features were entirely intertidal, but since the mid- 19th century, Platters has remained within a metre of MLWS whilst Andrews Spit has persisted at around this low water mark. The remaining bathymetric high associated with Harwich Haven is the Ridge, which appears to be formed in the resistant London Clay platform. The Ridge is recognised on early charts, and exhibits a sustained vertical lowering over the course of last 400 years at a rate of about 9.1 mm yr^{-1} (Appendix 3).

The deeper features in this area are HDWC (which has been increasingly deepened over the last 40 years), Cork Hole and Pitching Ground. The history of Cork Hole is quite variable, possibly due to the inconsistency in its depth and the low probability of finding the deepest point. Pitching Ground historically comprised a bathymetric depression between Cork Spit and Ridge: HDWC cuts through this area now.

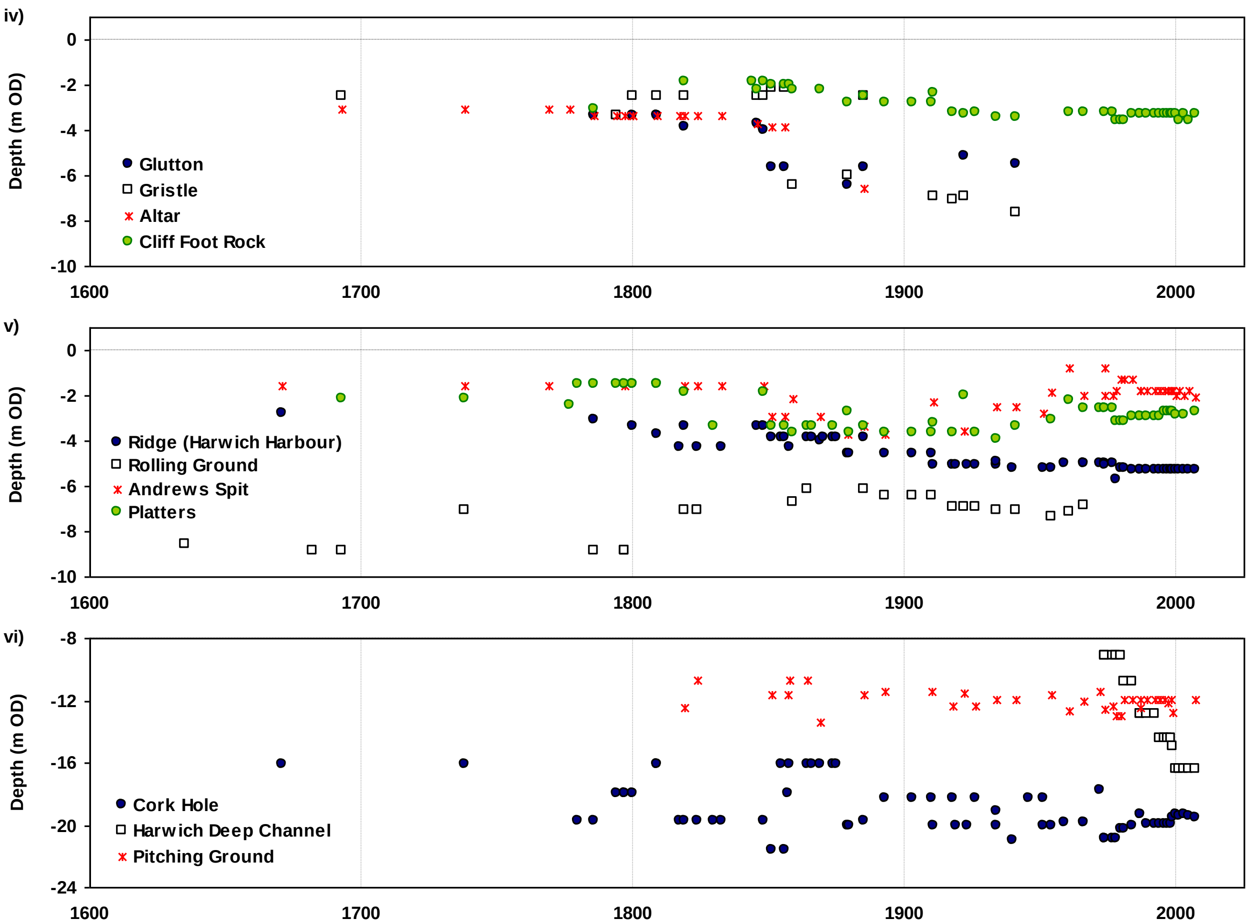

Figure 6 (cont.)

3.2 Area B

Area B extends about 40km offshore from the south Suffolk coast to the open shelf ridges of the Inner and Outer Gabbards and an unnamed bank to the north (Figure 7). Closer to the Suffolk shoreline, the Whiting-Bawdsey-Shipwash complex are tidal-stream aligned headland-associated banks.

Whiting Bank is a depositional feature that has a long history, but shows little change in minimum depth over this period (Figure 8i). The feature is occasionally intertidal and otherwise very close to MLWS. Middle is a historic bank that lay between Whiting and the Orford shoreline. The depths associated with this feature are highly variable, and it ceases to be recognised by the 1840s. In the 1820s, a feature to the southwest of Whiting is recognised: Flagstone is certainly a distinctly different feature to Middle, and is formed in the London Clay bed that outcrops closer to Harwich. Flagstone is thought to provide an anchor for Whiting Banks (HR Wallingford, 2002) and has barely changed in depth over its history.

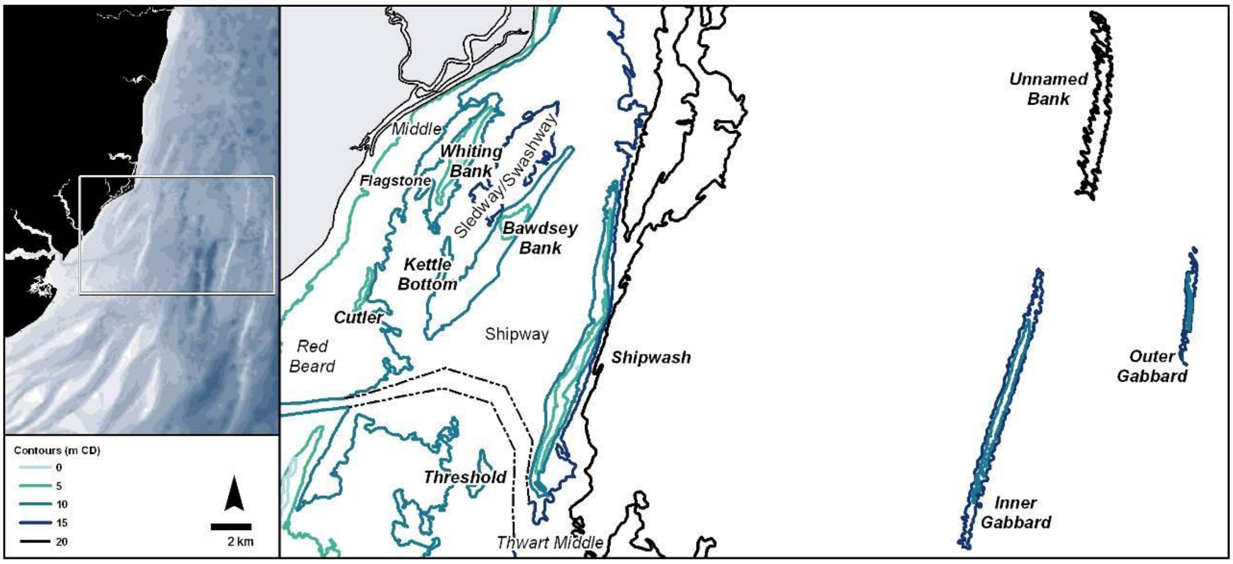

Figure 7 Guide to features present in Area B.

The history of Bawdsey Bank, another depositional feature, is complicated. Most of the pre-19th century charts suggest that the feature is intertidal, but from the 1770s there is an increasing reference to significant depths over the feature (Figure 8ii). From the early 1800s, the bank is consistently recognised as having at least 2m depth at low water. There is no clear trend in the record until the 20th century, when it starts accreting vertically at a rate of 16 mm yr^{-1} (Appendix 3). Kettle Bottom forms a northerly spur from the southern tip of Bawdsey Bank. It is thought to be a similar feature to Flagstone, formed in London Clay, and provides an anchor for Bawdsey Bank (HR Wallingford, 2002). But unlike Flagstone, Kettle Bottom has experienced a sustained and significant decrease in vertical level at a rate of about 17.6 mm yr^{-1} (Appendix 3) over the last 200 years. To the southwest, a smaller depositional feature (Cutler) lies about 3km from the shoreline. This bank has been recognised since the 1671 Seller chart, and prior to the late 1800s, showed little evidence of change. The record suggests that the feature broke down over the course of the late

1800s to a low in 1905, and subsequently built up again to within 30cm of its previous height by 1920. Since then, the bank has experienced a gradual lowering of about 1m. To the southwest of Cutler existed a small shoal called Red Beard which was present on most charts up until the early 1800s. It is clear that this feature was eroded away quite rapidly over the first few decades of the 19th century.

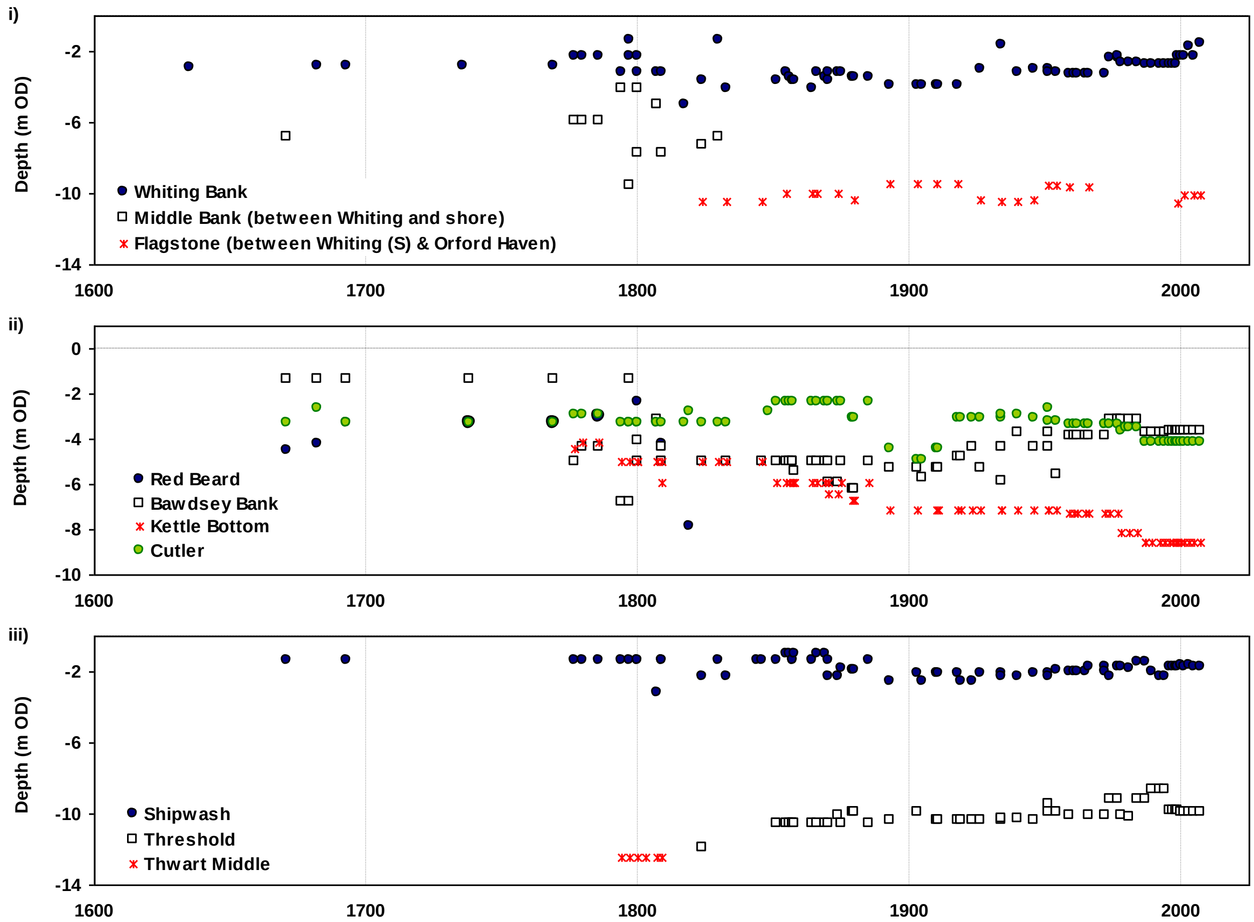

Figure 8 Changes in seabed feature depths in Area B.

Shipwash is a very elongated bank that lies about 13.5km offshore from the Suffolk shoreline. There has been very little change in the minimum depth of this feature over the last 350 years (Figure 8iii). The highest point on the bank is often intertidal, and if not, lies within a metre of MLWS. Threshold, to the southwest of Shipwash was discussed within the context of Area A. It is noted here due to the possible connection with a feature called Thwart Middle, which was located to the southwest of Shipwash at the turn of the 18th – 19th centuries. The data for Thwart Middle would support the vertical accretion trend already identified.

The channels that run between Shipwash, Bawdsey Bank, Whiting Bank and the shore are Shipway, Swashway/Sledway and Hollesley Bay Channel. Shipway and Hollesley Bay Channel show very little change over the course of their documented history (Figure 8iv), but the Swashway/Sledway does suggest a long-term deepening at a rate of about 19 mm yr^{-1}. There is an issue with consistency with this feature as the Sledway was originally defined as the pass within the London Clay basement between Kettle Bottom and Rough Shoals. More recently Sledway is used to describe the channel between Bawdsey and Whiting, which was originally called the Swashway. Despite this inconsistency, the data recorded here are geographically correct.

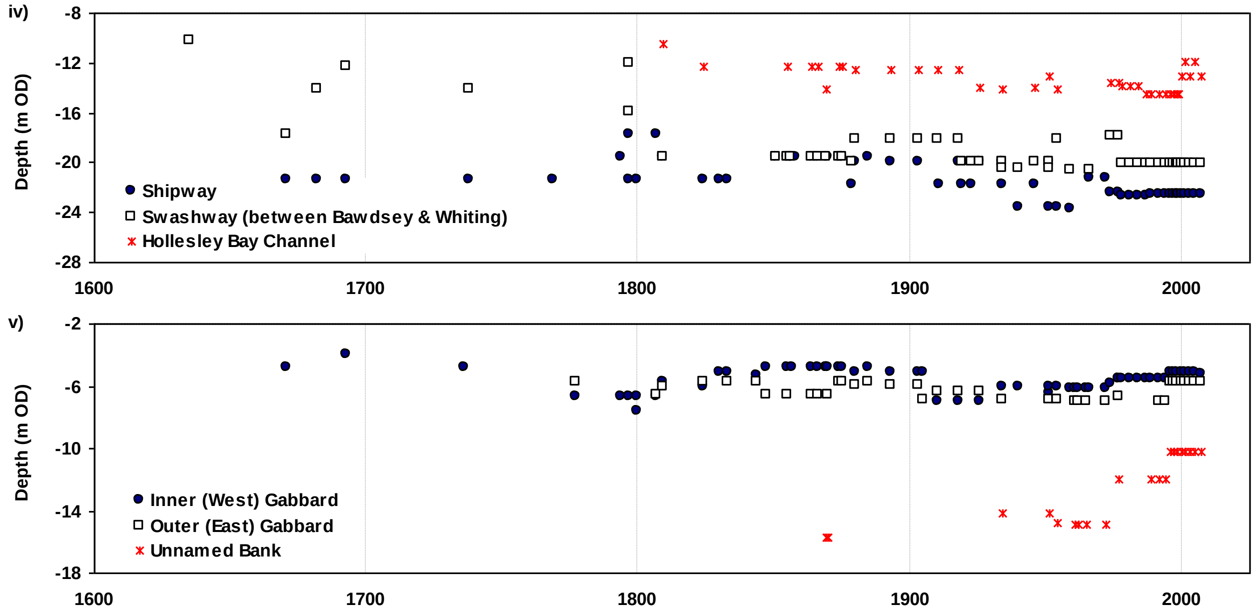

Figure 8 (cont.)

The open shelf ridges to the east of Area B have a shorter document history, probably due to their distance from shore (Figure 8v). The Inner Gabbard was first recognised in the 1671 Seller chart: charted minimum depths suggest that the vertical level has changed by over 3.5m over the course of its' history, but with no specific trend. The last 30 years appear to suggest a small but progressive shallowing over the bank. The Outer Gabbard was first noted in the 1777 Arnold survey. Again, its minimum depth has varied, but with no consistent trend. A further bank to the north of the Gabbards was first recognised in the 1870s and has a sparse history. It has never been named, but the data suggests that it is building up at a rate of about 109 mm yr^{-1} since the mid-1900s (Appendix 3). The recent Admiralty surveys suggest that this bank is not laterally consistent like the Gabbards, and is formed of large northwest-southeast sand ridges. It is possible that early surveys would not have been detailed enough to capture the complex character of this feature, and therefore may not have found the actual minimum depth.

3.3. Area C

Area C corresponds to the ridges extending northeast from Orfordness (Figure 9). Aldeburgh Ridge is a headland-associated bank, connected via sediment transport to Orfordness (HR Wallingford, 2002). Aldeburgh Napes is thought to be a relic equivalent of Aldeburgh Ridge, but associated with an older, more seaward shoreline (HR Wallingford, 2002).

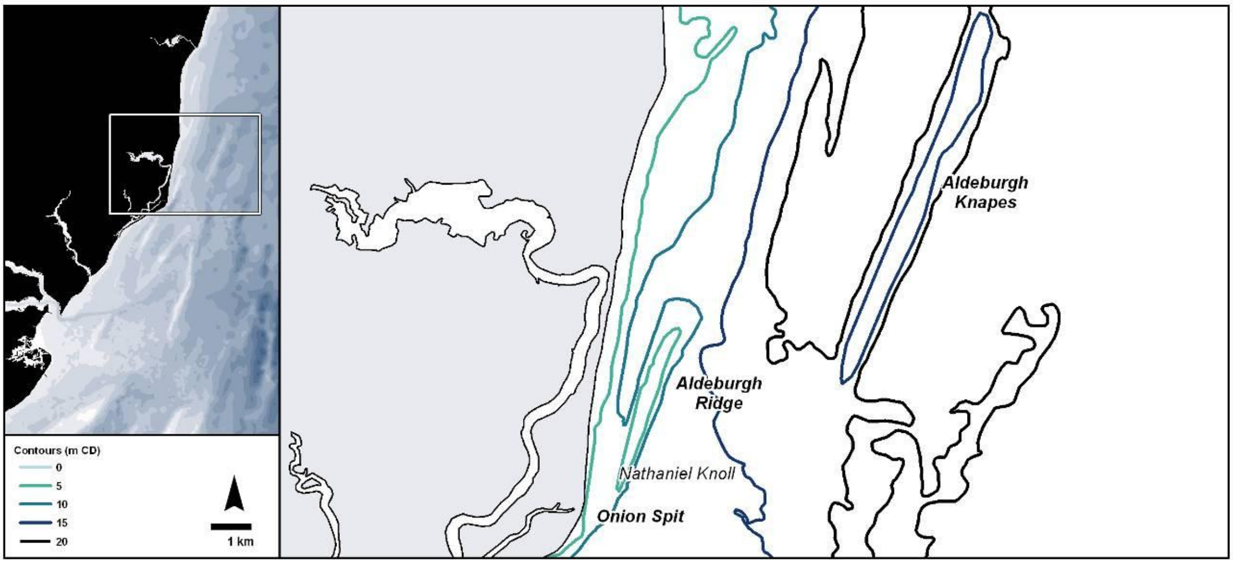

Figure 9 Guide to features present in Area C.

Aldeburgh Napes is the largest of these features and has the longest recognised history (Figure 10i). The pre-19th century history is very variable, but importantly demonstrates that this bank sustained a vertical level 7m higher than the contemporary feature. Since 1800, minimum water depths over the feature have progressively increased at a rate of 40 mm yr^{-1} (Appendix 4). Aldeburgh Ridge presents a different history: over the period 1860s-1960s, the bank shows a small decrease in height at a rate of about 11 mm yr^{-1}, which then dramatically changes to a vertical accretion trend of over 72 mm yr^{-1} until present (Appendix 4).

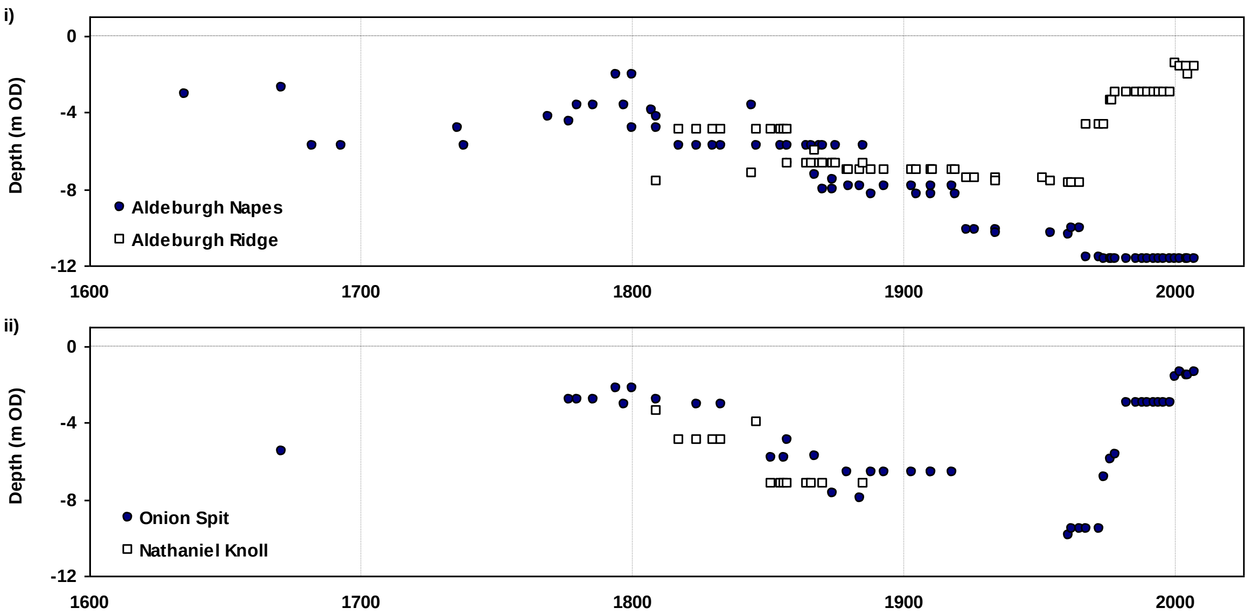

Figure 10 Changes in seabed feature depths in Area C.

Closer to Orfordness, there are two small shoals that have been recognised at various points over the last 350 years (Figure 10ii). Onion Spit, which is simply a northeast pointing spur directly attached to Orfordness, was noted in the 1671 Seller chart, and then not recognised again until the 1870s. From then until the 1920s, it progressively decreased in height at a rate of about 39.4 mm yr^{-1} (Appendix 4). It was not recognised on charts again until 1965, and since then, it has been increasing in height by over 175 mm yr^{-1}. Nathaniel Knoll appears to be a transient shoal between Onion Spit and Aldeburgh Ridge. It was recognised in addition to Onion Spit throughout the 19th century, and exhibited a similar fate with a decrease in height at a rate of 55.9 mm yr^{-1} (Appendix 3). The sediment transport and supply connectivity between these four features is not clear, but their historical morphological behaviour suggests a close link.

3.4 Area D

Area D encompasses the open shelf ridges of the Galloper and North Falls, and the estuary-associated, tidal-stream aligned features of Long Sand, the Sunk and Kentish Knock (Figure 11). The outer banks are similar to their northerly counterparts in their extensive length and narrow breadth. Both banks have a long recorded history, and exhibit considerable variation in minimum depth, but neither display any significant long-term trend (Figure 12i).

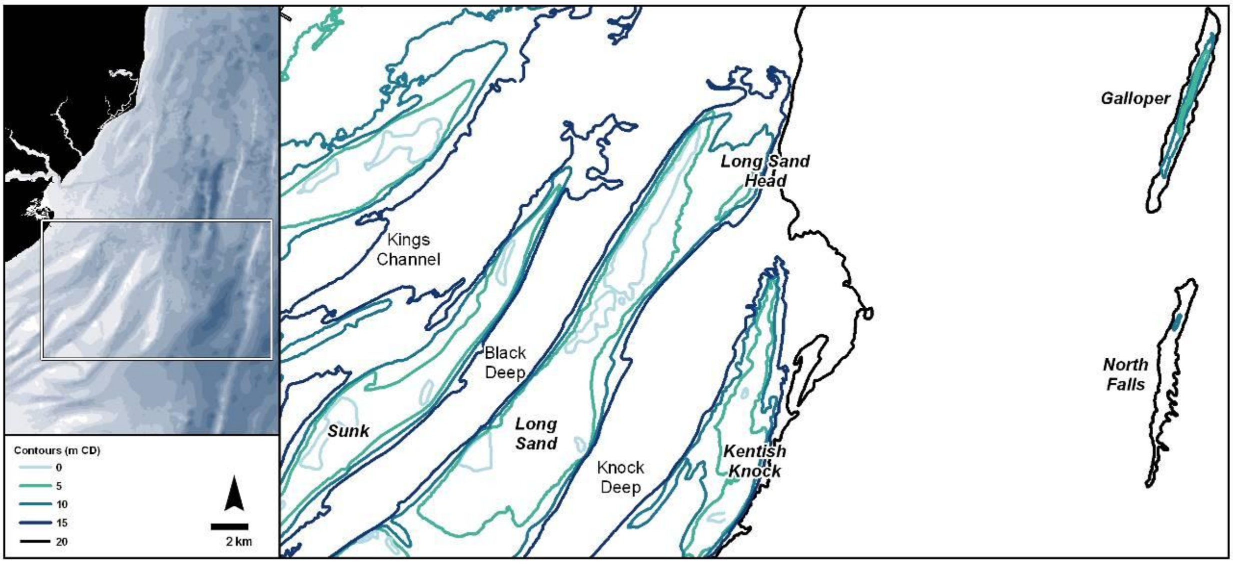

Figure 11 Guide to features present in Area D.

Kentish Knock also has a long recorded history (Figure 12ii). Early surveys were limited in terms of planform character, but by the early 1800s it was clear that bank comprised spurs that extend north and south. Over the course of the last 200 years, the feature has changed in planform shape, whereby the spurs have strengthened/weakened and extended/shortened at various points in time. As such, the record of minimum depths over this feature has been divided into a southeast and a northwest component. In the early part of the 19th century, the bathymetric highs across the bank were focused on its northerly arm. There is no suggestion up to this point that any part of the feature dried at low tide, but by 1820 and onwards the northerly arm was regularly, though only slightly, intertidal: this historic trend is an overall vertical accretion rate of 9 mm yr^{-1} (Appendix 3). Over the course of the 19th century the bank reconfigured, and by the late 1800s, the southerly arm had attained a similar intertidal height to the northerly arm. Whilst the northerly arm maintained its intertidal characteristic, subsequent reconfiguring caused a decrease in the vertical level of the southerly arm, which reached a low in the 1920s. Since then, this part of the bank has been building up at a rate of about 63 mm yr^{-1} (Appendix 4).

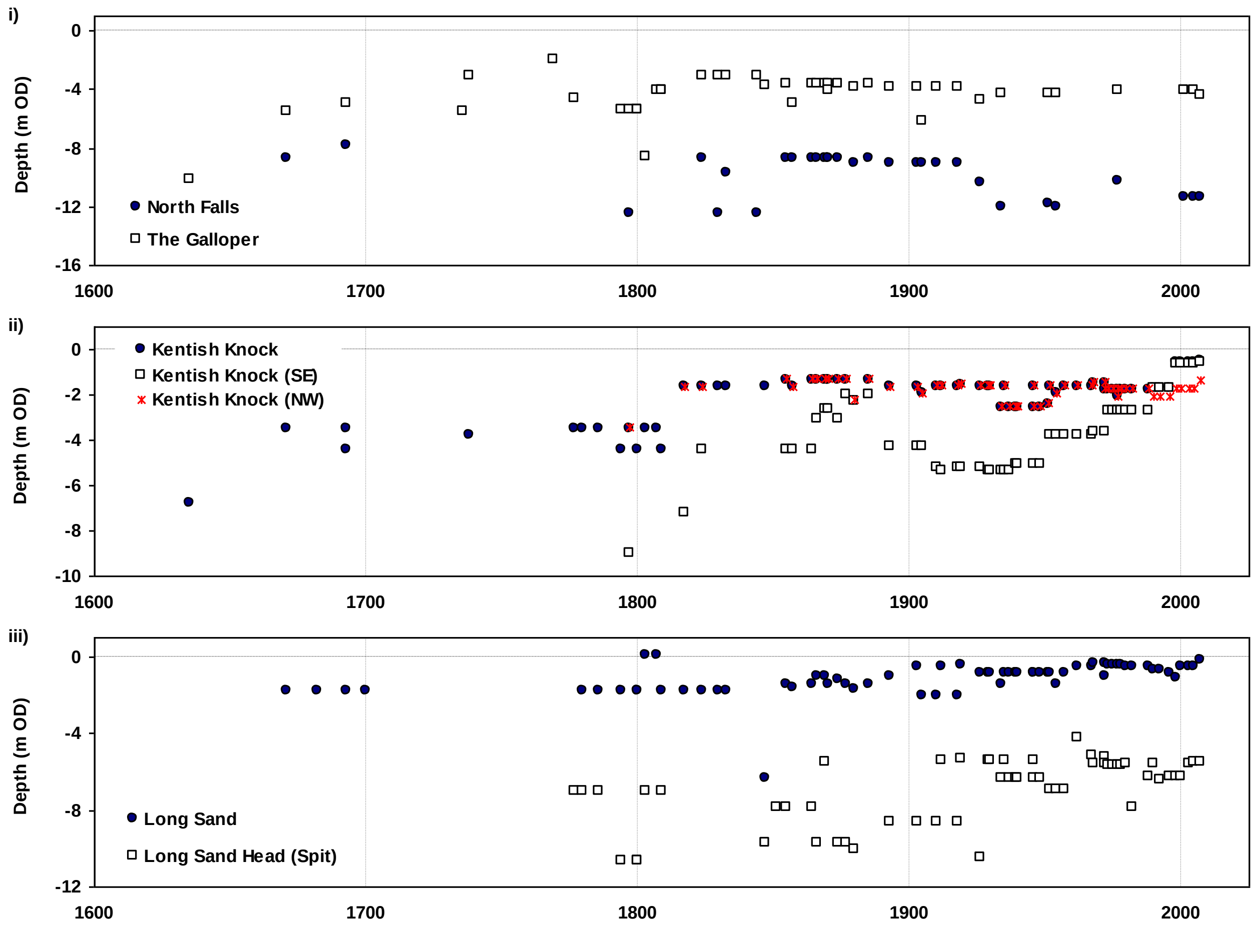

Figure 12 Changes in seabed feature depths in Area D.

The Long Sand extends for over 31km. Although the minimum depth of this feature has been consistently about low water, the surface character is variable, and the intertidal components are localised (Figure 12iii). The lack of real intertidal bathymetry throughout the pre-20th century charts (the feature was simply defined as 'dry') precludes any identification of long-term trend, but even the post-1900 data shows little evidence of a specific trend. Long Sand Head is a subtidal extension of the Long Sand. It has been recognised since the later 1700s, and its history is extremely variable.

The Sunk is a comparable feature to Long Sand, and has a similar length (Figure 12iv). Again, the minimum depth has consistently been above low water, and the intertidal character is patchy, organised into geographically-consistent shoals - Great, Little, Middle and Southwest (Figure 12v). These sub-features do demonstrate that the overall bank is dynamic, but the intertidal topography does not exhibit any specific trends.

Data relating to the channels between these main estuary banks are highly variable and do not appear to display consistent long-term changes (Figure 12vi). The Long Sand Head Bell (buoy) is included here as a geographical position as opposed to being a particular feature, and simply demonstrates that Long Sand is extending in a northeasterly direction, causing shoaling at the Bell at a rate of about 49.4 mm yr^{-1} (Appendix 3).

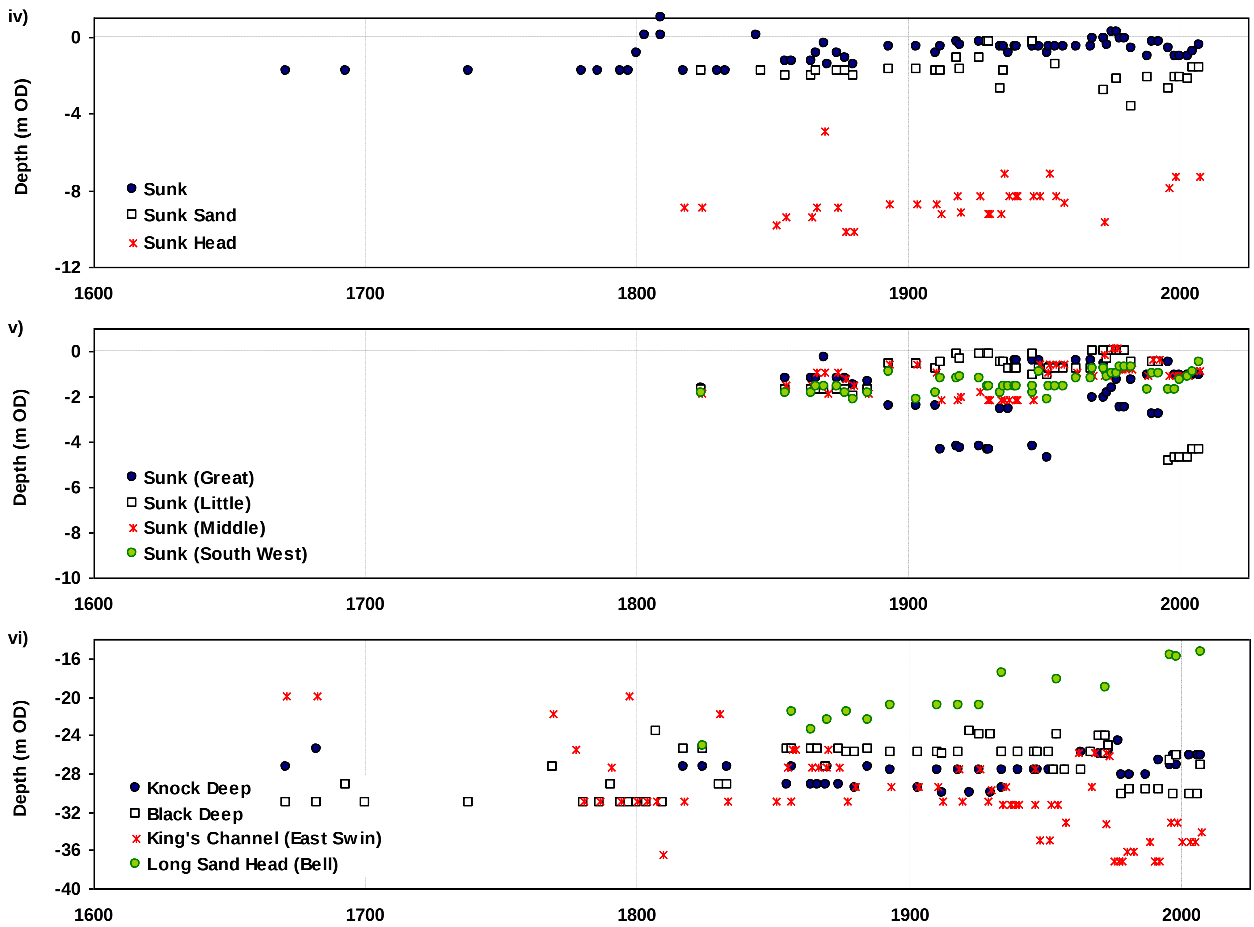

Figure 12 (cont.)

3.5 Area E

Area E corresponds to the features associated with the Gunfleet and Buxey Sand complex (Figure 13). Gunfleet (which can be divided into East and West components) and Buxey have been consistently described as intertidal, and there is no suggestion in the recent intertidal heights of any significant changes in vertical level of these features (Figure 14i,ii). Gunfleet Head (the northern extent of Gunfleet) does suggest a shoaling of about 26 mm yr^{-1} (Appendix 3), but the spatial extent of this feature is vague and this change is noted with caution. The small features of Tripod, Priory Spit and Eagle closer to the Clacton shoreline are probably formed in London Clay, and these also have not changed significantly over their history. The small Sunken Buxey shoal, in Whitaker Channel changed very little until the mid 1900s, when it appears to have shallowed by about 1.5m over a 20 year period: it has since remained relatively stable.

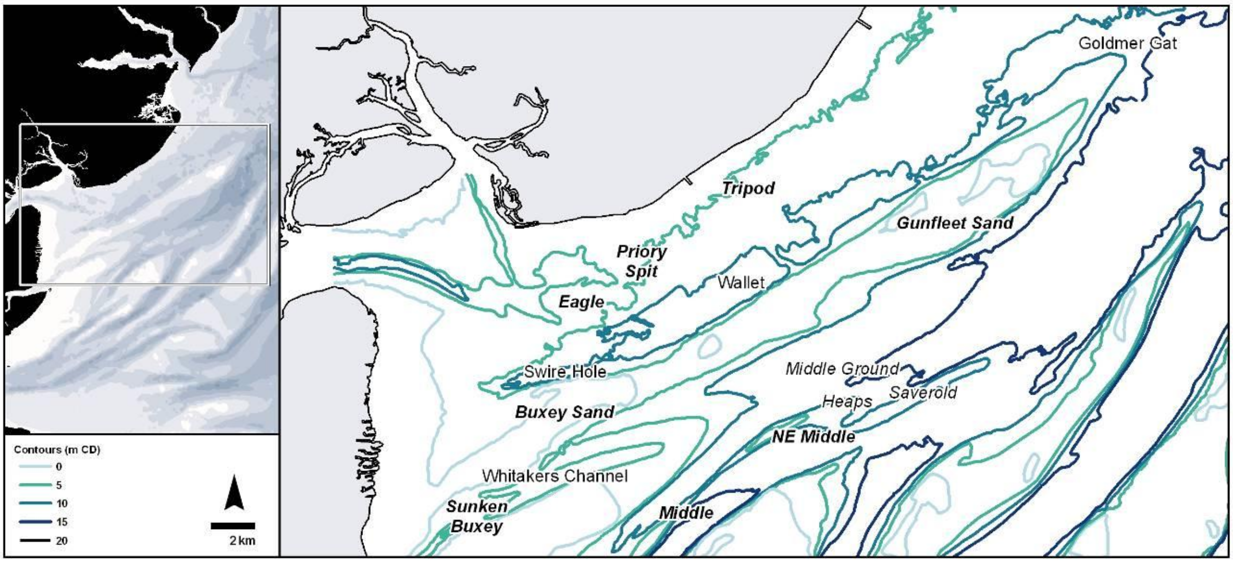

Figure 13 Guide to features present in Area E.

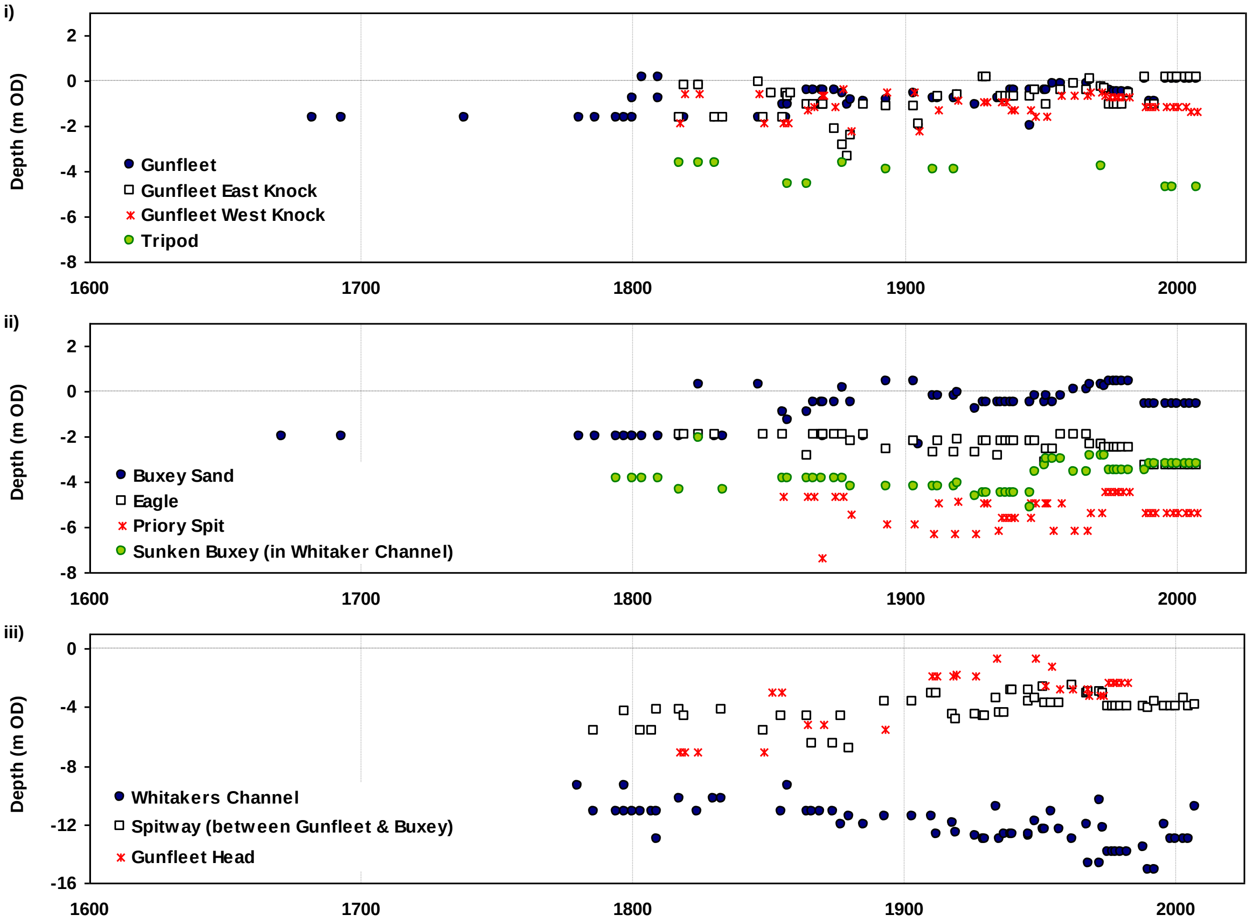

Figure 14 Changes in seabed feature depths in Area E.

Whitakers Channel, however, appears to have deepened over its 250 year history (Figure 14iii). This feature shows a progressive increase in depth of about 14 mm yr^{-1} since the late 1700s (Appendix 3). The Spitway channel that crosses the Gunfleet-Buxey seems to shoal slightly over this period, but this trend does not appear to be statistically significant.

The deeper channel running along the southeast margin of the Gunfleet-Buxey Sands comprises a number of smaller and elongate banks (Figure 14iv). Middle has been a relatively constant feature over the full history reported here, and was present on some 17th century charts. Minimum depths over this bank are variable in the early part of the record, but relatively consistent since the later 1800s. To the northeast of Middle is a bank called NE Middle. This was first charted in the 1860s and has subsequently maintained a very similar minimum depth to Middle. Northeast of NE Middle are three features that were much more clearly defined in the past than they are today. Middle ground, to the north of NE Middle was a relatively deep feature that can be currently identified as a small bathymetric high, but is no longer named as a feature. Minimum depths over this have varied, but there has been no significant net change over the last 250 years. Heaps was a shoal to the northeast of NE Middle, and the name continued to be associated with a marker buoy in this region until the 1970s. The bed elevation here has deepened considerably over its history, particularly between the mid-1800s and mid-1900s, at a rate of around 100 mm yr^{-1} (Appendix 3). Saverold was a further bathymetric high to the northeast of Heaps, but was only recognised between the 1780s and 1830s. The records suggest that this feature lost over 5m in height, which may explain why it is no longer present.

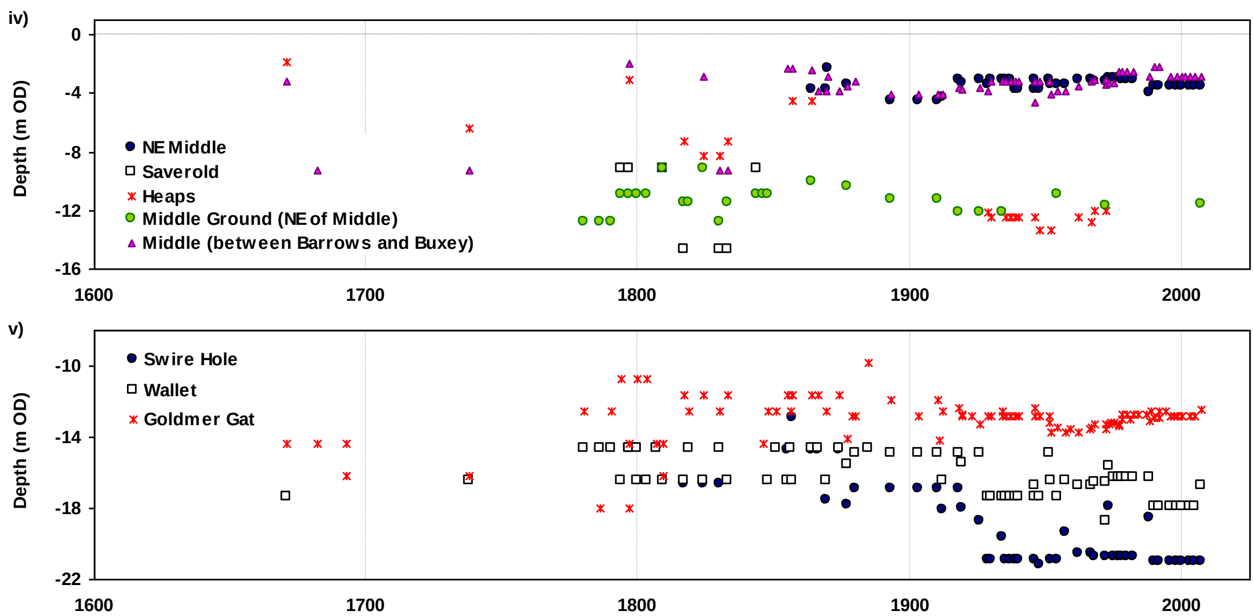

Figure 14 (cont.)

The main bathymetric lows associated with the Gunfleet-Buxey Sands (Figure 14v) are Goldmer Gat (defining the northern extent of Gunfleet), the Wallet (between Gunfleet-Buxey and the shore) and Swire Hole (a discrete low to the southwest extent of the Wallet). There is considerable variability in these records, although the post-1800 data are more consistent. Goldmer Gat does not display any significant long-term trends, whilst the Wallet shows a hint of deepening over the 20th century (though not significant). Over the last 200 years, Swire Hole appears to have deepened at a rate of around 36 mm yr^{-1} (Appendix 3). As in the case of Cork Hole, this may be a reflection of improved surveying methods and increases in survey resolution which increases the likelihood of recording discrete bathymetric lows.

3.6 Area F

Area F centres on the Barrows. It is quite a complicated region where change in feature depths is often obscured by changes in planform configuration (Figure 15). The Barrows comprises East and West components, and a smaller Sand feature toward the centre. Some early surveys do not differentiate between East and West, but on the whole, the intertidal nature of this feature has been consistently noted over its documented history (Figure 16i). There are fluctuations in the more recent intertidal heights, but no trend is observed.

To the southeast of the Barrows are a number of smaller banks loosely associated with the landward extent of Long Sand and Sunk (Figure 16ii). Knock John lies to the southwest of the Sunk: it was defined as ‘dry’ throughout its early history until the 1860s when it acquired a depth of around 2m below low water. Since then, it has very consistently and progressively built up at a rate of about 18 mm yr^{-1}, attaining an intertidal presence in the 1960s (Appendix 3). The shift from sub- to intertidal has not affected the trend observed. To the southwest of Knock John lies North Knob, which has also been termed New Knob in the past. This feature displays a similar history to Knock John, and has been building up at a rate of about 25 mm yr^{-1} since the mid-1800s (Appendix 3). North Knob became intertidal in the 1980s and this has not affected its’ continued growth.

Tizard bank is a subtidal feature that lies to the southwest of Long Sand. It was previously called East Knock John owing to its easterly position relative to Knock John. The feature has been recorded since the mid-1800s and has exhibited a variable growth over the last 150 years, averaging at a rate of around 35 mm yr^{-1} (Appendix 3), which appears to have been tailing off over the recent decade. Knob Shoal to the southwest of this has a complicated history. Arnold’s survey of 1777 suggests a near-intertidal bank, whilst subsequent charts throughout the 19th and early 20th century indicate that the shoal was covered by 3-5m water at low tide. Since the 1940s, however, the shoal appears to be vertically accreting.

To the west, the Mouse bank was recognised in the late 18th century (Figure 16iii), and over the course of the next 100 years was noted as either dry or intertidal. Between 1880 and 1970, however, the bank appeared to break down, with a vertical loss of 61 mm yr^{-1} (Appendix 3). Since the 1970s, the bank has stabilised and depths suggest that it has possibly entered a new slow phase of growth. To the west of Mouse, North Mouse is a relatively recent addition having been initially defined in the 1950s. It occupies the geographic position of the original Mouse which has migrated eastward over the course of its history. North Mouse shows little change over the last 50 years.

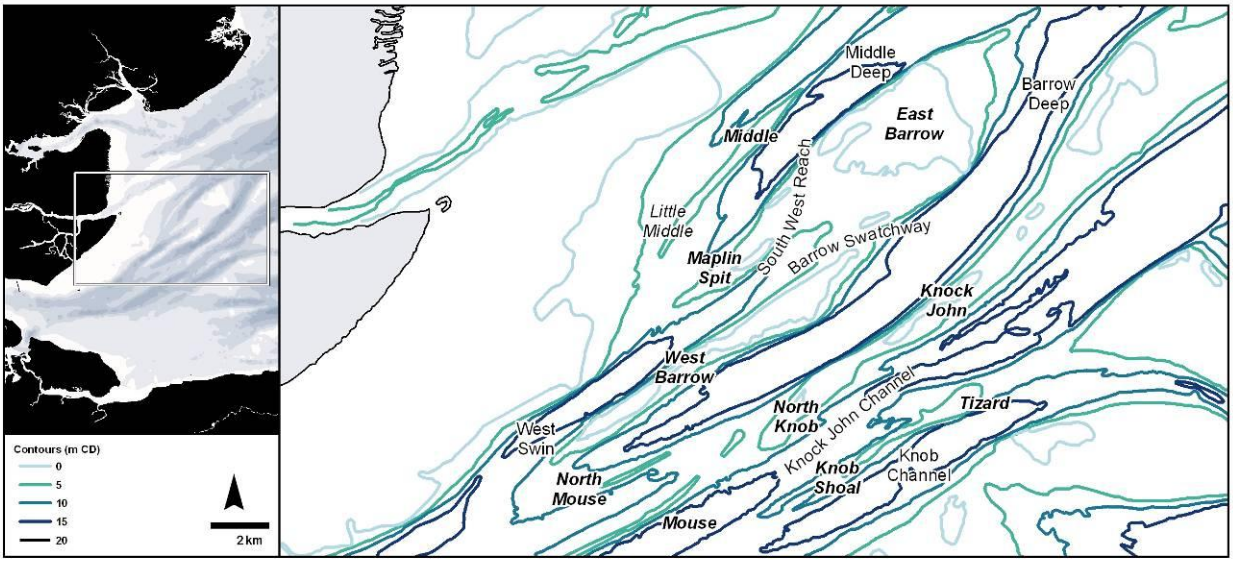

Figure 15 Guide to features present in Area F.

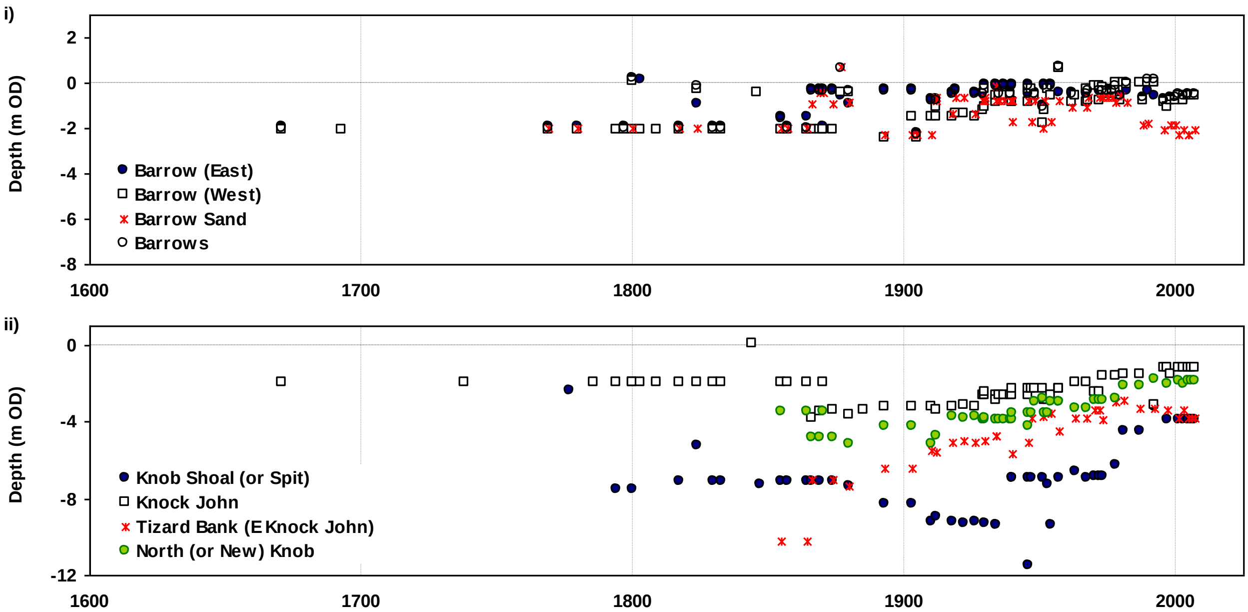

Figure 16 Changes in seabed feature depths in Area F.

Maplin Spit is also a migratory feature that was originally attached to the Maplin Sands shoreline, but subsequently extended across the West Swin to attach to the Barrow Sand. Detachment from the Maplin Sands shore began in the 1920s, and attachment to the Barrows started in the 1970s. This changing configuration is also evidenced by the minimum depth data: the feature was intertidal until the early 20th century as it began to shift northeast. During the period of detachment, variable depths over the feature were recorded, but as it started to attach to the Barrows, the bed level progressively increased and the bank is once again intertidal. Associated with this shifting shoal is the behaviour exhibited by South West Reach, the channel between Maplin Spit and the Barrows (Figure

16iv). Before the migration, this channel maintained a significant depth. As it became confined between the northeast moving Maplin Spit and stationary Barrows, the channel shoaled significantly in the 20th century at a rate of 158 mm yr^{-1} (Appendix 3), which increases to 246 mm yr^{-1} between 1935 and 1977.

The behaviour of the Barrow Swatchway (between East and West Barrows) may also be linked to these changes in configuration. From 1800 to the 1970s, this channel deepened at a rate of 51 mm yr^{-1} but since the attachment of Maplin Spit to Barrow Sand, the channel has shoaled at a rate of 136 mm yr^{-1} (Appendix 4). Knock John Channel appears to have deepened since the early 1900s, but other bathymetric lows in this region show little consistent of significant changes in depth (Figure 16v).

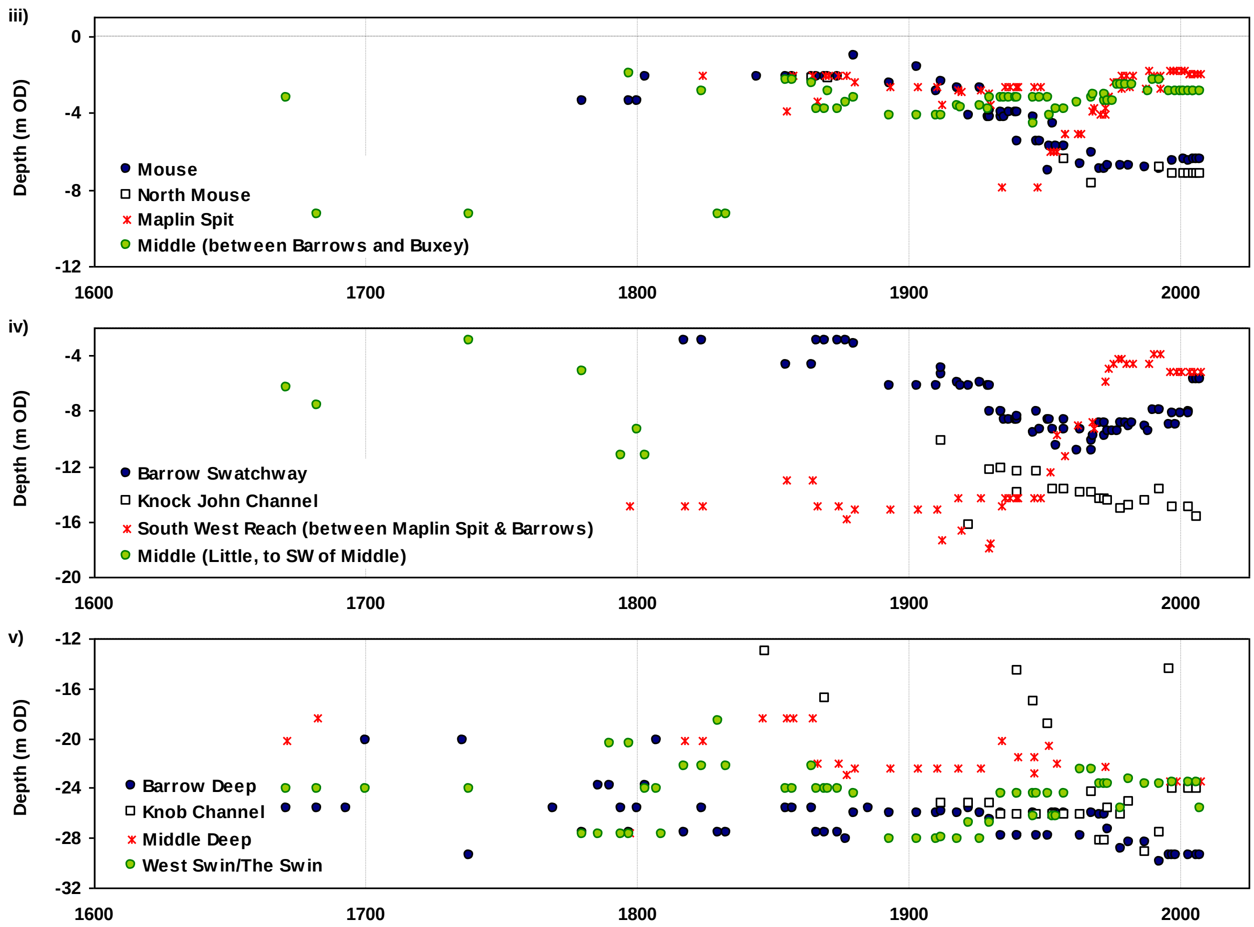

Figure 16 (cont.)

3.7 Area G

Area G corresponds to the region around Shingles and Edinburgh Channels. This feature forms the southerly extent of Long Sand (Figure 17). It is clear from the historic charts that Girdler referred to a much broader area across Long Sand than it covers today. This is partly a product of increase resolution of survey, affording the identification of more specific features. More importantly, it is also the result of a significant change in configuration of the lower Long Sand area.

Independent of size/extent, Girdler has been consistently intertidal throughout its' history until the 1990s since when the surface has lowered to just below low water (Figure 18i). Early surveys suggest that Shingles was originally subtidal, but it has maintained an intertidal presence since the early 19th century, and there is no evidence of any specific long-term trend. Albion Knowl no longer exists, but was charted throughout the 1780s-1830s. It is possible that this bank migrated toward and welded to the southwest margin of Long Sand. It is certainly clear that it was a disappearing feature that was deepening at a rate of 59 mm yr^{-1} (Appendix 3).

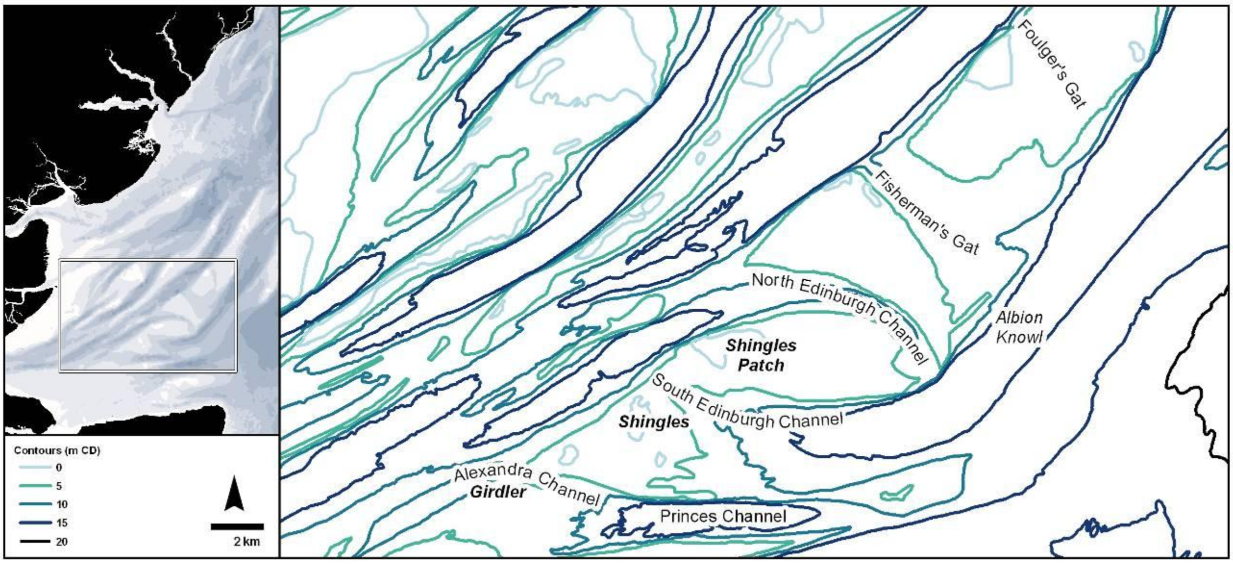

Figure 17 Guide to features present in Area G.

Shingles Patch has evolved within the Edinburgh channels region (with a vertical accretion rate of 74 mm yr^{-1} (Appendix 3)) throughout the earlier to mid-20th century. Its formation appears to be closely connected to the development of these cross-bank channels. Until the 1890s only one swatchway occupied this part of Long Sand, recorded as Smugglers Swash (1786-1809), then Thomas' New Channel (1817-1857), but this channel shoaled and was replaced by Bullock's Channel (1855-1880), which was renamed Duke of Edinburgh Channel in 1870. By 1893, the beginnings of a mid-channel bank were already visible, and over the last 100 years, this bank has expanded into Shingles Patch, forcing the northward movement of aptly named North Edinburgh Channel and the similarly southward migration of South Edinburgh Channel. This sequence of morphological change (Figure 19) suggests that the swatchway shifted from a predominately unidirectional tidal regime to a bidirectional one. In other words, a single tidal stream (flood or ebb) was joined by an opposing current (both flood and ebb tidal streams) at some stage during the mid-19th century. Flood and ebb tidal currents rarely occupy the same channels in open, sedimentary environments, and so these currents would have quickly settled into their respective paths. The Shingles Patch has developed between these.

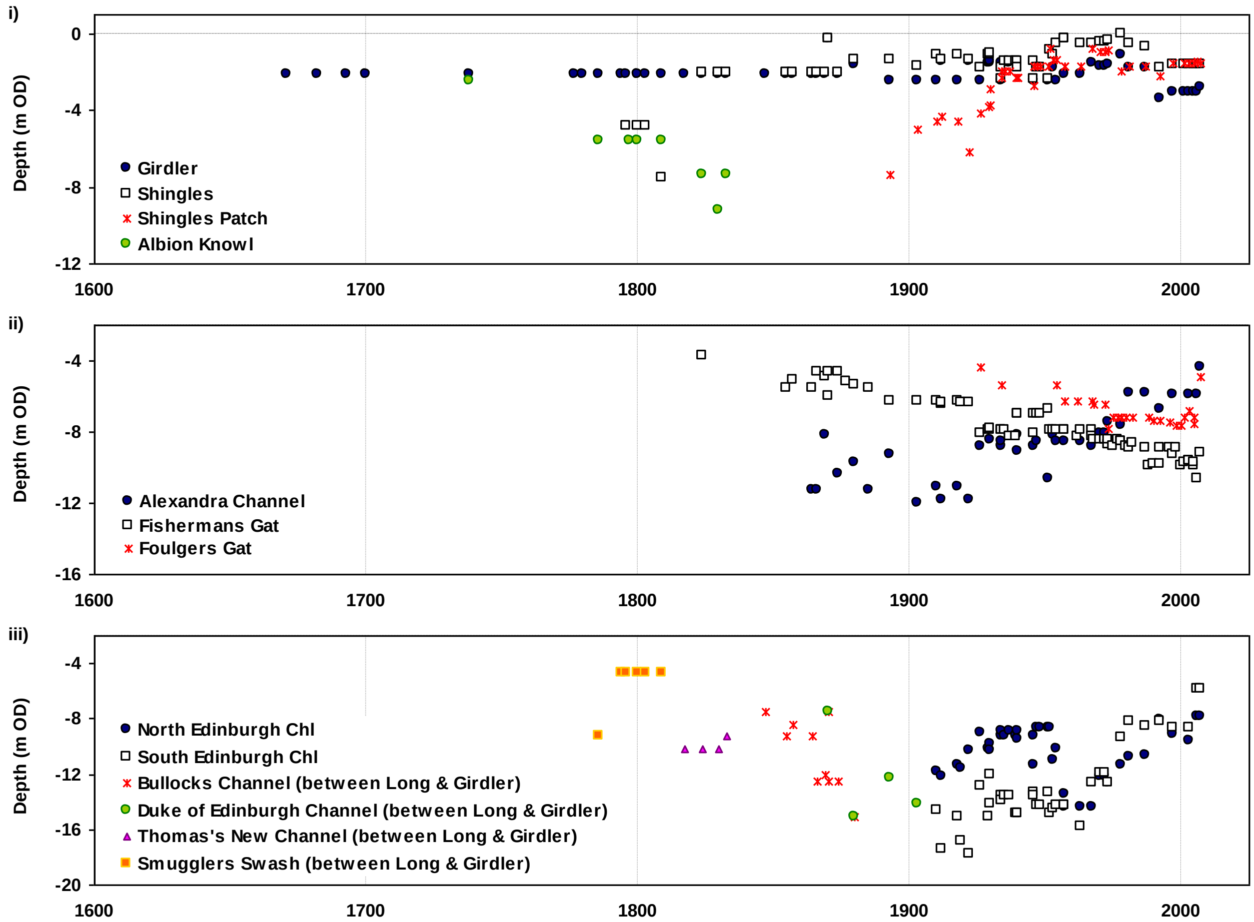

Figure 18 Changes in seabed feature depths in Area G.

The various forms of the Edinburgh cross-bank channels exhibit a deepening throughout the 19th century, but with the development of two channels, the features shoal throughout the 20th century (Figure 8iii). South Edinburgh Channel has shoaled at a rate of 99 mm yr^{-1} (Appendix 3), whilst North Edinburgh Channel exhibits two periods of shoaling: between 1900 and 1940 at a rate of 105 mm yr^{-1} and after a sharp deepening, at 130 mm yr^{-1} from 1960 to the present (Appendix 4).

The cross-bank channels to the north also display some marked trends (Figure 8ii). Fishersman's Gat has become increasingly navigable over the course of its history, exhibiting a deepening of 33 mm yr^{-1} (Appendix 3). Foulger's Gat shows a less significant 20th century deepening followed by a very recent shoaling. Further south, Alexandra Channel, which crosses between the Girdler and Shingles, has been shoaling at 59 mm yr^{-1} throughout the 20th century. This is likely to be related to the growth of the Shingles Patch region, thereby forcing the Shingles bank southwest to confine Alexandra Channel.

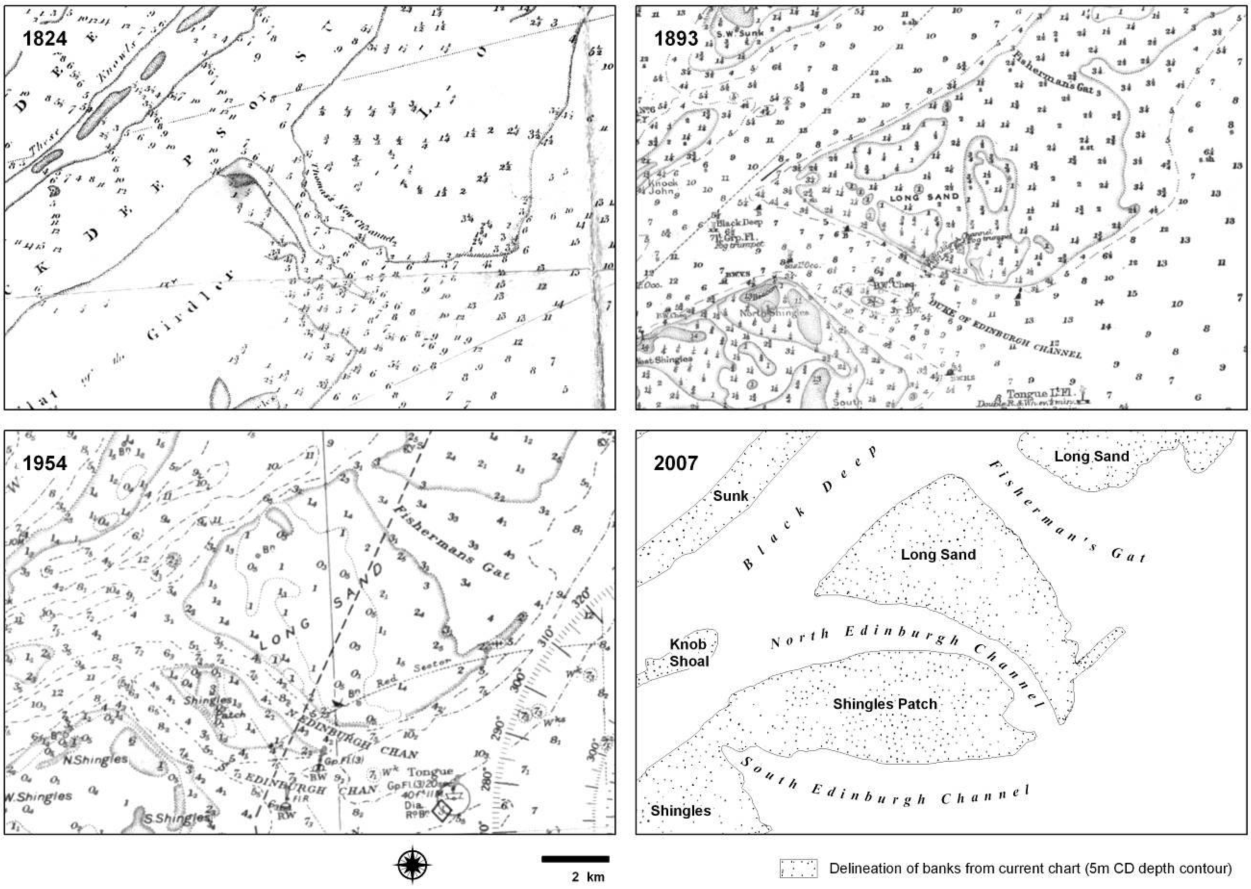

Figure 19 Historical comparison of the Edinburgh Channels and Fisherman's Gat region (scale applies to all; chart depths are in fathoms).

3.8 Area H

Area H encompasses the seabed offshore of the north Kent coastline (Figure 20). This contains the historically important navigation routes of Princes and Queens Channels, and the extensive sand banks of Margate Sand and Hook. To the north of the region, Tongue and Ridge are connected linear banks that divide Princes Channel and Queens Channel. Both features have been depicted on charts since the late 18th century, and both exhibit a strong and comparable trend (Figure 21i). Vertical accretion of Tongue has proceeded at around 19 mm yr^{-1} until the late 20th century when it appears to have lowered slightly Appendix 3). At Ridge, significant vertical growth trend has occurred at 21 mm yr^{-1} (Appendix 3). Both these features became intertidal in the 1890s. To the west, this banked feature merges into Pan Sand, which has been intertidal (or at least very close to intertidal) throughout its charted history (Figure 21ii). There is no evidence of a significant change in the bed level of Pan Sand. The associated features to the north (Patch and Speck) also show little quantifiable change over their short history.

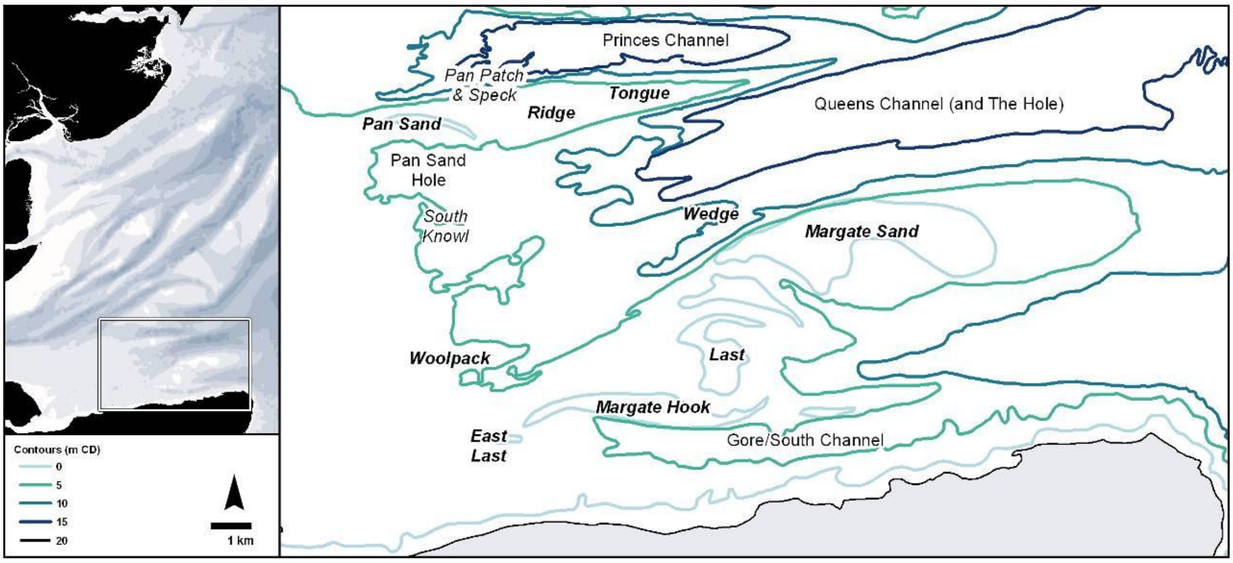

Figure 20 Guide to features present in Area H.

The Wedge and Pan Sand Hole both show a mid-19th century shift in behaviour (Figure 21iii). A significant linear trend in the Wedge record estimates an average deepening of 50 mm yr^{-1} until the mid-1900s (Appendix 3). The Woolpack has fluctuated around MLWS with a suggestion of a slight deepening. South Knowl was present in the 1780s-1820s, but has not been documented since.

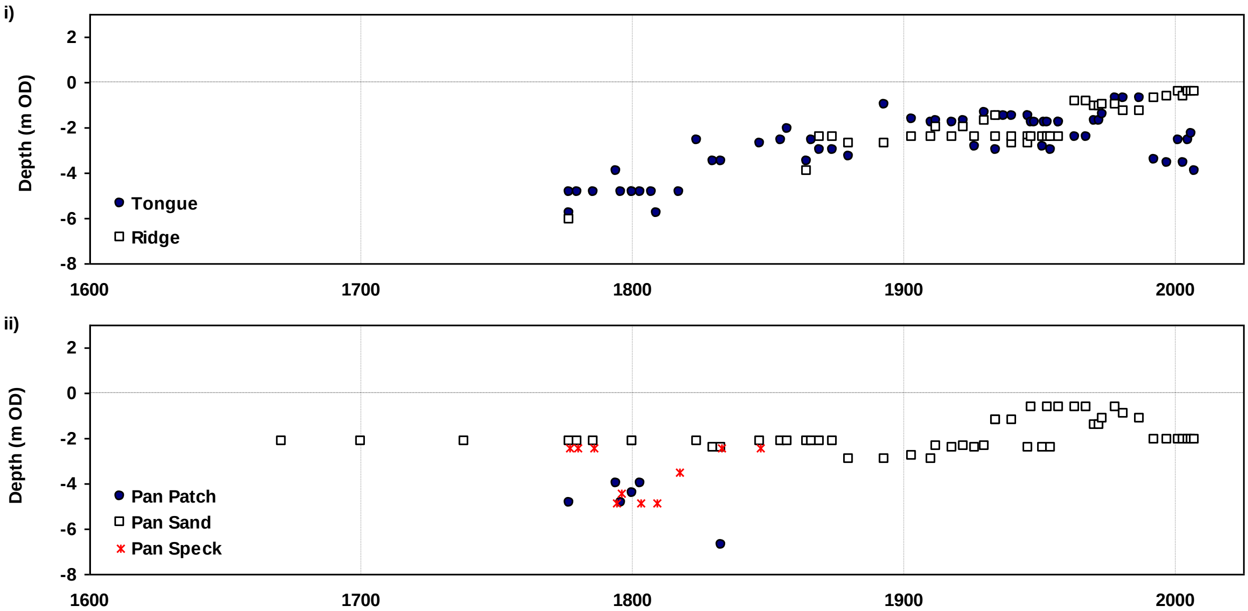

Figure 21 Changes in seabed feature depths in Area H.

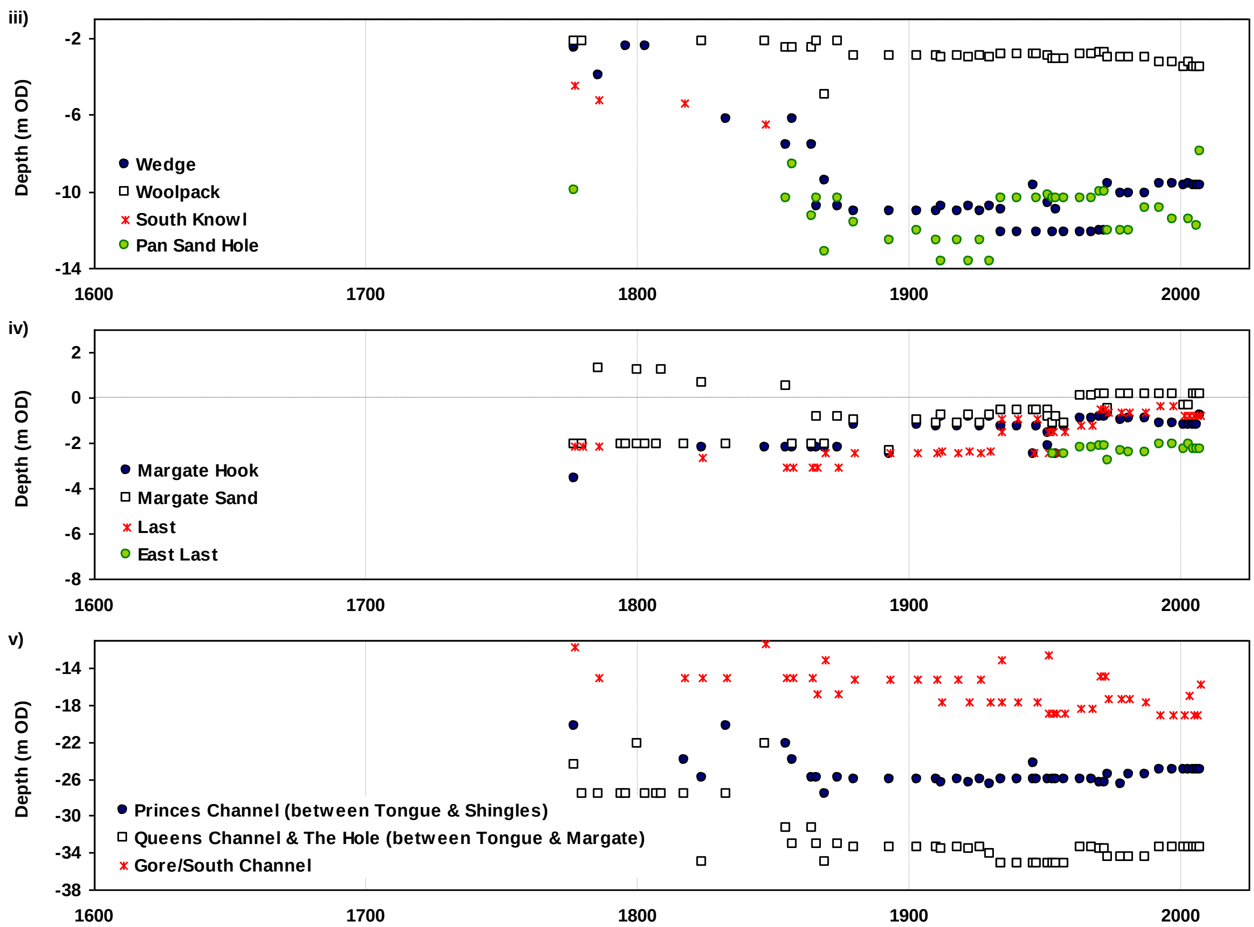

Figure 21 (cont.)

Within the Margate Sand complex, there is little evidence of any significant trends. The discrepancies in the early records simply relate to the difference between 'dry' and a real intertidal height. The records for Last suggest a shoaling of around 17 mm yr^{-1} (Appendix 3), but the recently charted East Last does not yet show any systematic trend. The three major bathymetric lows of this region all indicate long-term deepening. This is more likely an artefact of changing survey style and resolution, particularly in the context of Queens Channel/The Hole which comprises a localised dip in the seabed.

3.9 Area I

Area I corresponds to the initial widening of the Thames estuary, along the north Kent coast (Figure 22). The region is dominated by the broad Kentish Flats, the northwest margin of which is defined by the Oaze Deep. Historically, this margin has been occupied by a range of small banks. The Cant Edge Shoals were superceded by Cant and East Cant, but any overall trend here is minimal (Figure 23i). To the north of Oaze Deep is the narrow Oaze bank. This was a relatively stable feature until the 1930s when it went through a period of breakdown, only to rebuild slightly by the 1980s. This equates to an average historical deepening of 15 mm yr^{-1} (Appendix 3).

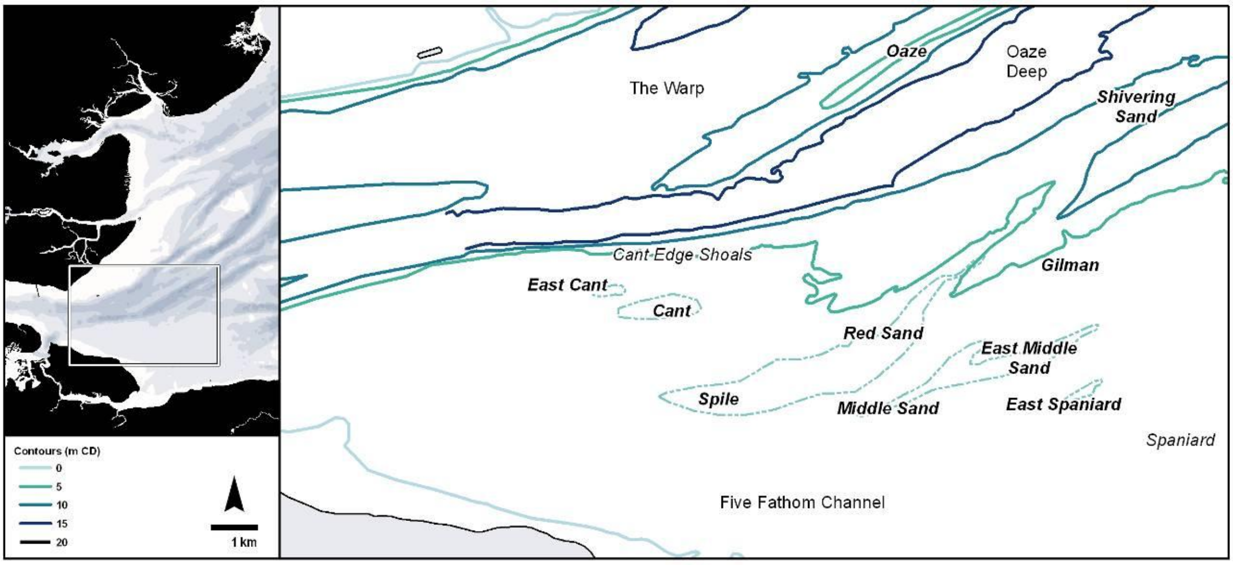

Figure 22 Guide to features present in Area I.

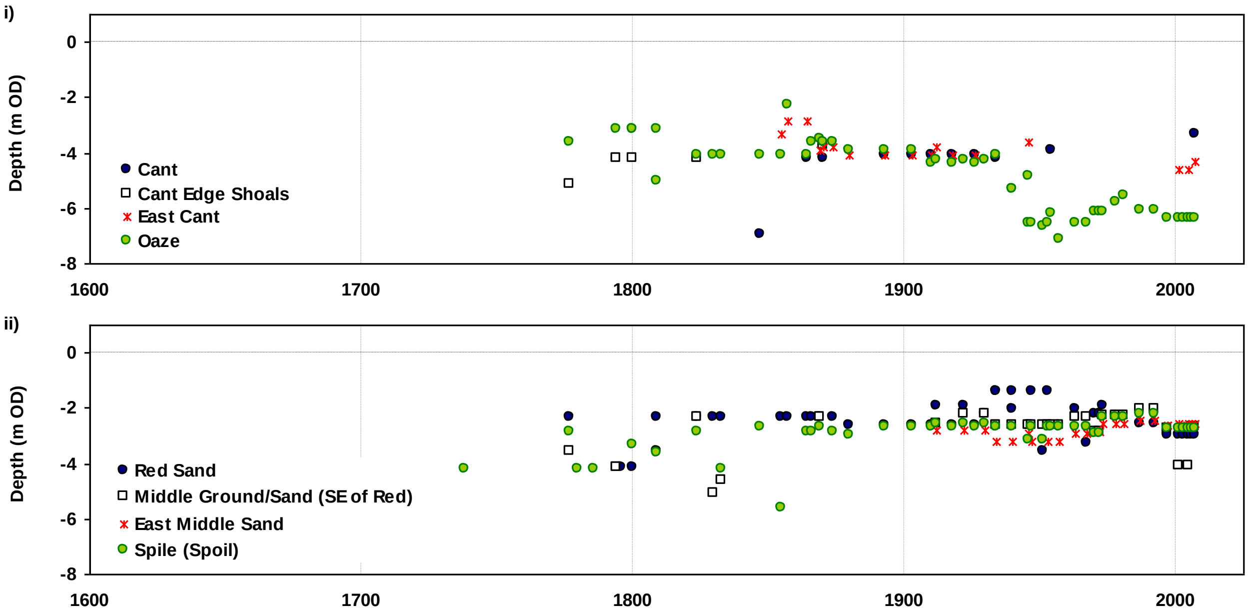

Figure 23 Changes in seabed feature depths in Area I.

Further east on the Kentish Flats, the Red Sand, Middle Ground, East Middle and Spile features do not follow any significant long-term trends (Figure 23ii). East Spaniard has remained relatively consistent over its 200 year history, whilst Spaniard and Gilman both show long-term lowering; Gilman at a significant average rate of 21 mm yr^{-1} since the late 17^{th} century (Appendix 3). Shivering Sand has a complicated record that indicates that the bank was intertidal until the 1870s when 3-5m of bank height was removed. Since then, the feature has maintained a relatively consistent subtidal elevation.

The bathymetric lows of this region are Oaze Deep and the Warp – Sea Reach. These main channels do not show evidence of a long-term trend, although records are quite variable. Four Fathoms Channel was originally called Five Fathoms Channel, which provides a clear indication that this region has shoaled, although this is not supported statistically by the data.

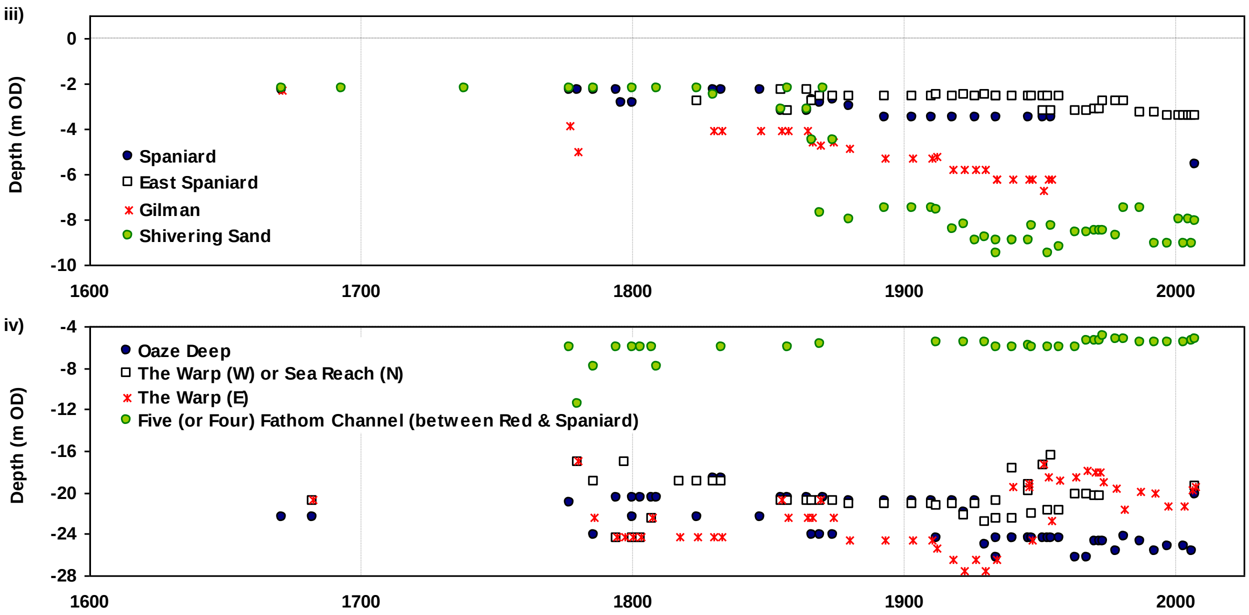

Figure 23 (cont.)

4. Conclusions

The historical changes in seabed elevation, derived from published charts, are spatially and temporally variable. There is evidence of progressive long-term vertical accretion and degradation, in addition to stepped or cyclic variability.

In many cases the changes observed are associated with shifts in bank and channel configuration, and this is particularly true of the *type 2A - estuary mouth* banks within the central Thames estuary. Here, features of close proximity exhibit opposing trends (Figure 24) where channels and banks migrate and go through processes of constriction, attachment and detachment.

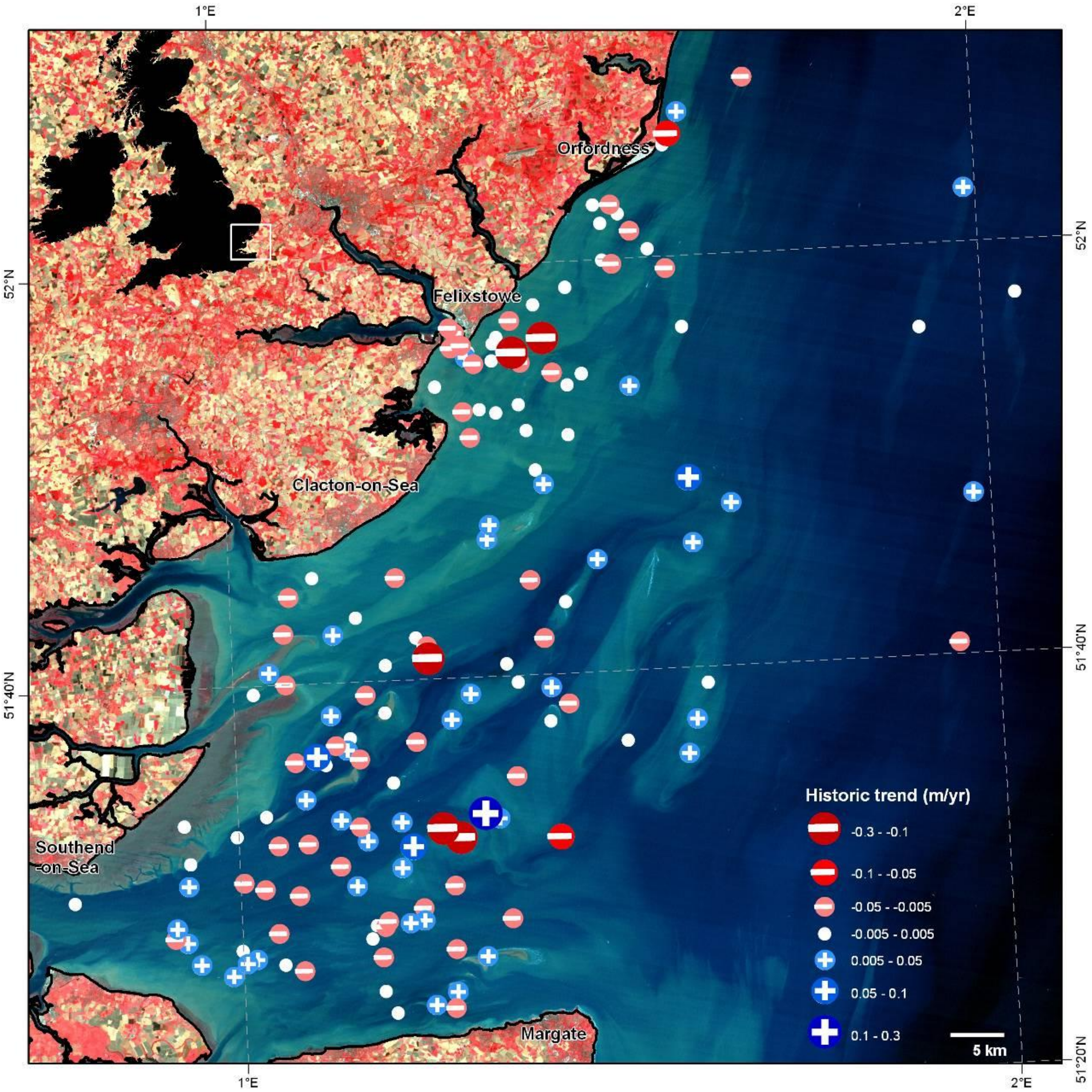

Figure 24 Summary of seabed evolution in the greater Thames estuary as derived from historical trend analysis of charted depths. Note that this summary relates only to overall linear trends (i.e. average historical trends), and some of these are not necessarily significant.

The regional summary suggests that the area around the southern extents of these 2A banks is deepening and that the northern extents are shoaling (Figure 24). The northward extension of Sunk and Long Sand Heads does suggest a general northeasterly shift in these entire features, which would explain the general deepening/shoaling trends observed. Kentish Knock however, is systematically accreting and configuration changes suggest the feature is at the very least sustaining its footprint.

The Suffolk shoreface (in the region of Harwich to Orfordness) appears to show an overall deepening over the history reported here. There is very little evidence in this area of any significant increases in bed elevation, and the majority of features exhibit a negative trend. Much of this appears to be associated with a gradual and progressive down-wearing of the London Clay platform associated with most of the nearshore features. The depositional features, which are mainly *type 3A - headland associated* banks, associated with this region do not display a clear trend, and there is evidence to suggest that a more significant change is occurring in their lateral extent and orientation with respect to the Suffolk shoreline. Further north, Aldeburgh Napes appears to be disconnected from sediment supply and is gradually being denuded, whilst the Onion-Aldeburgh Ridge system displays a possible sediment source-supply coupling.

The general history of the offshore *type 1 – shelf ridges* is not consistent, and there is no evidence that the Gabbards have changed over their documented history. The Galloper and the unnamed bank to the north suggest a positive trend, but the narrowness or spatial inconsistency of these features suggests that this may simply be a factor relating to changes in survey resolution.

5. References

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Appendices

Appendix 1a: List of published charts and pilots consulted (non-Admiralty).

Chart	Date	Publisher/Surveyor	Region
	1580	Norman	Chart of part of the Coasts of Kent, Essex and Suffolk and of the outward Sands between the South Foreland and Orfordness
	1588	Waghenaer	Mariners Mirrour: Coasts between Dover and Orford ... famous River of Thames with all the sands, banks, flats ...
	1635	Blaeu	Thames estuary; Suffolk and Norfolk coasts
	1671	Seller	Thames estuary: sands, channels and buoys
	1682	Thornton	Thames Estuary, Aldeburgh to the South Foreland
	1693	Greenville Collins	Atlas
	1693	Jaillot	Thames, Yarmouth to North Foreland
	1700	Lee	Thames, Orwell, Stour, Deben
	1736	Greenville Collins	Chart of part of coast of England, Holland & Flanders
	1738	Seller	South Foreland to Orford; Suffolk coast
	1769	Mount & Page	Thames, Yarmouth to North Foreland
	1777	Arnold	Chart of part of the Coasts of Kent, Essex and Suffolk and of the outward Sands between the South Foreland and Orfordness
	1780	Sayer & Bennett	A new and accurate chart of the mouth of the Thames and its entrances
	1786	Sayer, Stephenson & Burn	Outer Thames, Thorpeness to N Foreland; Suffolk offshore
	1790	Stanier	Chart of the River Thames from London to the Nore, Margate and the Downs, North, Middle and South Channels, from a survey taken in 1789 and 90
	1794	Heather	Chart of the Entrances to The River Thames
	1796	Heather	Chart of the Downs and Margate Roads
	1797	Diston	Suffolk, Essex, Norfolk coast
	1797	French Admiralty	Thames, Suffolk to Kent
	1800	Burn (Laurie & Whittle?)	Nore to Orfordness containing the Swin and Kings Channel, with the Wallet, Harwich-Harbour & Horsley Bay to Alborough Knapes, And from the Nore to the North Foreland, containing the Five Fathom and South Channels with the Oaze, Deeps, Nub, & Queens Channel & to Kentish Knock
	1800	Heather	Chart of the Entrances to the River Thames
	1803	Steel & Knight	The entrances of the River Thames
	1807	Mudge & Dessiou	Chart of the east coast of England from Orfordness to the South Foreland
	1809	Chandler	The new seaman's guide and coaster's companion
	1809	Laurie & Whittle	Sheet 1: New and correct chart of the Thames mouth; London Bridge to Orfordness (Essex/Suffolk) and North Foreland, The Downs and South Foreland (Kent) Sheet 2: Eastern coast of England
	1817	Norie	A new Chart of the Entrances to the River Thames, extending from the Downs and Orfordness to London
	1819	Laurie	A Chart of the Coasts of Essex and Suffolk, from the Western Spitway to Orford Haven, including the Harbour of Harwich
	1824	MacKenzie	Thames, Orfordness to North Foreland
	1833	Norie	A new Chart of the Southern part of the North Sea ... from the Thames, Harwich, & the Downs to Calais, Dunkirk, Ostend
	1844	Baharie	The improved coaster's guide, and Marine board examination, for the east coast of England and Scotland and the English Channel
	1846	Norie	New and extensive sailing directions for the navigation of the North Sea
	1847	Norie	Sailing directions for the river Thames, from London, to the Nore and Sheerness
	1848	Laurie	Catalogue of the Sea-Charts, and other Nautical Works.
	1857	Norie & Wilson	Chart of the South Eastern Coast of England (The River Thames, from London to Gravesend)
	1857	Laurie	Chart of the South Eastern Coast of England (The River Thames, from London to Gravesend)
	1858	Imray	The River Thames (and approaches to Harwich)
89, 102	1870	Imray, James & Sons	The East Coast of England from Dungeness to Flamborough Head
	1875	Wilson	Harwich to Flamborough Head
89, 102	1885	Imray, James & Sons	East Coast of England [Sheets 1-4]
	1905	Brown & Son	Three Fathom Chart of the Thames and approaches, etc. (Harwich & Ipswich).
5	1946	Stanfords	The Thames Estuary
14	1951	Imray, Laurie, Norie & Wilson	River Thames
Y6	1972	Norie	Thames Estuary: Northern Part

Appendix 1b: List of published charts consulted (Admiralty).

Chart	Date	Publisher/Surveyor	Region
102	1867	British Admiralty	England. East Coast. Pakefield Gateway to Orfordness
1183	2007	British Admiralty	Thames Estuary
1504	1961, 1962, 1965, 1972	British Admiralty	Cromer to Orford Ness
1543	1962, 1965, 1967, 1972, 1974, 1976, 1978, 1982, 1986, 1988, 1990, 1992, 1994, 1996, 1998, 2000, 2002, 2004, 2005	British Admiralty	Winterton Ness to Orford Ness
1607	1912, 1922, 1930, 1934, 1940, 1947, 1953, 1957, 1963, 1967, 1970, 1972, 1973, 1978, 1981, 1987, 1992, 1997, 2003, 2006	British Admiralty	Thames Estuary Southern Part
1610	1855, 1864, 1866, 1870, 1874, 1880, 1893, 1903	British Admiralty	England. East Coast. Sheet 2. Entrance to the Thames
1610	1910, 1918, 1926, 1934, 1954, 1977	British Admiralty	England. East Coast. North Foreland to Orfordness including the Entrance to the Thames.
1630	1874, 1884, 1888, 1910	British Admiralty	England. East Coast. Orfordness to Cromer
1895	1951	British Admiralty	England. South Coast. Sheet VII. Dungeness to the Thames, including Dover Strait
1975	1877, 1912, 1919, 1929, 1930, 1935, 1937, 1939, 1940, 1946, 1948, 1952	British Admiralty	England. East Coast. Kentish Knock and the Naze to the West Swin
1975	1957, 1962, 1967, 1968, 1972, 1973, 1975, 1977, 1978, 1980, 1982, 1988, 1990, 1992, 1996, 1998, 2000, 2003, 2005, 2007	British Admiralty	Thames Estuary Northern Part
2052	1851, 1856, 1911, 1919, 1923, 1934, 1940, 1951, 1959	British Admiralty	England. East Coast. Approaches to Harwich.
2052	1966, 1974, 1977, 1978, 1981, 1984, 1987, 1989, 1992, 1994, 1996, 1997, 1998, 2000, 2003, 2007	British Admiralty	Orford Ness to The Naze
2693	1859, 1922, 1941, 1961	British Admiralty	England - East Coast: Orwell and Stour Rivers
2693	1966, 1974, 1980, 1987	British Admiralty	Approaches to Felixstowe, Harwich and Ipswich with the Rivers Stour, Orwell and Deben
5607	1999, 2001, 2005, 2007	British Admiralty	Thames Estuary. Essex and Suffolk coast
5606	2001, 2005	British Admiralty	Thames Estuary. Ramsgate to Tower Bridge

Appendix 2: List of banks and features analysed.

Feature	Depth
Albion Knowl	min
Aldeburgh Napes	min
Aldeburgh Ridge	min
Alexandra Channel	min/bar
Altar	min
Andrews Spit	min
Barrow (East)	min
Barrow (West)	min
Barrow Deep	max
Barrow Sand	min
Barrow Swatchway	min/bar
Barrows	min
Bawdsey Bank	min
Black Deep	max
Blacktail	min
Bullocks Channel (between Long & Girdler)	min/bar
Burrows Knowl (between West Burrows & Maplin)	min
Buxey Sand	min
Cant	min
Cant Edge Shoals	min
Cliff Foot Rock	min
Cork Hole	max
Cork Knoll	min
Cork Ledge	min
Cork Sand	min
Cork Spit	min
Crossbank (NE of Gunfleet Head)	min
Cutler	min
Duke of Edinburgh Channel (between Long & Girdler)	min/bar
Eagle	min
East Cant	min
East Knowl	min
East Last	min
East Middle Sand	min
East Shivering	min
East Spaniard	min
Felixstowe Ledge	min
Fishermans Gat	min/bar
Five (or Four) Fathom Channel	min/bar
Flagstone (between Whiting (S) & Orford Haven)	min
Foulgers Gat	min/bar
Gilman	min
Girdler	min
Glutton	min
Goldmer Gat	max
Gore/South Channel	max
Gristle	min
Gullet Channel/The Well	max
Gunfleet	min
Gunfleet East Knock	min
Gunfleet Head	min
Gunfleet West Knock	min
Halliday Rock Flats	min

Feature	Depth
Harwich Deep Channel	max
Heaps	min
Hollesley Bay Channel (between Whiting and Middle)	max
Inner (West) Gabbard	min
Kentish Knock	min
Kentish Knock (NW)	min
Kentish Knock (SE)	min
Kettle Bottom	min
King's Channel	max
Knob Channel	max
Knob Shoal (or Spit)	min
Knock Deep	min/bar
Knock John	min
Knock John Channel	max
Last	min
Long Middle	min
Long Sand	min
Long Sand Head	min
Maplin Sands	min
Maplin Spit	min
Margate Hook	min
Margate Sand	min
Medal	min
Medusa Channel	max
Middle (between Barrows and Buxey	min
Middle (between Whiting and shore)	min
Middle (Little, to SW of Middle)	min
Middle Deep	max
Middle Ground (NE of Middle)	min
Middle Ground/Sand (SE of Red)	min
Mouse	min
Mouse Channel	min/bar
Nathaniel Knoll	min
Naze Ledge	min
NE Middle	min
North (or New) Knob	min
North Edinburgh Channel	max
North Falls	min
North Mouse	min
Oaze	min
Oaze Deep	max
Onion Spit	min
Outer (East) Gabbard	min
Pan Patch	min
Pan Sand	min
Pan Sand Hole	max
Pan Speck	min
Pennyhole Bay	min
Pitching Ground	max
Platters	min
Princes Channel (between Tongue & Shingles)	max
Priory Spit	min
Pye Sand	min

Feature	Depth
Queens Channel & The Hole	max
Red Beard	min
Red Sand	min
Ridge	min
Ridge (Harwich Harbour)	min
Rolling Ground	min
Rough (Lower)	min
Rough (Upper)	min
Rough Shoals	min
Saverold	min
Shingles	min
Shingles Patch	min
Shipwash	min
Shipway	max
Shivering Sand	min
Shoe	min
Shoe Hole	max
Shoeburyness	min
Sledway (original, S of Kettle)	min/bar
Smugglers Swash (between Long & Girdler)	min/bar
South East Spit	min
South Edinburgh Channel	min/bar
South Knowl	min
South West Reach (between Maplin Spit & Barrows)	min/bar
Spaniard	min
Spile (Spoil)	min
Spitway (between Gunfleet & Buxey)	max
Stone Banks	min

Feature	Depth
Sunk	min
Sunk (Great)	min
Sunk (Little)	min
Sunk (Middle)	min
Sunk (South West)	min
Sunk Head	min
Sunk Sand	min
Sunken Buxey (in Whitaker Channel)	min
Swashway (modern Sledway)	max
Swire Hole	max
The Galloper	min
The Warp (E)	min/bar
The Warp (W) or Sea Reach (N)	max
Thomas's New Channel (between Long & Girdler)	max
Threshold	min
Tripod	min
Thwart Middle	min
Tizard Bank (E Knock John)	min
Tongue	min
Unnamed Bank	min
Wadgate Ledge	min
Wallet	max
Wedge	min
West Knowl	min
West Rocks	min
West Swin/The Swin	max
Whitakers Channel	max
Whiting Bank	min
Woolpack	min

Definition of depths
min: the minimum depth over banks/shoals
min/bar: the minimum depth of cross-bank channels
max: the maximum depth of between-bank channels

Appendix 3a: Subset of linear regression (single trends) of historical changes in depth.

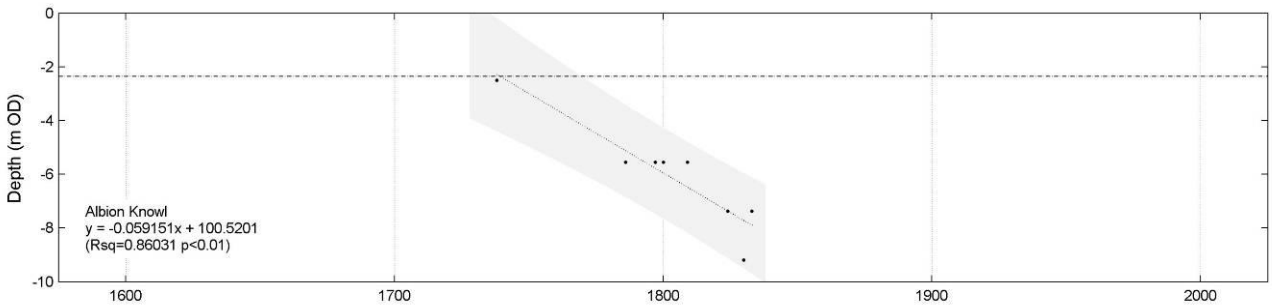
These features exhibit a significant linear relationship (r^2>0.5 and $p \leq 0.001$) between depth and time. The table provides the relevant statistics, and the subsequent figures (Appendix 3b) present the time-series of depths and linear trends (in alphabetical order).

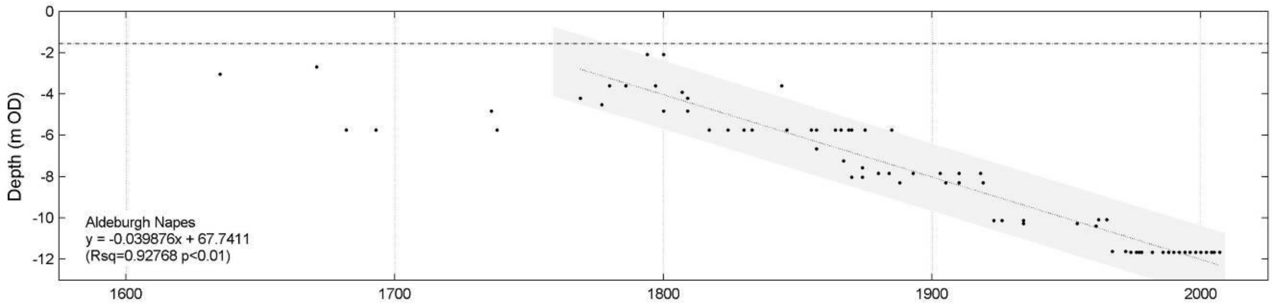
Feature	**r^2**	***p*-value**	**Historic trend (m yr^{-1})**	**Trend time period**		
Banks/bathymetric highs						
Albion Knowl	0.86	0.001	-0.059	1738	to	1833
Aldeburgh Napes	0.93	0.000	-0.040	1769	to	2007
Andrews Spit	0.59	0.000	0.014	1869	to	2005
Barrow (West)	0.83	0.000	-0.013	1800	to	1929
Barrow Sand	0.90	0.000	-0.050	1968	to	2007
Bawdsey Bank	0.71	0.000	0.016	1858	to	2007
Cliff Foot Rock	0.82	0.000	-0.009	1819	to	2007
Cork Knoll	0.86	0.000	-0.013	1817	to	1946
Cork Ledge	0.89	0.000	-0.013	1870	to	2007
Cutler	0.85	0.000	-0.021	1934	to	2007
Gilman	0.95	0.000	-0.021	1830	to	1954
Girdler	0.63	0.000	-0.016	1870	to	2007
Glutton	0.74	0.001	-0.031	1786	to	1885
Gristle	0.66	0.000	-0.043	1800	to	1941
Gunfleet Head	0.57	0.000	0.026	1817	to	1982
Heaps	0.98	0.000	-0.099	1857	to	1952
Inner (West) Gabbard	0.88	0.000	0.019	1910	to	2007
Kentish Knock	0.58	0.000	0.010	1635	to	2007
Kettle Bottom	0.93	0.000	-0.018	1777	to	2007
Knob Shoal (or Spit)	0.78	0.000	0.066	1910	to	2007
Knock John	0.82	0.000	0.018	1866	to	2007
Last	0.87	0.000	0.017	1855	to	2007
Long Sand Head (Bell)	0.90	0.000	0.049	1824	to	2007
Nathaniel Knoll	0.69	0.000	-0.056	1809	to	1885
North (or New) Knob	0.88	0.000	0.026	1874	to	2007
Oaze	0.70	0.000	-0.015	1777	to	2007
Pan Sand	0.80	0.000	-0.029	1947	to	2007
Ridge	0.87	0.000	0.021	1777	to	2007
Ridge (Harwich Harbour)	0.84	0.000	-0.009	1671	to	2007
Shingles	0.71	0.000	0.026	1796	to	1987
Shingles Patch	0.82	0.000	0.074	1893	to	1973
Shivering Sand	0.77	0.000	-0.052	1830	to	1957
Threshold	0.57	0.000	0.009	1824	to	1999
Tizard Bank (E Knock John)	0.89	0.000	0.035	1866	to	1997
Tongue	0.79	0.000	0.019	1777	to	1987
Unnamed Bank	0.90	0.000	0.109	1954	to	2007
Wedge	0.84	0.000	-0.050	1777	to	1972
Whiting Bank	0.58	0.000	0.009	1817	to	2007
Channels/bathymetric lows						
Alexandra Channel	0.81	0.000	0.059	1903	to	2007
Fishermans Gat	0.91	0.000	-0.033	1824	to	2007
Foulgers Gat	0.85	0.000	-0.042	1926	to	2000
Knock John Channel	0.94	0.000	-0.065	1940	to	1981
South Edinburgh Chl	0.76	0.000	0.099	1912	to	2007
South West Reach	0.86	0.000	0.158	1910	to	2007
Swire Hole	0.68	0.000	-0.036	1817	to	2007
Whitakers Channel	0.53	0.000	-0.014	1780	to	2005

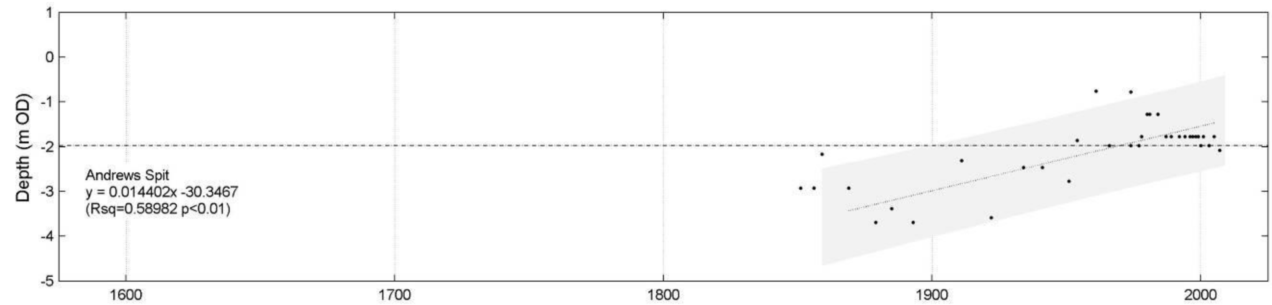
Appendix 3b: Subset of linear regression results (single trends) for historical changes in depth (plots).

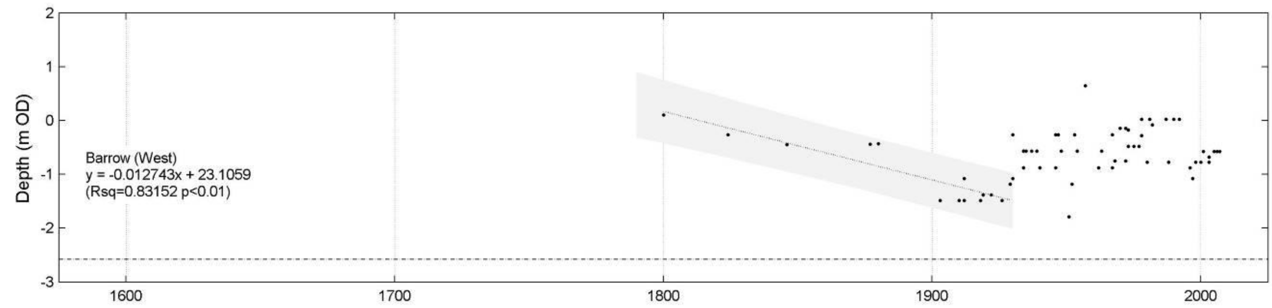
Graphs show all data excluding those only defined as 'dry'. Modelled chart datum at each feature is provided on each plot as a reference level (dashed line). The shaded zone around the regression trend corresponds to the 95% confidence interval.

Banks/bathymetric highs









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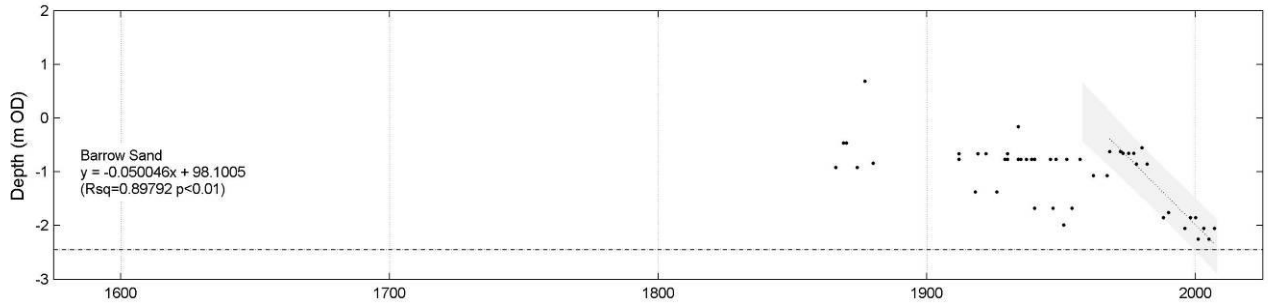

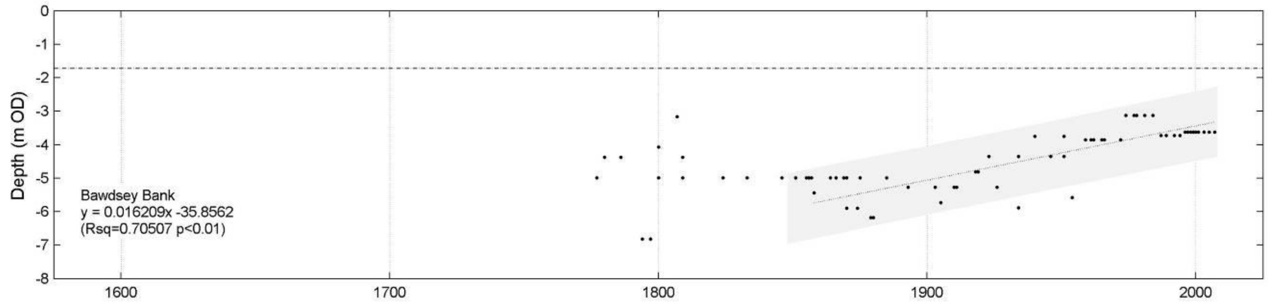

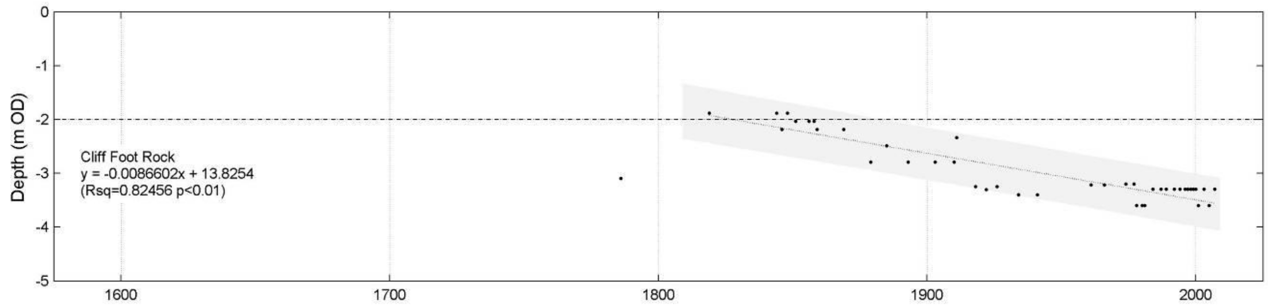

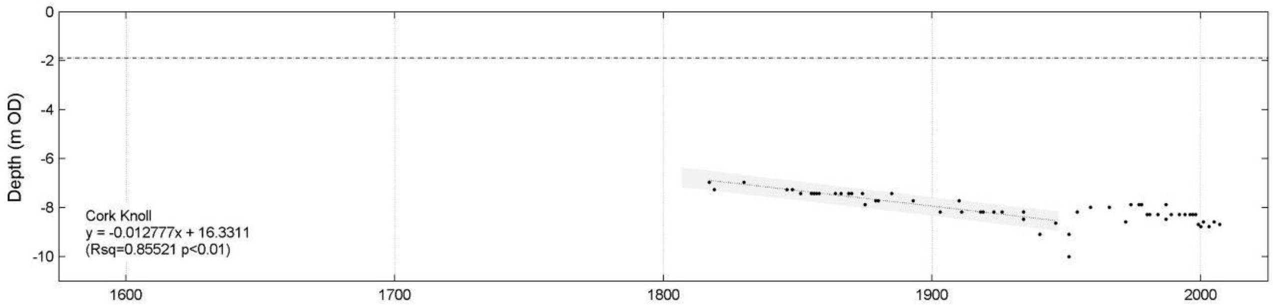

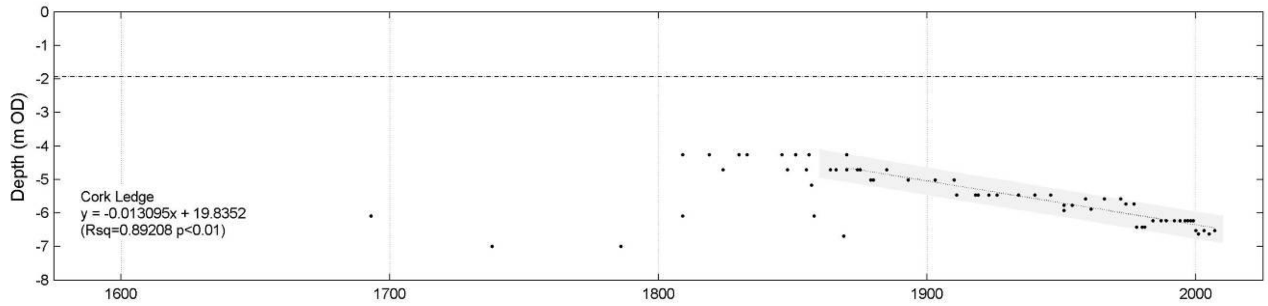

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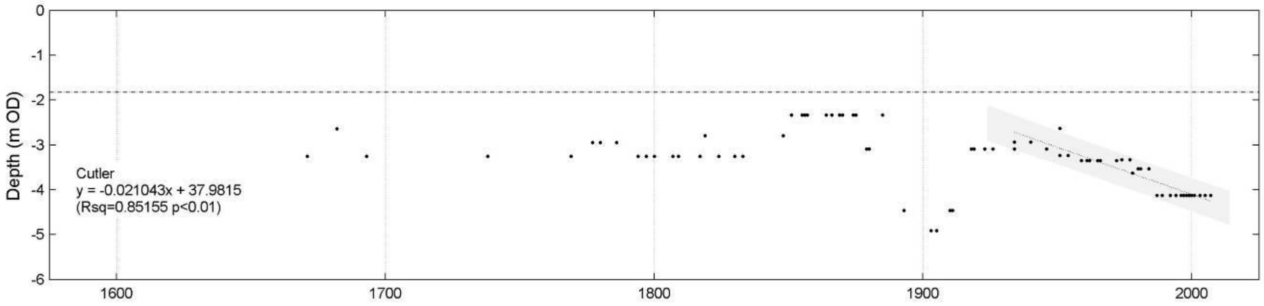

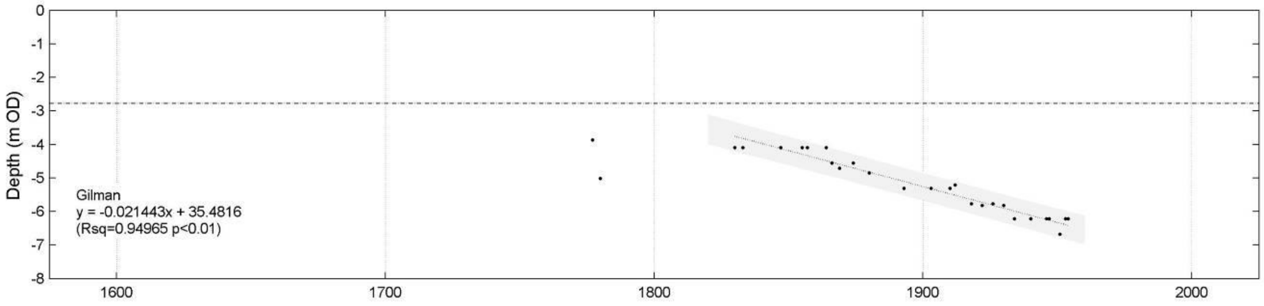

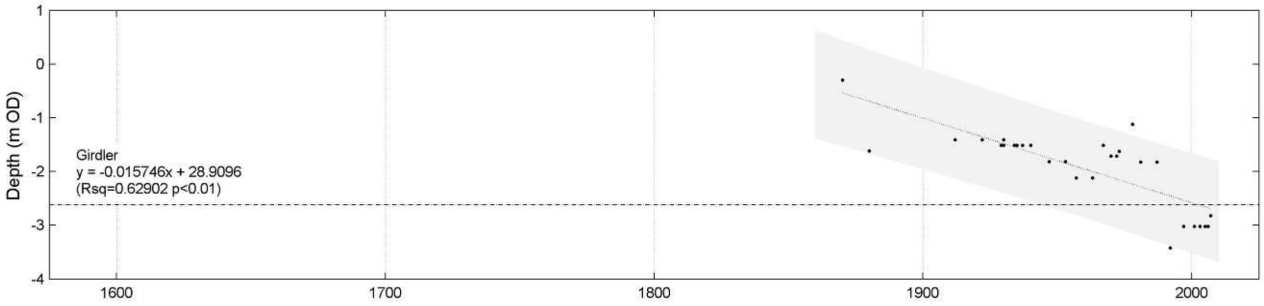

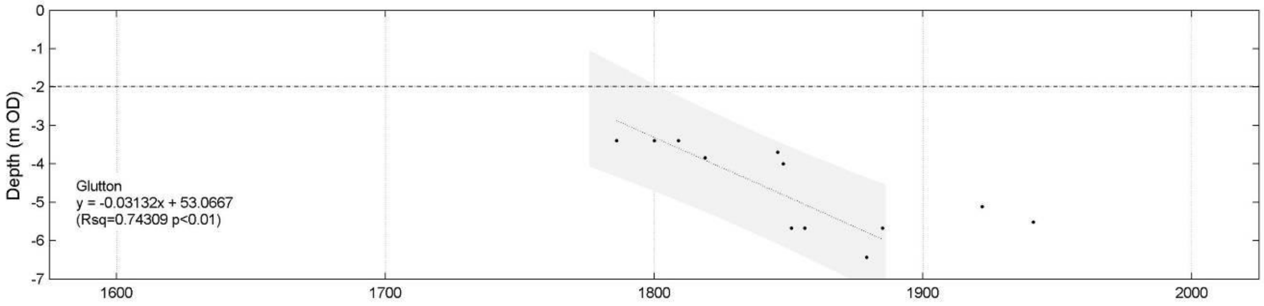

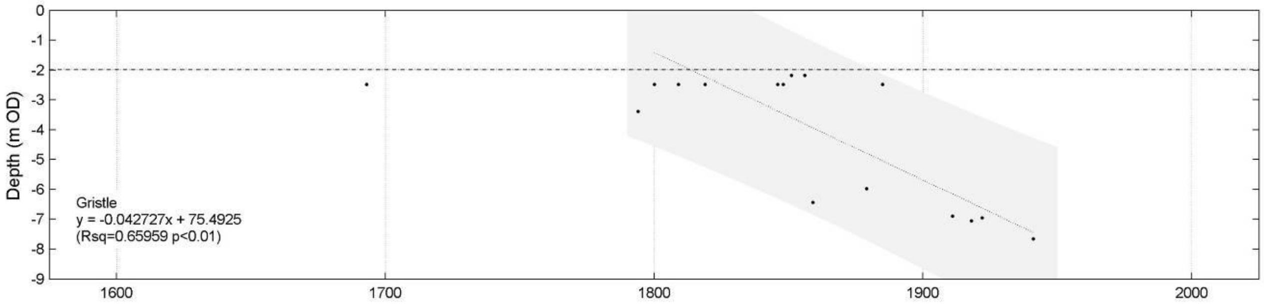

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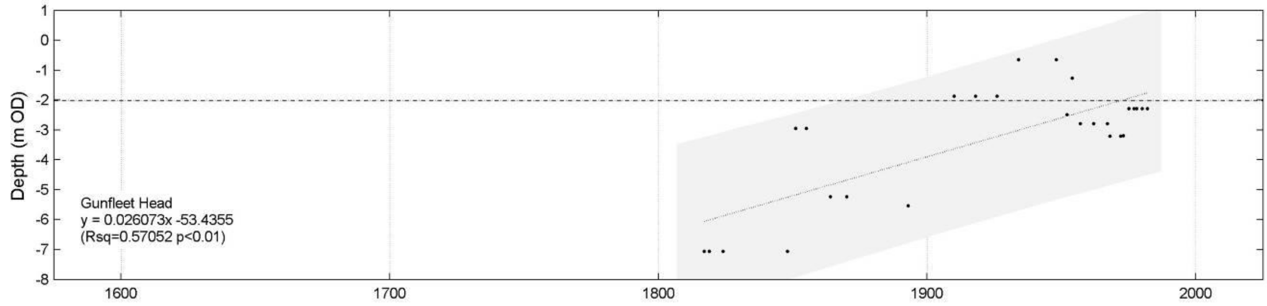

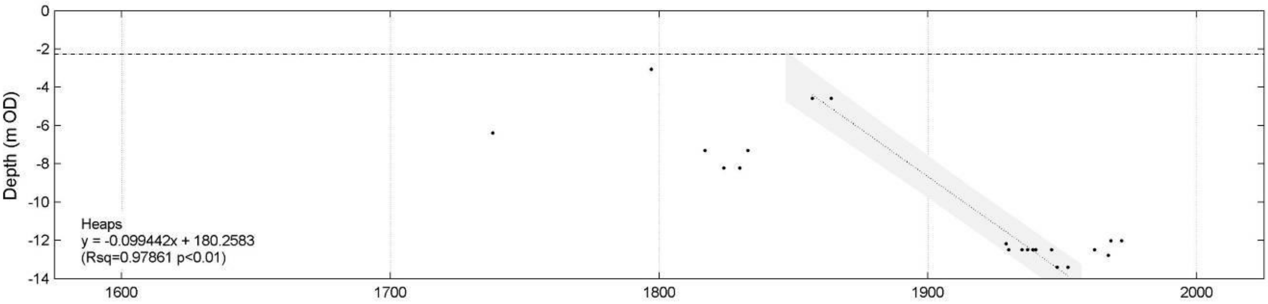

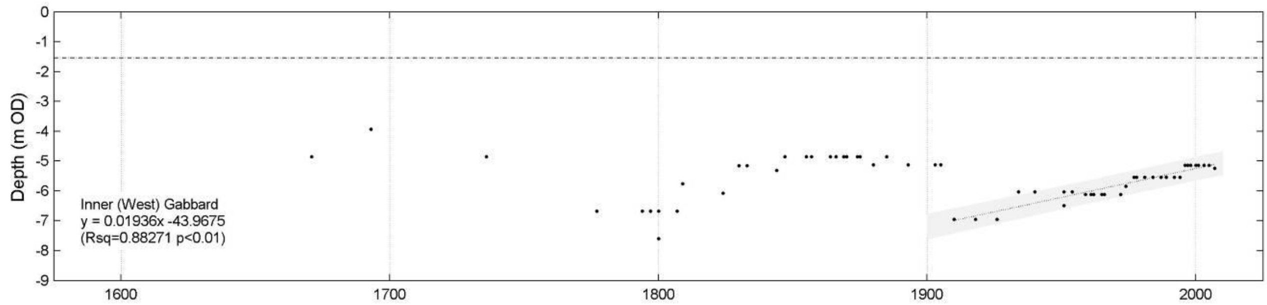

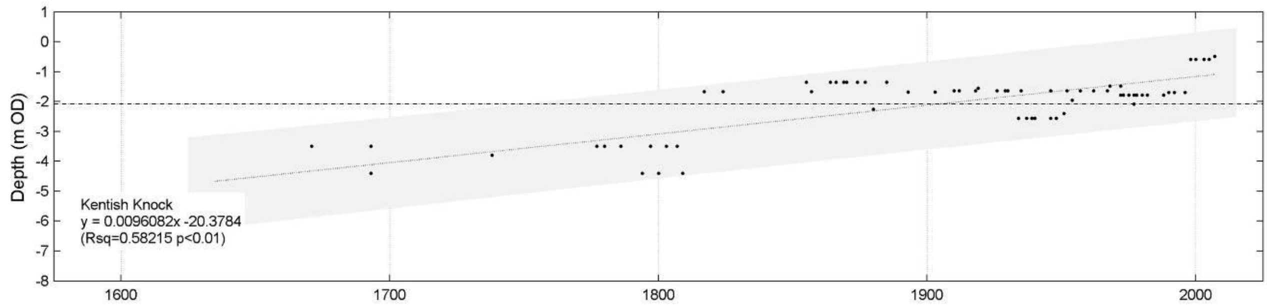

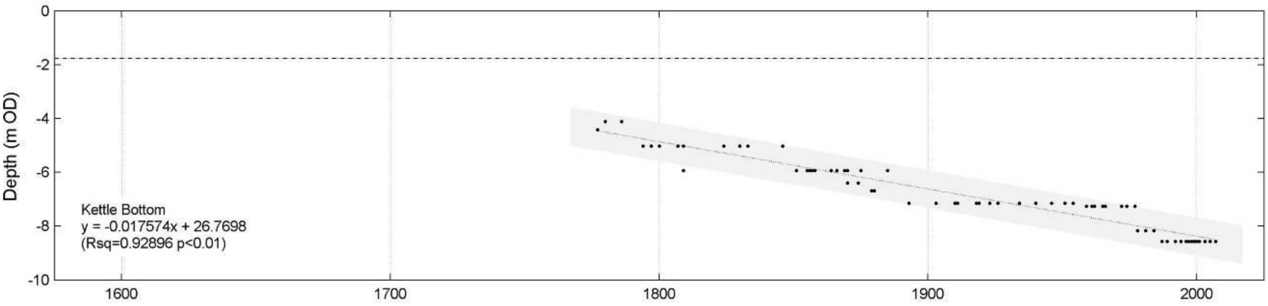

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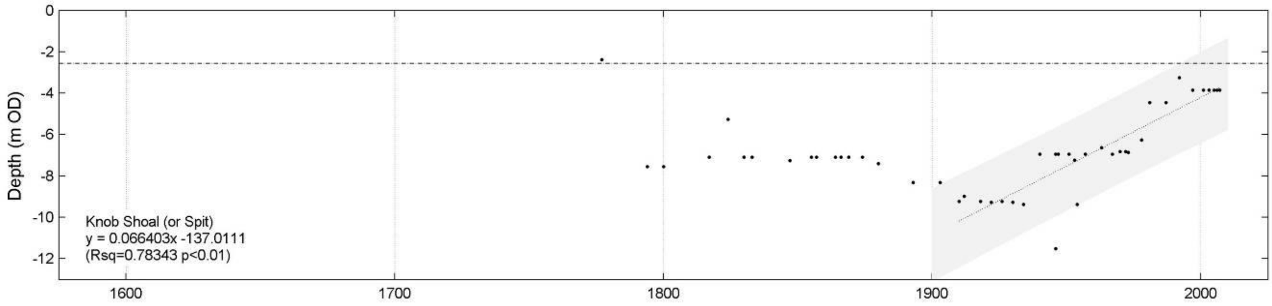
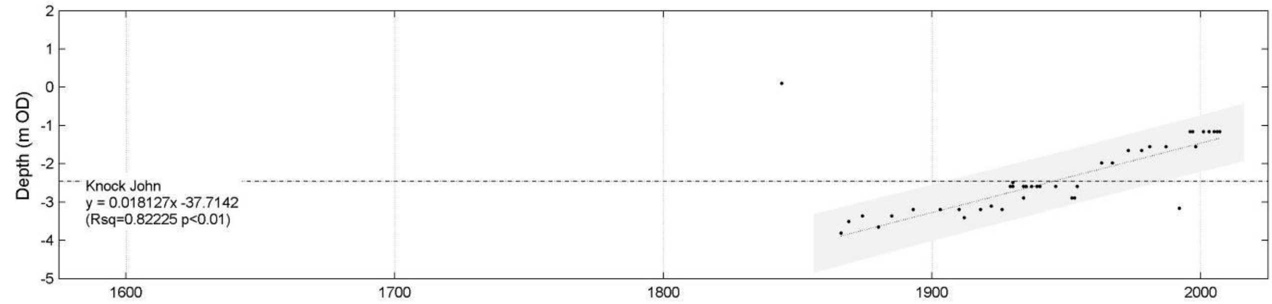
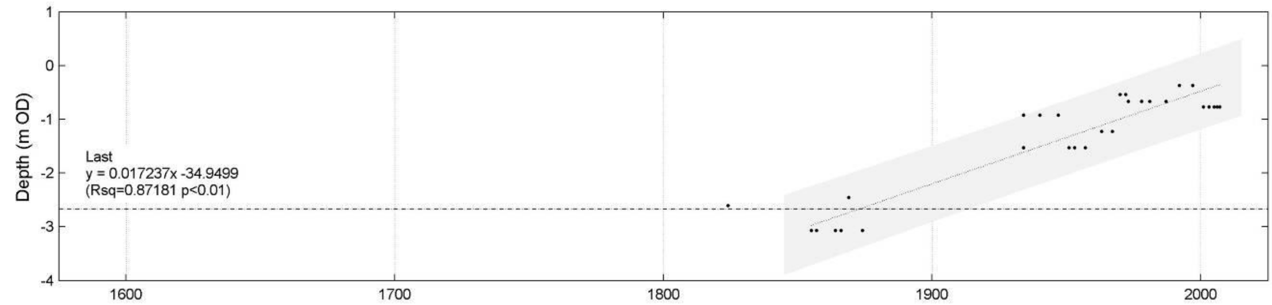
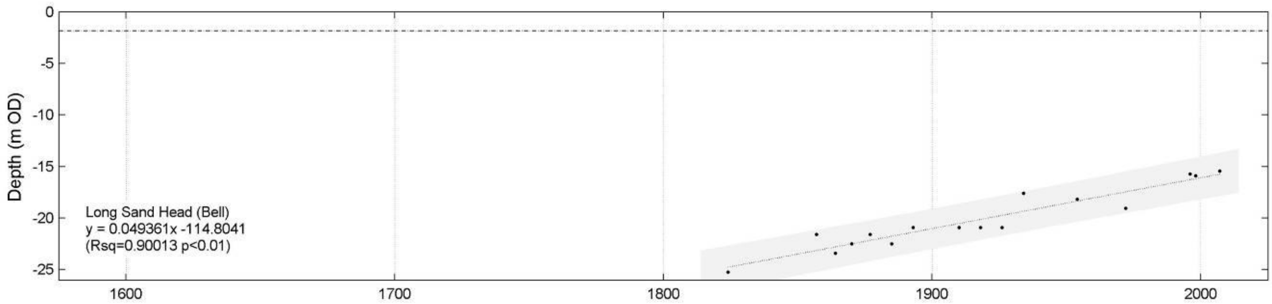
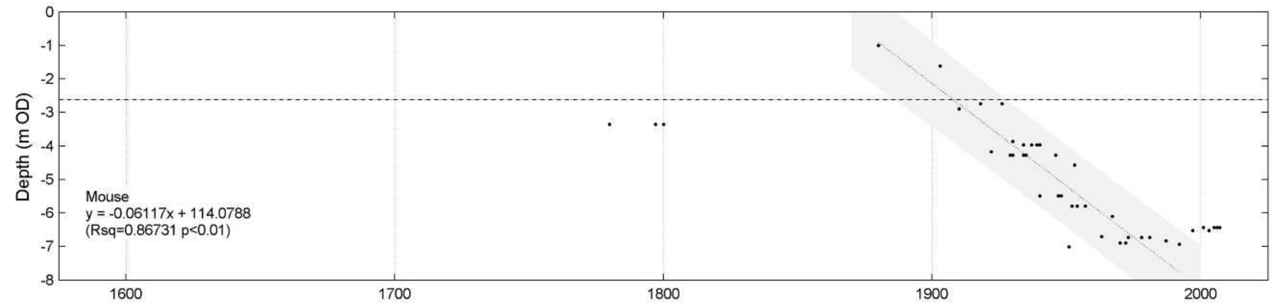


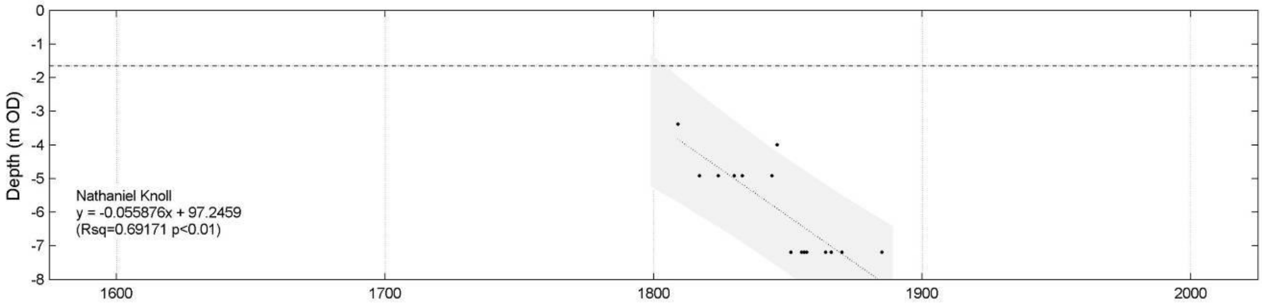


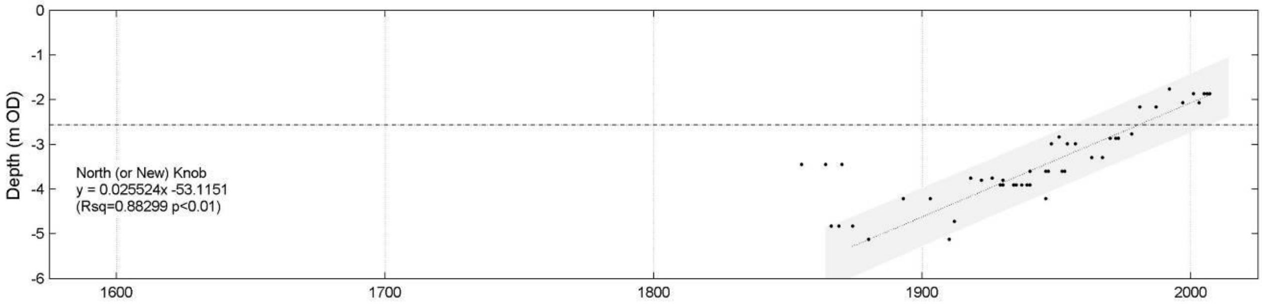


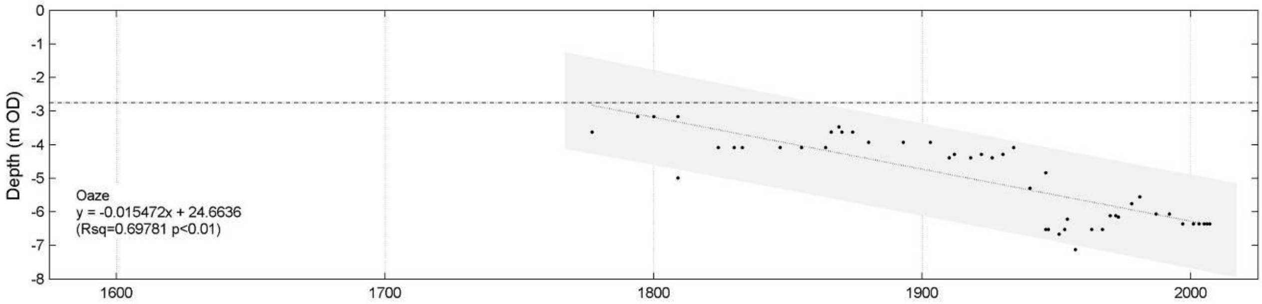


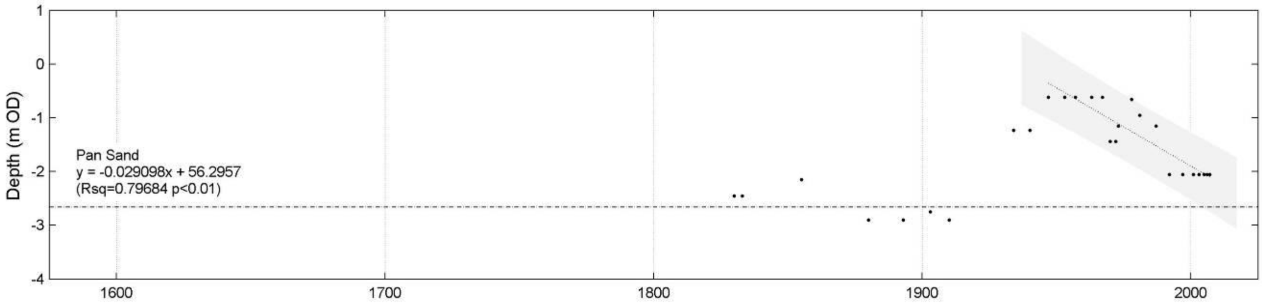


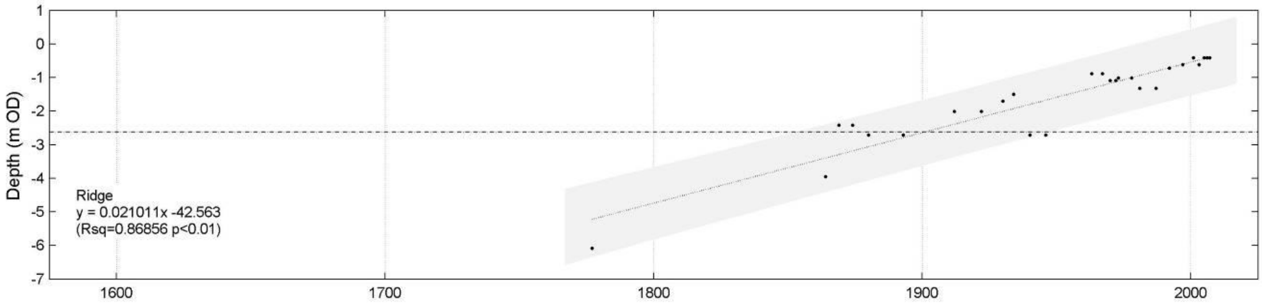
Appendix 3b (cont.)



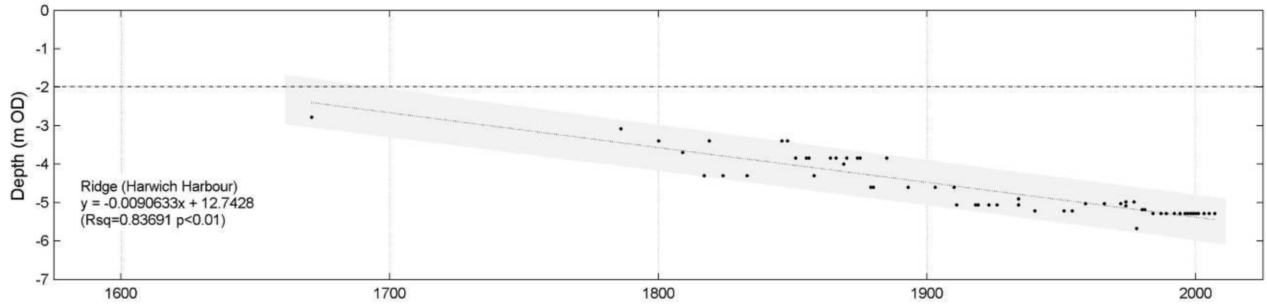


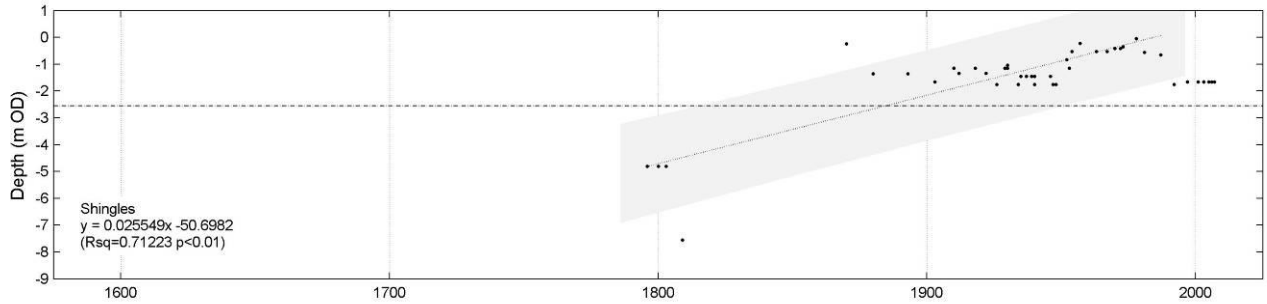


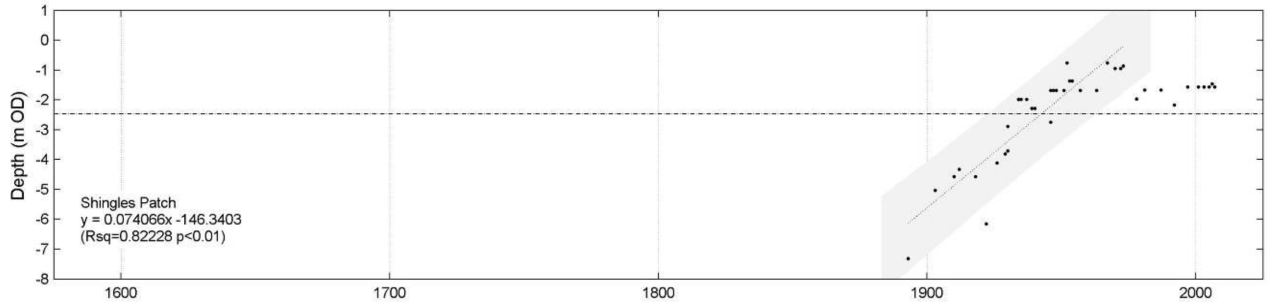


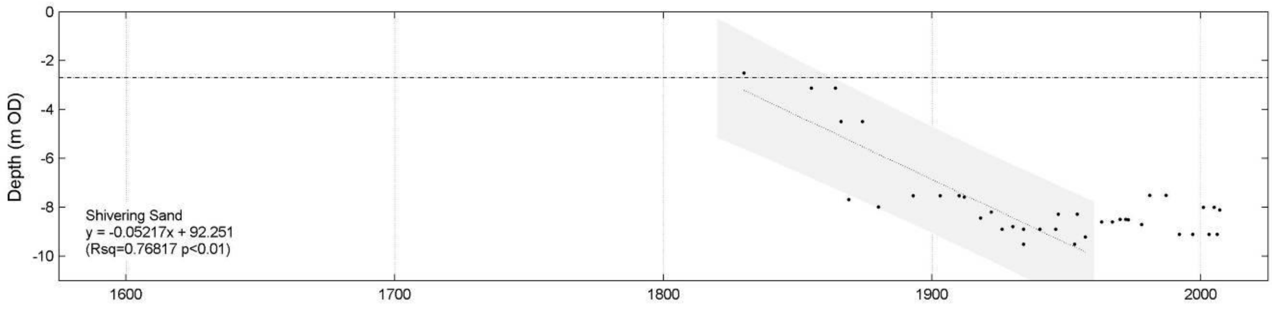


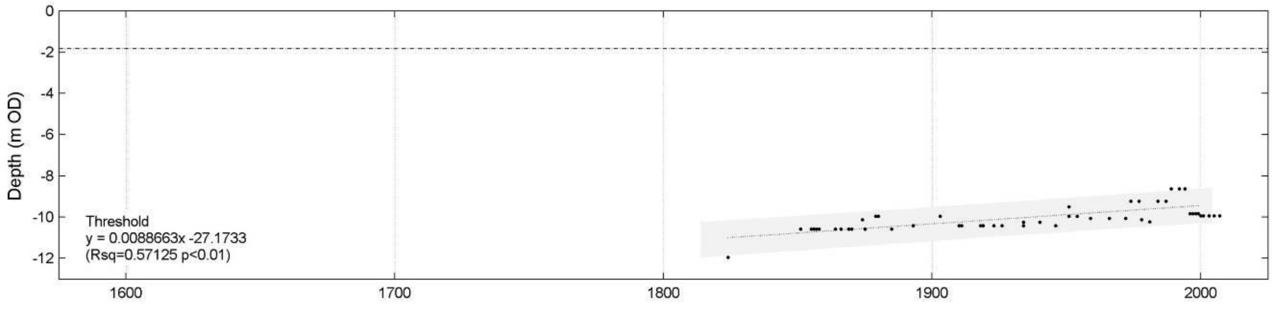
Appendix 3b (cont.)



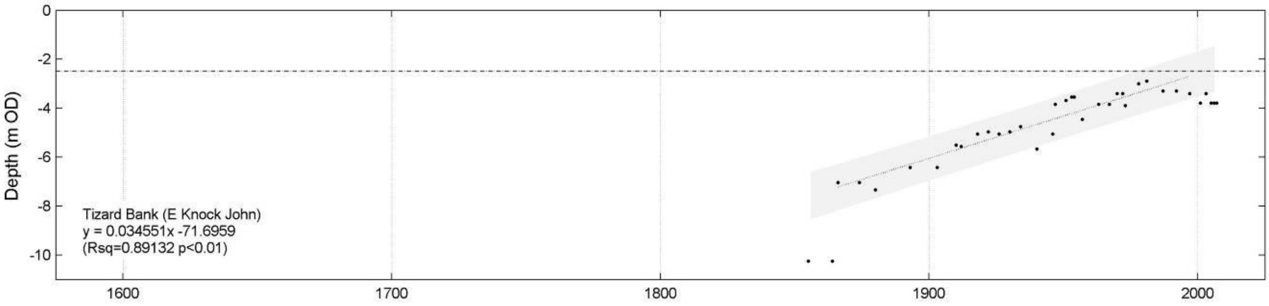


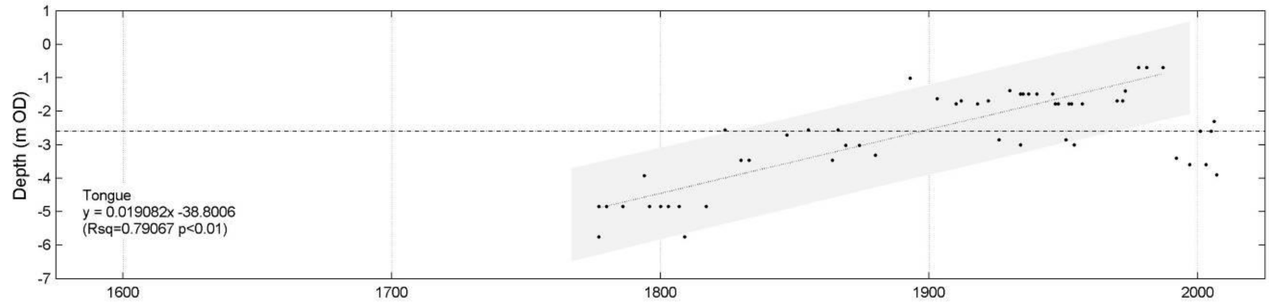


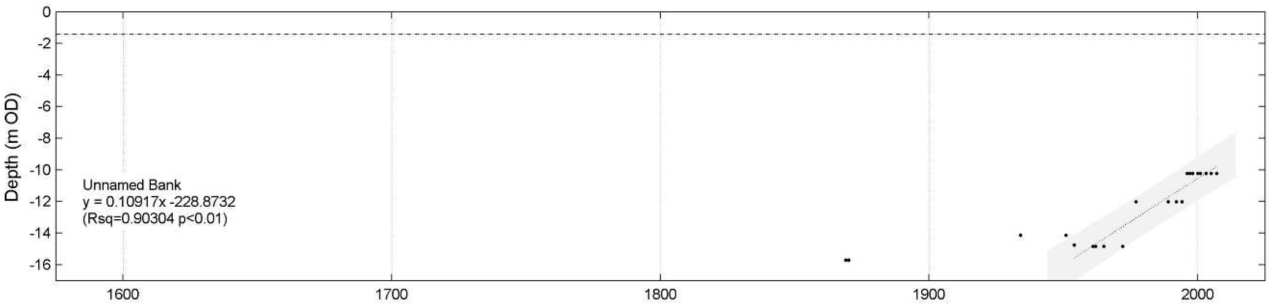


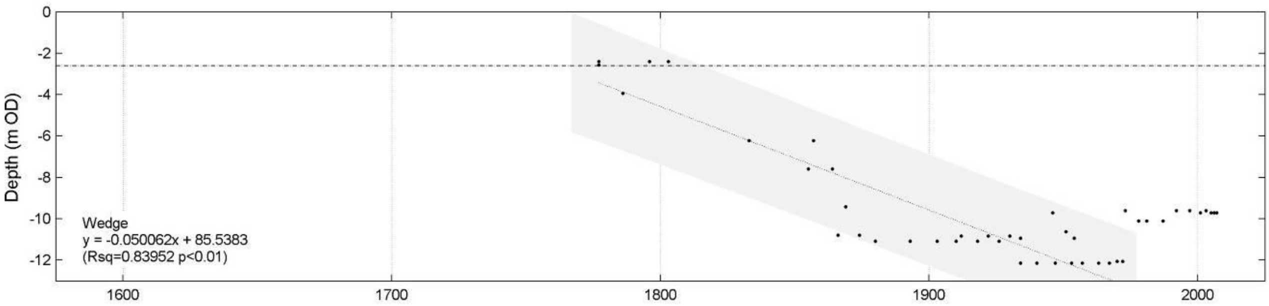


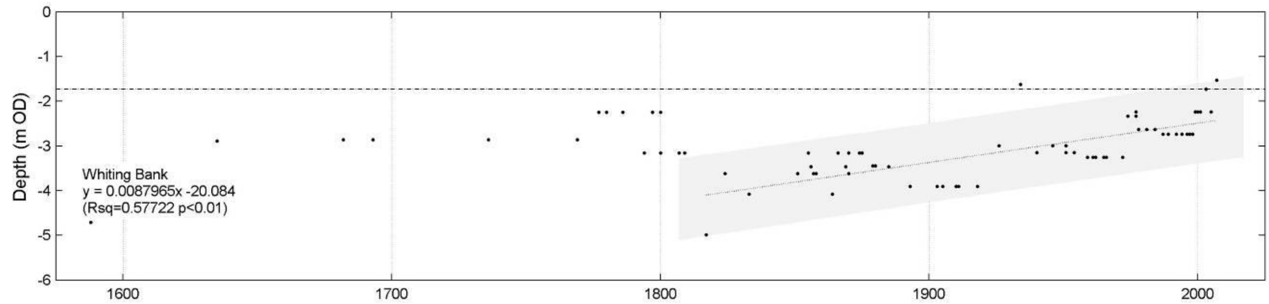
Appendix 3b (cont.)





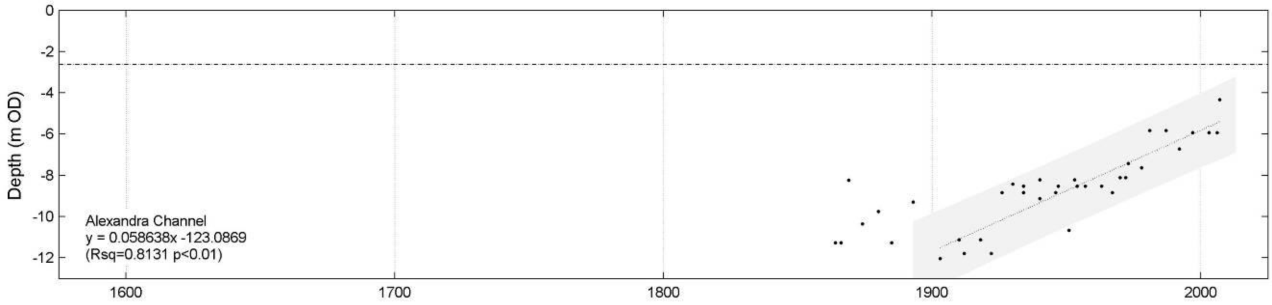


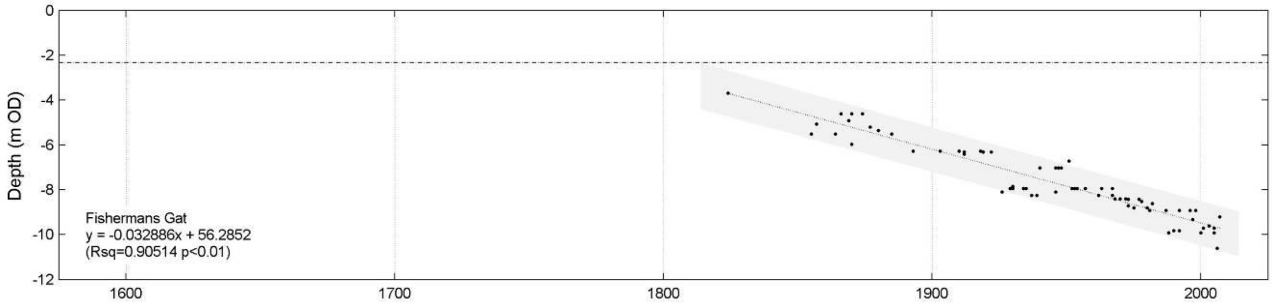


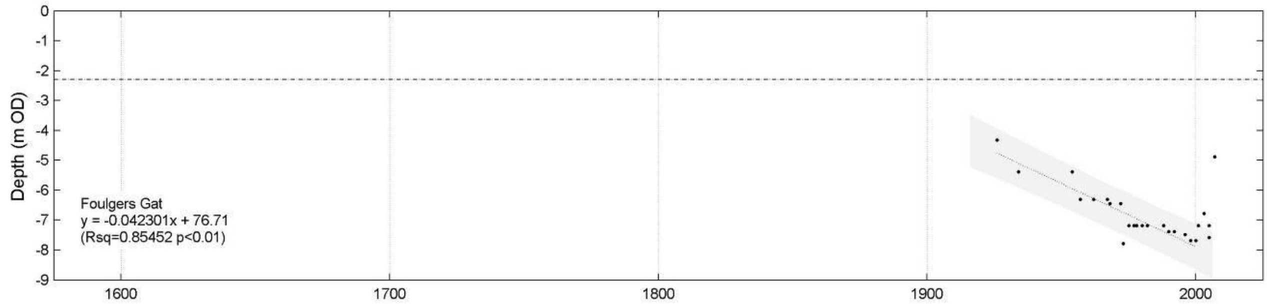


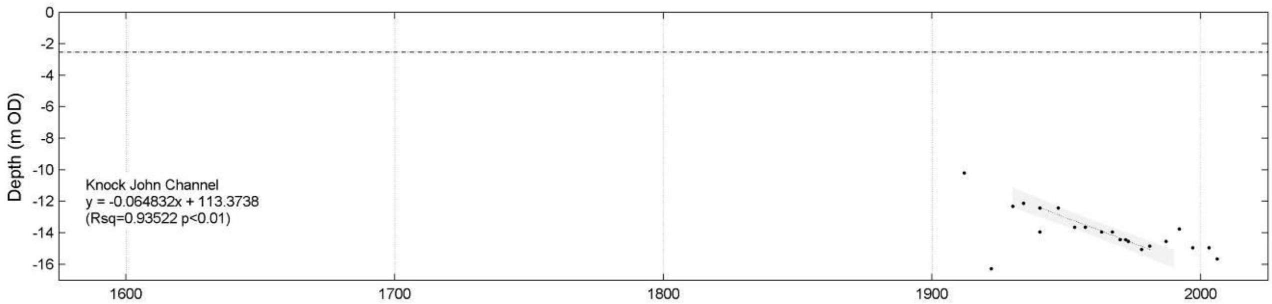
Appendix 3b (cont.)

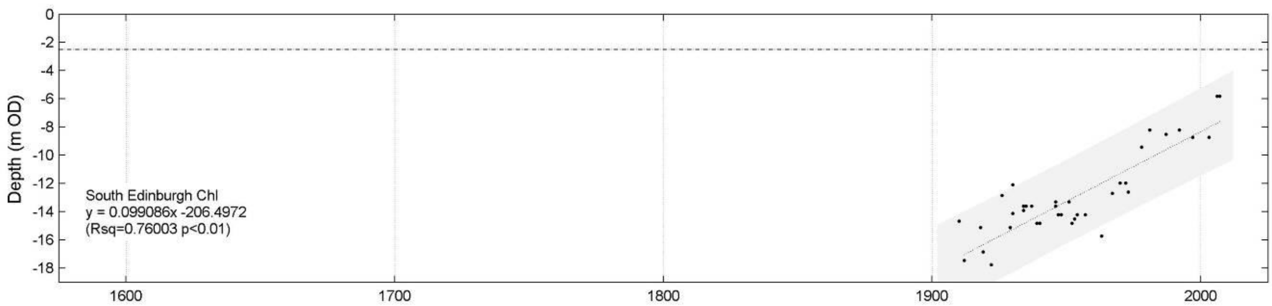
Channels/bathymetric lows



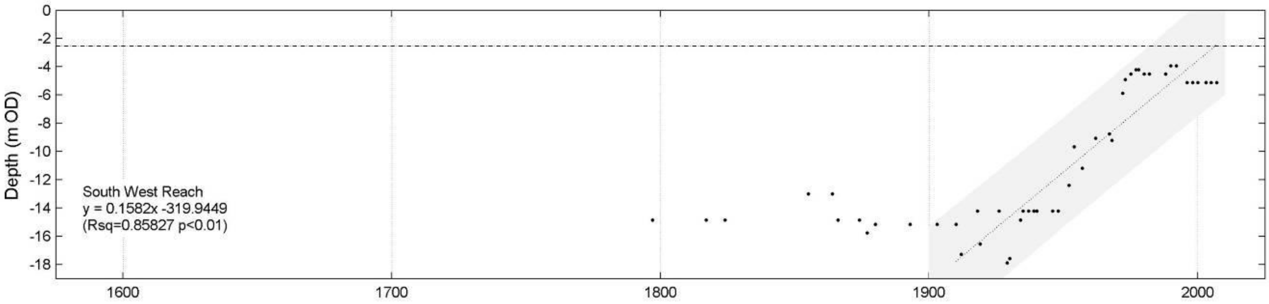


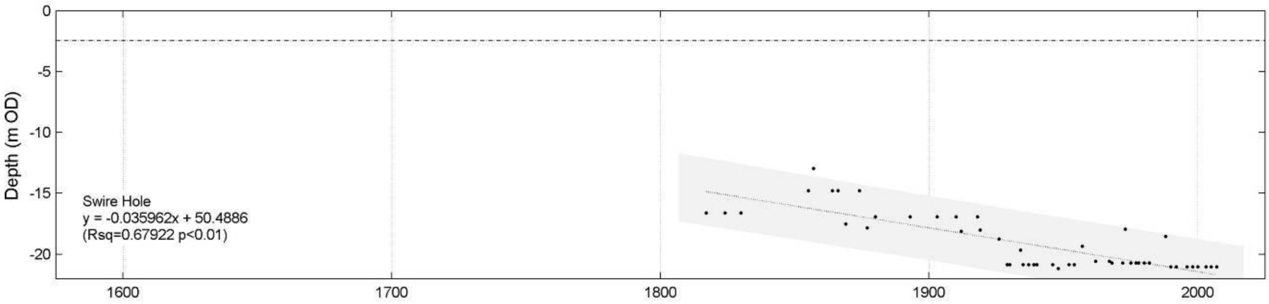


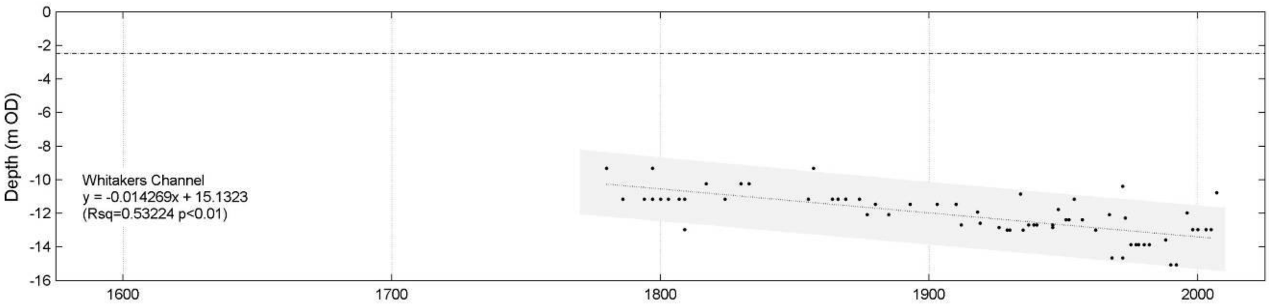




Appendix 3b (cont.)







Appendix 4a: Subset of linear regression (segmented) results for historical changes in depth (statistics).

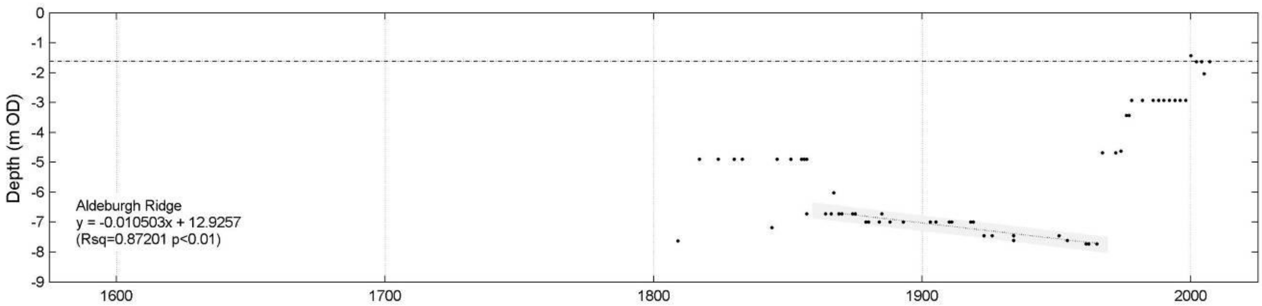
These features exhibit one or more significant linear relationships (r^2>0.5 and p<0.01) between depth and time within a subsection of the full time series. The table provides the relevant statistics, and the subsequent figures present the time-series of depths and segmented linear trends (in alphabetical order).

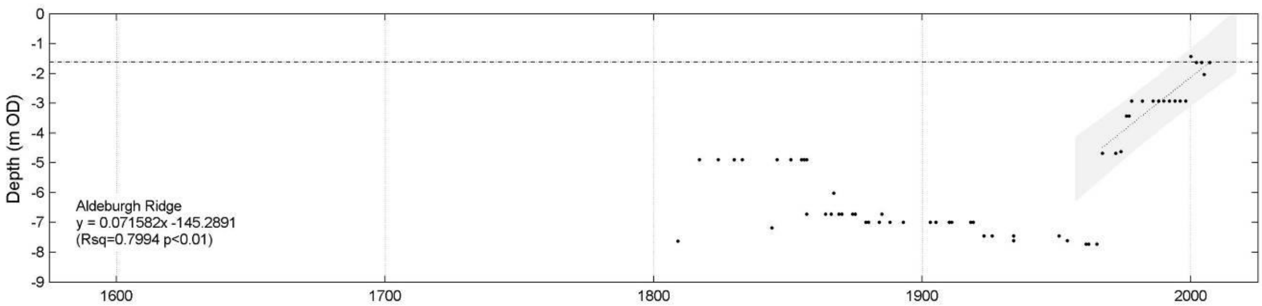
Feature	r^2	*p*-value	Historic trend (m yr^{-1})
Banks/bathymetric highs			
Aldeburgh Ridge (1869-1965)	0.87	0.000	-0.011
Aldeburgh Ridge (1967-2007)	0.80	0.000	0.072
Kentish Knock - SE arm (1797-1885)	0.88	0.000	0.073
Kentish Knock - SE arm (1885-1926)	0.74	0.003	-0.070
Kentish Knock - SE arm (1926-2007)	0.95	0.000	0.063
Margate Sand (1786-1880)	0.88	0.001	-0.026
Margate Sand (1880-2007)	0.59	0.000	0.011
Onion (1777-1972)	0.92	0.000	-0.039
Onion (1972-2007)	0.78	0.000	0.176
Channels/bathymetric lows			
Barrow Swatchway (1817-1988)	0.82	0.000	-0.051
Barrow Swatchway (1987-2007)	0.54	0.003	0.136
North Edinburgh Channel (1910-1940)	0.82	0.000	0.105
North Edinburgh Channel (1957-2007)	0.89	0.000	0.130

Appendix 4b: Subset of linear regression (segmented) results for historical changes in depth (plots).

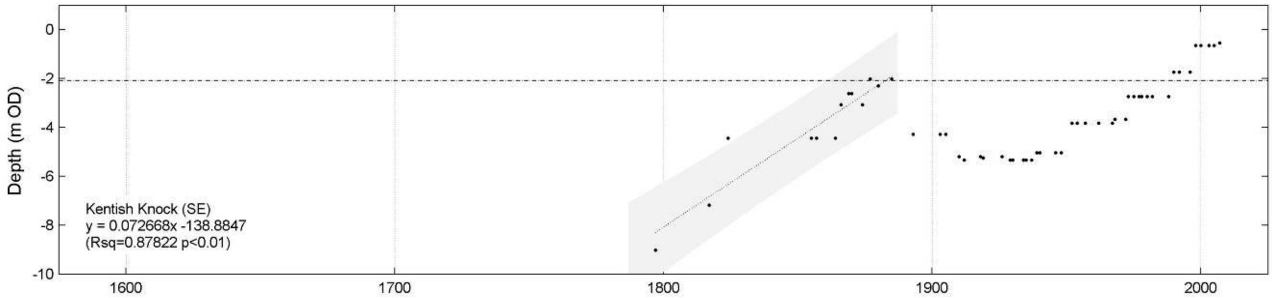
Graphs show all data excluding those only defined as ‘dry’. Modelled chart datum at each feature is provided on each plot as a reference level (dashed line). The shaded zone around the regression trend corresponds to the 95% confidence interval.

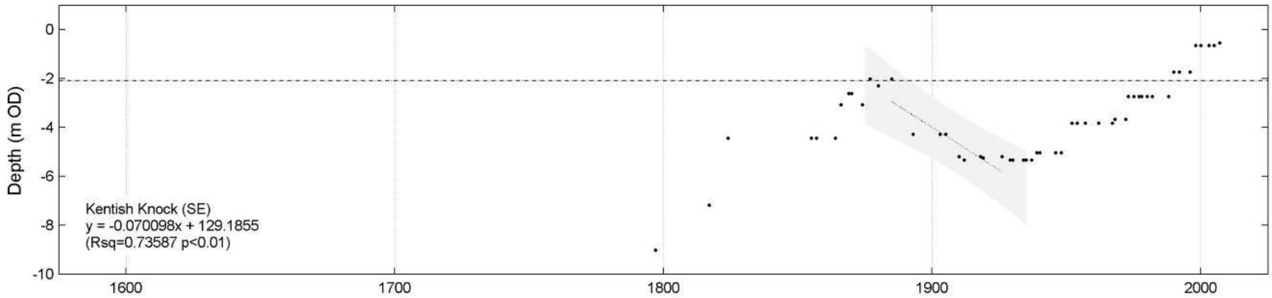
Banks/bathymetric highs

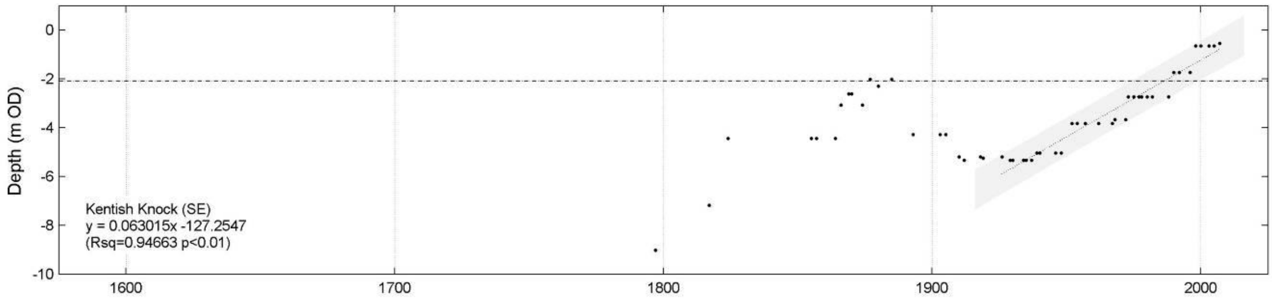


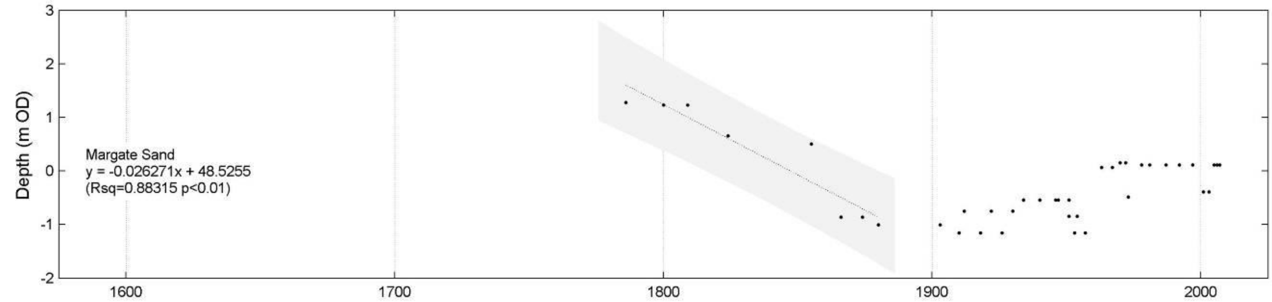


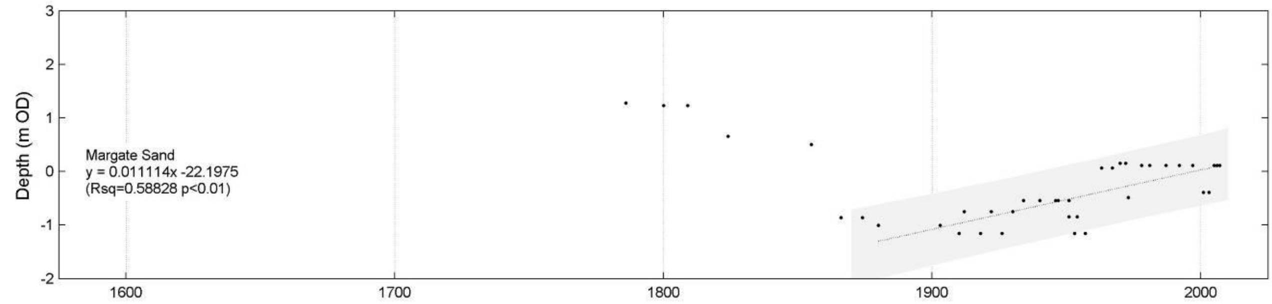
Appendix 4b (cont.)

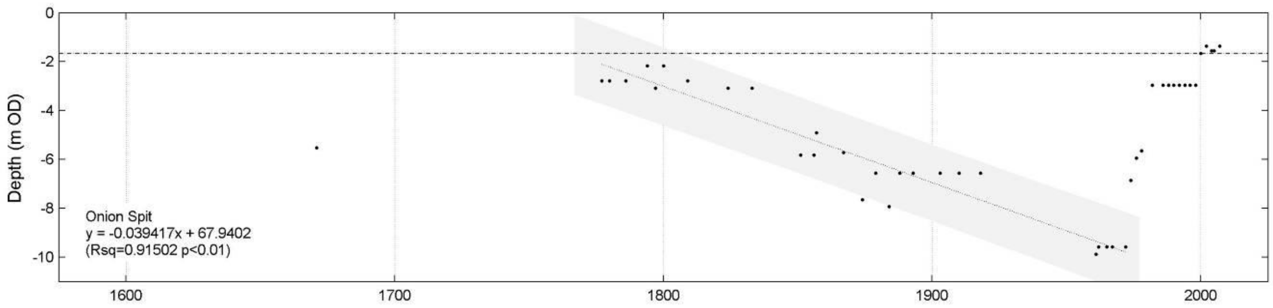


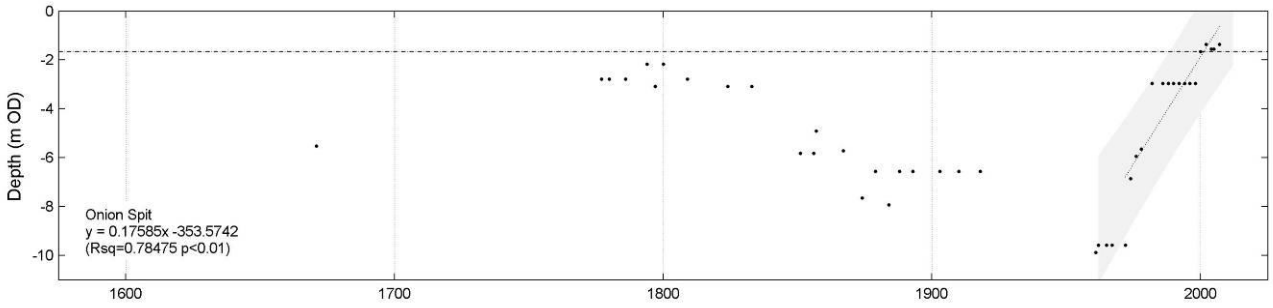






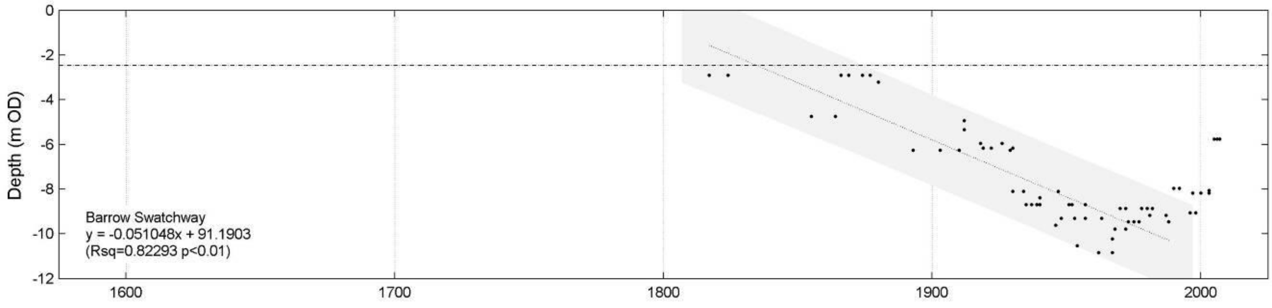


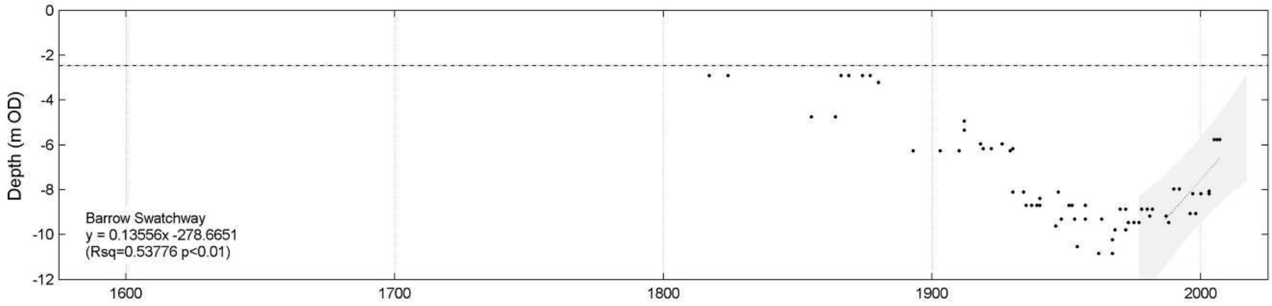

Depth (m OD)
Onion Spit
y = -0.039417x + 67.9402
(Rsq=0.91502 p<0.01)
0
-2
-4
-6
-8
-10
1600
1700
1800
1900
2000

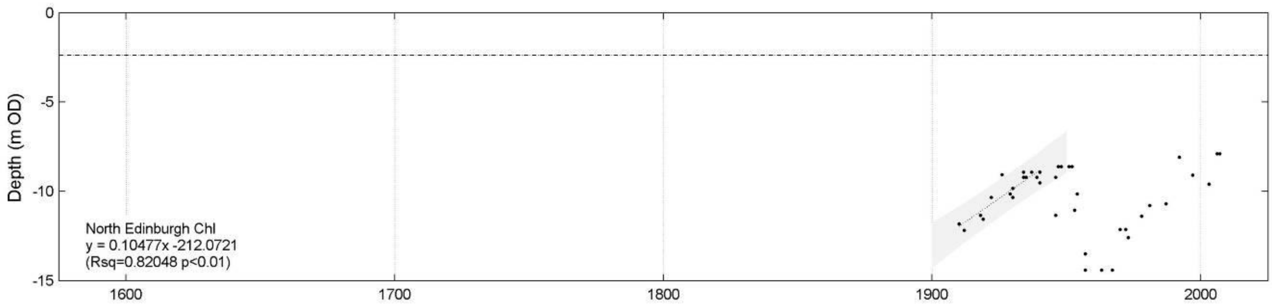

Depth (m OD)
Onion Spit
y = 0.17585x -353.5742
(Rsq=0.78475 p<0.01)
0
-2
-4
-6
-8
-10
1600
1700
1800
1900
2000

Appendix 4b (cont.)

Channels/bathymetric lows







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16 New Burlington Place
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Tel: 020 7851 5080
www.thecrownestate.co.uk
ISBN: 978-1-906410-04-9