Marine Estate Research Report

Seabed mobility in the greater Thames estuary

Seabed mobility in the greater Thames estuary

The Crown Estate – Caird Fellowship Research Project

Final Report – January 2009

Helene Burningham
Jon French

Coastal & Estuarine Research Unit
Department of Geography
University College London

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) at 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

Dissemination Statement

Disclaimer

Authors' Disclaimer

Suggested Citation

Burningham, H. and French, J. 'Seabed mobility in the greater Thames estuary'.

The Crown Estate, 62 pages

ISBN: 978-1-906410-09-4

First published 2009

Contents

i. Executive Summary

This report presents results from a Caird-Crown Estate research project 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 180 years have been analysed to assess the geomorphological evolution of the greater Thames seabed.

Charts published since the early 1800s comprise sufficient grid reference or ground control detail for georectification onto a common coordinate system (British National Grid), and a total of 10 charts were used here to reconstruct the historical changes in seabed morphology. Systematic errors in the positioning of offshore features proved only problematic for the earliest chart (1824). Soundings were digitised as points from each chart, and the depth measures at each point were converted to Ordnance Datum. The point data were interpolated onto a regular 100 x 100 m grid (3D surface), which formed the basis of further analysis.

The historical evolution of the greater Thames seabed was examined using cross-estuary and shore-normal transects; bathymetric change maps and spatial statistics. The analyses illustrated considerable spatial variability in seabed mobility. Within the central Thames, the banks of Barrows, Sunk Sand, Long Sand and Kentish Knock have experienced significant depth changes associated with lateral shifts. In many cases, the bank surface comprises numerous bathymetric highs that appear to migrate along the banks.
Progressive changes can be seen at Long Sand Head, which has been prograding northward over the last 180 years, and Kentish Knock, which has been lengthening and changing shape over this period.

The Suffolk shoreface has also experienced some gradual shifts in bank position. Cutler bank has moved seaward, whereas Whiting and Aldeburgh Ridge have moved landward. Bawdsey Bank appears to be extending northward, and the Shipwash has shifted around a central axis, with more recent change in shape. It is not clear whether the offshore banks (Gabbards, Galloper) have moved due to systematic positional errors, but the head and tails of these banks do show evidence of growth and decay.

ii. Glossary

Accommodation space

Accommodation space refers to the space available for sediment deposition and morphological progradation. Within a coastal and estuarine context, geological and antecedent structures impart controls on the physical space available for the development of sedimentary environments, such as intertidal flats and subtidal banks, within a body of water. Accommodation space can be spatially and temporally available, depending on the nature of system boundaries and constraints.

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.

Eigenvalue

Eigenvalues of a component (as derived in principal component analysis) are a measure of the variance in the dataset explained by the component. Eigenvalues can be expressed as a proportion of the total variance (i.e. the total sum of all eigenvalues), thereby allowing the importance of the component (in terms of the degree to which it explains the variance in the data) to be expressed as a percentage.

Eigenvector

Eigenvectors (as derived in principal component analysis) show how each component is related to each of the original variables. Eigenvectors work similarly to correlation coefficients: a value close to zero indicates that the component is poorly related to the input variable, a positive value suggests a positive relationship and a negative value shows a negative relationship. Those variables associated with the maximum and minimum eigenvectors of one component would therefore represent opposite ends of the gradient or variance expressed in that component.

Georeferencing and georectification

This is the process of assigning real-world coordinates to a spatial dataset that does not contain inherent spatial referencing, such as a scanned aerial photograph or map. Ground control points (GCPs) are used to assign real-world coordinates to specific points on the spatial dataset. A rectification algorithm is then used to define the adjustment between the real coordinates of the GCPs and their location on the photograph or map. Applying this adjustment to the whole photograph or map allows every pixel of the scanned photograph or map to be georectified into a real coordinate system.

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).

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.

Principal component analysis (PCA)

A PCA is a form of multivariate statistical analysis, the aim of which is to analyse and account for the variability in multivariate datasets by deriving principal components that explain the variance in a reduced number of measures. PCA is a useful technique for the analysis of large datasets comprising many measurements. Principal components are produced in order of importance: the first principal component expresses the main variation, and subsequent components will account for the remaining (decreasing) variance. The spatial expression of a PCA, as undertaken here in ArcGIS Spatial Analyst, has the aim of explaining the variance in the original data layers in the form of a smaller number of principal component layers that maintain the spatial reference of the original layers.

Projection (map)

Coordinates quoted in degrees latitude/longitude are based on a geographic (polar) coordinate system. A projected (cartesian) coordinate system allows positions to be given in x,y based on the linear unit of the coordinate system. For analytical work based on distance measures, it is useful to transform spatial data into a projected coordinate system as this allows positioning and measurement within linear distance units. British National Grid is a commonly used coordinate system in the UK.

Swatchway

The terms swatchway, spitway, gat and gatway refer to channels that cross large or elongated banks. These words have been used for centuries to describe both transient and permanent cross-bank channels throughout the Thames region. The terms appear to be specific to the UK, although the word ‘gat’ is Dutch for ‘hole’. Spitways seem to refer to smaller swatchways, and both refer to shallow channels that are prone to movement and shoaling: these channels are generally only navigable late around high water. Swatchways that become well developed channels are then generally referred to as gats (or gatways).

1. Introduction

This report disseminates results from a Caird-Crown Estate research project 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 an examination of seabed mobility over the last 200 years, as derived from the analysis of published bathymetric charts.

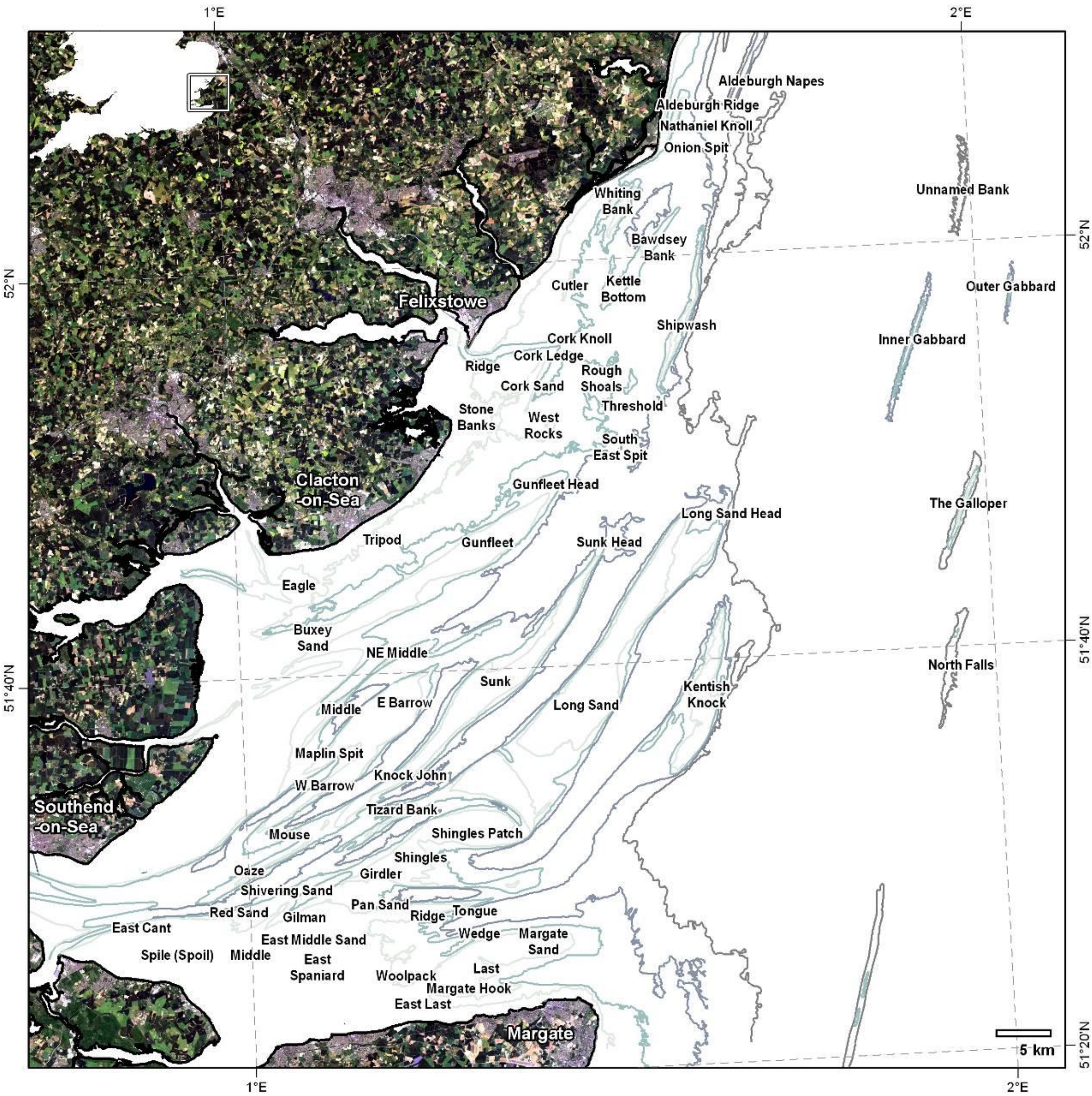


Figure 1 The greater Thames estuary study area, showing the main bank features.

2. Data and technical approach

2.1. Data sources

Although charts covering the greater Thames region exist back to the 16th century, it is only those published since the early 19th century that have sufficient spatial reference detail (e.g. grid references and projection information) and ground control points (structures located on maps that remain static through the time period considered, such as Martello Towers) for georectification, thereby enabling direct spatial comparison of features. Admiralty charts published by the Hydrographic Office have been produced with increasing regularity over the last 180 years, and a selection of charts from this period are examined here (Table 1). Chart 100 was published between 1812 and 1848, extending from Orfordness to Southend and to North Foreland. It was a precursor to chart 1610 (as published between 1855 and 1954), which also covered the entire greater Thames region at a scale around 1:150,000. Since then, chart 1610 has focused on a broader area with reduced detail, but coverage of the greater Thames has been divided between northern (chart 2052) and southern (chart 1183) extents. Chart 2052 has been published since the mid-1800s, but only covered the approaches to Harwich until the more recent expansion to Orfordness.

Table 1 Hydrographic charts used in this study.

Date	Chart	Scale	Datum	Date range	Georeferencing RMS error (m)	Number of. soundings[1]
1824	No. 100: A survey of the entrances or channels into the River Thames	~1:140,000	MLWS[2]	1812-1842	209	6999
1847	No. 2052: England, East Coast. Approaches to Harwich.[3]	1:50,000	MLWS[2]	1847-1851	29	6341
1864	No. 1610: England, East Coast. Sheet II. Entrance to the Thames	1:170,000	MLWS	1855-1864	66	4254
1893	No. 1610: England, East Coast. North Foreland to Orfordness, including the Entrance to the Thames	~1:150,000	1 foot below MLWS	1880-1893	45	9596
1910	No. 1610: England, East Coast. North Foreland to Orfordness, including the Entrance to the Thames	~1:150,000	1 foot below MLWS	1880-1910	52	9736
1918	No. 1610: England, East Coast. North Foreland to Orfordness, including the Entrance to the Thames	~1:150,000	1 foot below MLWS	1880-1918	62	9072
1926	No. 1610: England, East Coast. North Foreland to Orfordness, including the Entrance to the Thames.	1:145,080	1 foot below MLWS	1880-1927	67	9183
1934	No. 1610: England, East Coast. North Foreland to Orfordness, including the Entrance to the Thames.	1:145,000	1 foot below MLWS	1933-1938	50	4383
1954	No. 1610: England, East Coast. North Foreland to Orfordness, including the Entrance to the Thames.	1:150,000	1 foot below MLWS	1953-1955	41	6327
2003	No. 2052: England, East Coast. Orfordness to the Naze.	1:50,000	LAT	1973-2006	4	5765
2003	No. 1183: England, East Coast. Thames Estuary.	1:100,000	LAT	1973-2006	3	10030

[1] not including additional points digitised along chart contours
[2] datum not indicated on chart, but estimated based on comparable surveys
[3] covers Suffolk shoreface only

2.2. Digital conversion

Hydrographic charts were scanned whole on a large-scale scanner by the National Maritime Museum at 300dpi. Raster images (TIFF format) of each chart were then georeferenced in ESRI ArcMap 9.2 (www.esri.com) using all available grid references and ground control points, to the cartesian British National Grid (OSGB36) coordinate system. The degree of error in the rectification process was variable (Table 1). The earliest chart used (1824), despite incorporating latitude/longitude coordinates appeared to exhibit systematic errors in grid position, specifically longitude. Inclusion of both grid references and ground control points (shoreline structures and features across the embayment of the greater Thames) in the rectification process produced an RMS error of 300m, primarily due to the incorrect positioning of the grid on the chart. This appeared to be more problematic to the west than the east. For example, longitudes across the Isle of Sheppey appear to have an easterly offset of about 1-1.5 minutes in 1824 compared with 1864, whereas to the east at Margate, longitudes are comparable (Figure 2).

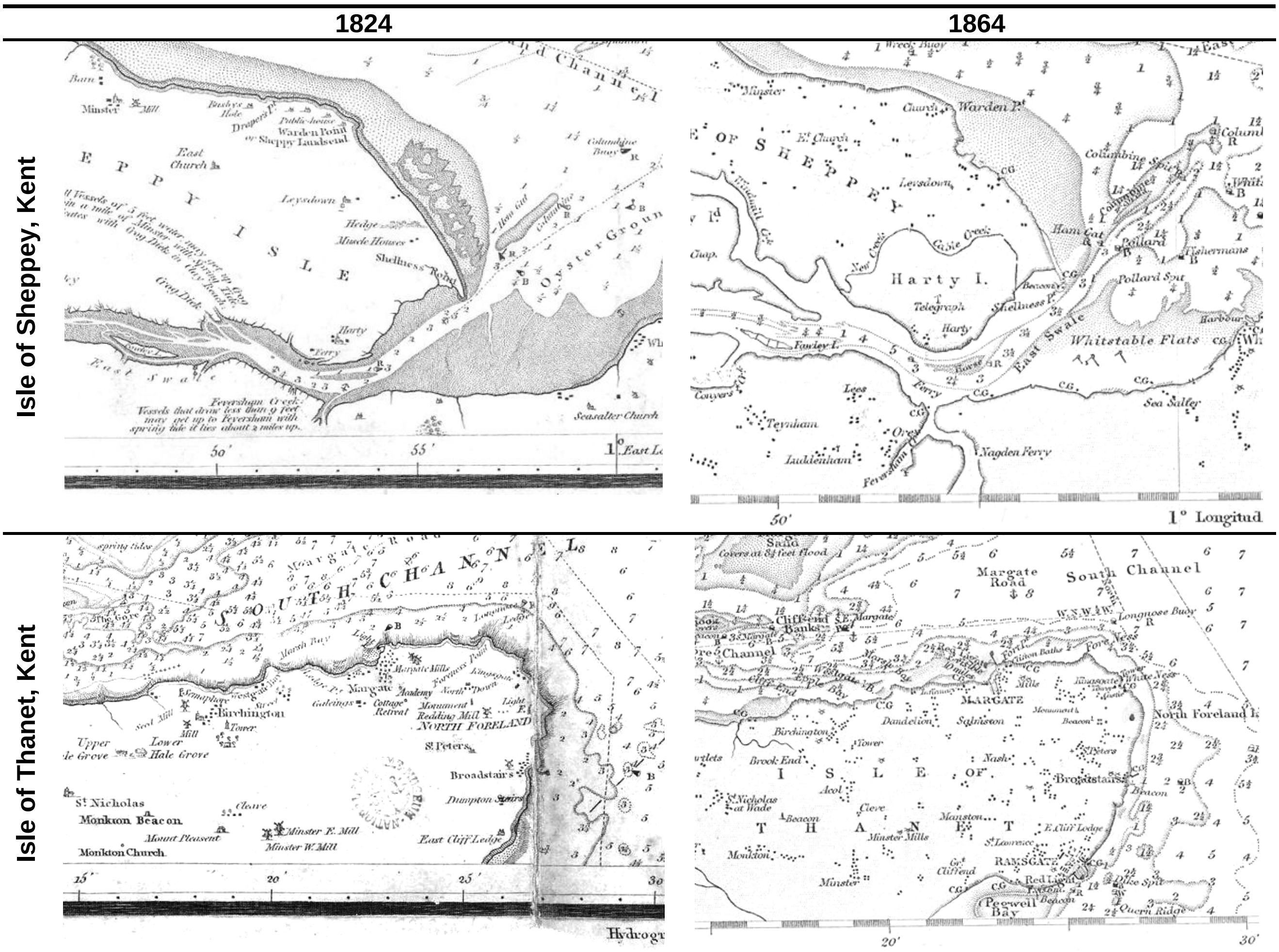


Figure 2 Comparison of geographic location and grid position between published charts. On the Isle of Sheppey, East Church lies at about 0°51.4′E, although on the 1824 chart, it is positioned at approximately 0°50′E. To the east on the Isle of Thanet, Foreness Point lies at 1°25.6′E, and the 1824 chart gives a position of 1°25.5′E.

Georectification using just ground control points reduced the RMS error to 178m, but this did not successfully correct the position of the offshore seabed (on the basis of a comparison with the later charts). A combination of shoreline ground control points with grid references for east of 1°30′E appeared to achieve the best positional fix with an RMS error of 209m. Clearly, this is still a very significant error, and comparison with later charts suggests the main errors lie in the positioning of the offshore seabed. The rectification of chart 1610 (1864-1954) was straightforward in comparison, with an average RMS error of 55m using a combination of grid references and ground control points. The most recent charts yielded RMS georeferencing errors of less than 5m.

Soundings and contours were digitised from the charts into point layers (Figure 3): depths were initially referenced to the chart datum and units of each chart. The 1824 chart was supplemented with inshore soundings from the 1819 Laurie chart of the Essex and Suffolk coast and offshore gaps were filled using soundings from the 1864 chart. There was some degree of re-use of soundings between the 1893 to 1926 editions of chart 1610 as it appears that only specific bank areas were resurveyed: 59% of the 1893 chart was incorporated into the 1910 chart, 45% of the 1910 chart was used in the 1918 edition and 39% of 1918 soundings were used in the 1926 edition.

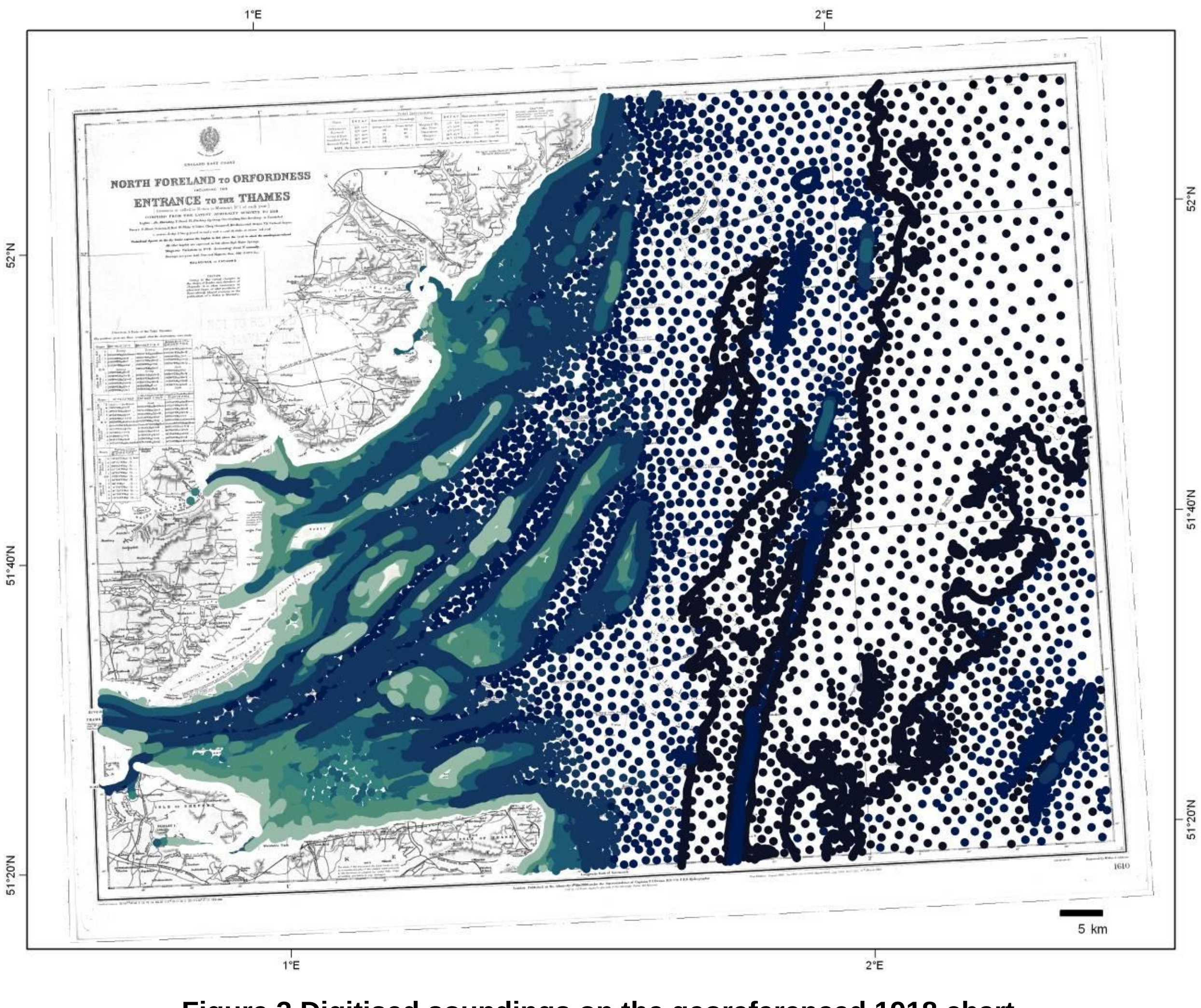


Figure 3 Digitised soundings on the georeferenced 1918 chart.

All depths were converted to metres relative to Ordnance Datum (OD) to enable direct comparison between charts. Due to the geographical variation in the relationship between chart datum (CD) and OD, a trend surface model was used to predict tidal levels for LAT, MLWS and 1' below MLWS (see Burningham & French (2008) for detail). A point-specific modelled CD to OD conversion factor was then extracted for each point on each chart, converting all measures to metres relative to the common datum of OD, 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 200 years (see Burningham & French (2008) for justification).

Bathymetric data were interpolated onto a regular 100 x 100 m grid, covering the maximum extent of each chart dataset, using the nearest-neighbour method in ArcGIS 9.2 3D Analyst. Due to the variable coverage of each chart, regions of interest (ROI) were defined, within which gridded bathymetric surfaces were extracted. The inner ROI covers the Type 2A (wide estuary mouth ridges) and Type 3A (headland-associated banner banks) banks and the outer ROI extends east to include the Type 1 (open shelf ridges), based on the Dyer & Huntley (1999) classification. This ensured that regional comparisons could be made with the inclusion of the offshore seabed, but that further analysis could be conducted within a region that was not hampered by the rectification problems of the 1824 chart.

2.3. Analytical approach

Bathymetric surfaces were analysed to assess the patterns of change in seabed elevation over the last 180 years. Transects crossing the Thames estuary and wider seabed were established at near-regular intervals along the northern and southern shorelines. A Matlab (www.mathworks.com) routine was developed to extract depths along each transect for each chart surface and plot as 2D profiles (to provide a simple expression of seabed change) and transect evolution plots (to highlight differences between progressive evolution and episodic shifts).

The broader patterns in seabed evolution were qualitatively assessed in terms of 3D morphological evolution using ArcGIS 9.2 ArcScene. Bathymetric change maps, which show a calculated depth change between successive surfaces, were also produced. Further analysis was achieved through standard descriptive statistics. A mean seabed surface was calculated using proportional accounting, where a weighting was applied to each layer based on the time interval between that and the next survey. A Principal Component Analysis (PCA) was used to extract the main variance in the data in the form of uncorrelated dominant factors. Chart data layers were transformed to remove the mean seabed surface, which would otherwise dominate the first component. PCA and other forms of eigenfunction analysis are increasingly used to help explain variance in bathymetric change data, particularly where extensive spatial and temporal datasets are concerned (see Buonaiuto *et al*. (2008); Reeve *et al*. (2008); Cuadrado & Perillo (1997); Maron *et al*. (2008)). These analyses were accomplished in ArcGIS 9.2.

Trend analysis was also performed on the spatial datasets to assess the temporal trends in seabed bathymetry across the entire region, using a routine developed in Matlab.

3. Analysis of seabed mobility

3.1. Seabed transects

One of the simplest and most effective ways of examining topographic or bathymetric change across complex morphologies is to reduce the dataset set to a series of 2D profiles or transects. Given a suitable time series length and interval, this can highlight the shifts in the position of features relative to estuary width or shoreface position. In the greater Thames region, 20 transects were established (Figure 4). Transects 1 to 7 are cross-estuary that extend from the Essex to Kent shorelines. Transects 8 to 20 cross the greater Thames seabed as shore-normal transects extending from the Essex (8), Suffolk (9-17) and Kent (18-20) coastlines. Standard depth profile plots for each charted survey consulted are provided in Appendix 1, in addition to the transect evolution plots in the following analysis (Figures 5, 7 and 8).

Figure 4 Seabed transects used to extract bathymetric profiles for temporal comparison.

3.1.1. Cross-estuary transects (1-7)

Cross-estuary transects, covering the region of Type 2A wide estuary mouth banks, are depicted in Figure 5 (as bathymetric transect evolution plots) and Appendix 1a (as standard 2D profiles). Transects 1 and 2 extend from Shoeburyness across Sea Reach to the Isle of Sheppey. Here, tidal flow is largely contained in one main channel, although the Medway Channel connects with the Great Nore subsidiary channel to the south. In transect 1, two bathymetric highs (Nore Sand and the point of Grain Spit) divide Sea Reach from Great Nore and the Medway Channel. The cross-estuary position of these features is consistent over the last 180 years, although there is some suggestion of small-scale modification of the bank/channel boundaries and some overall deepening (Figure 5). A similar change is exhibited in transect 2, which shows Sea Reach divided from Great Nore by Nore Sand, which all maintain their relative positions.

As the estuary broadens, Sea Reach is again dominated by a broad single main channel (transect 3) which shows little change in position or depth beyond small-scale changes in bed and margin character. There is some evidence that small bar features on the Cant (sub-tidal plain on the Kent margin) have lowered and moved shoreward since the late 19th century: their absence from the early 19th century is likely to be due to low resolution surveying rather than absence in reality. At transect 4, the channel is divided by one main bathymetric high (Oaze) into The Warp (broader channel) and Oaze Deep (deeper channel), but there are several other bathymetric highs and lows that contribute to the increasingly complex bathymetry. Oaze Deep has progressively deepened and widened over the timescale considered, at the expense of Oaze bank and Red Sand which have both significantly decreased in height and width. The Warp appears to have stayed relatively consistent in width and depth, but a small mid-channel bathymetric high (tail of Mouse bank) emerged over the 19th century and gradually attached to the Oaze in the mid 20th century. Overall, it appears that in-channel volume has increased (Figure 6).

Transects 5 to 7 extend over the maximum width of the estuarine embayment, from the north Essex coast, across the Wallet, Buxey/Gunfleet sands, through the central multiple channel-bank region Kentish Flats and Margate Sands on the north Kent shoreline. Transect 5 clips the Blackwater entrance and the extensive inter- and sub-tidal plain of Dengie Flats and Foulness/Maplin Sands, which show some small variations in depth (likely due to limited survey resolution across broad shallow areas). West Swin is the deeper and most consistent of the mid-estuary channels, entrenched between Maplin Sands and West Barrow. West Barrow widened significantly in the late 19th century due to the migration of the Mouse bank around its periphery, causing deflection and shallowing of Barrow Deep. Mouse has subsequently detached from West Barrow and Barrow Deep has regained a notable depth along the margin of West Barrow. Further across the estuary, transect 5 crosses Knob Channel (which has deepened), before reaching the bathymetric high of Shivering Sand (which has lowered): both of these features have maintained a relatively constant cross-estuary position.

Transects 6 and 7 illustrate the complexity of the multiple channel/bank character of the greater Thames estuary. The envelope of variability along these transects is relatively high, primarily due to the tendency for small lateral shifts to cause large vertical change along channel/bank boundaries. The bathymetric evolution plots show clear splitting and progressive migration of banks. On transect 6, a bank grows within Whitaker Channel

(~10km mark), where a flood channel has developed off East Swin as a separate feature to the existing ebb (Whitaker) channel. Further along the transect, Knock John bank (~25km mark) has moved northwest and a new bank (Tizard/Knob Shoal) has developed to the southeast. On transect 7, the small banks at the 15km mark (north tail of East Barrow and NE Middle) have lowered almost disappeared, whilst the Sunk (~20km mark) has shifted northwest, with little change in depths. Lateral and vertical shifts in Long Sand (~30km mark) show evidence of the development of the Edinburgh Channels and their migration north. In particular, the developing link between South Edinburgh Channel and Knock Deep is expressed as a notable deepening (around 34km); the eastward extent of Tongue sand appears to have built up in response (~37km mark).

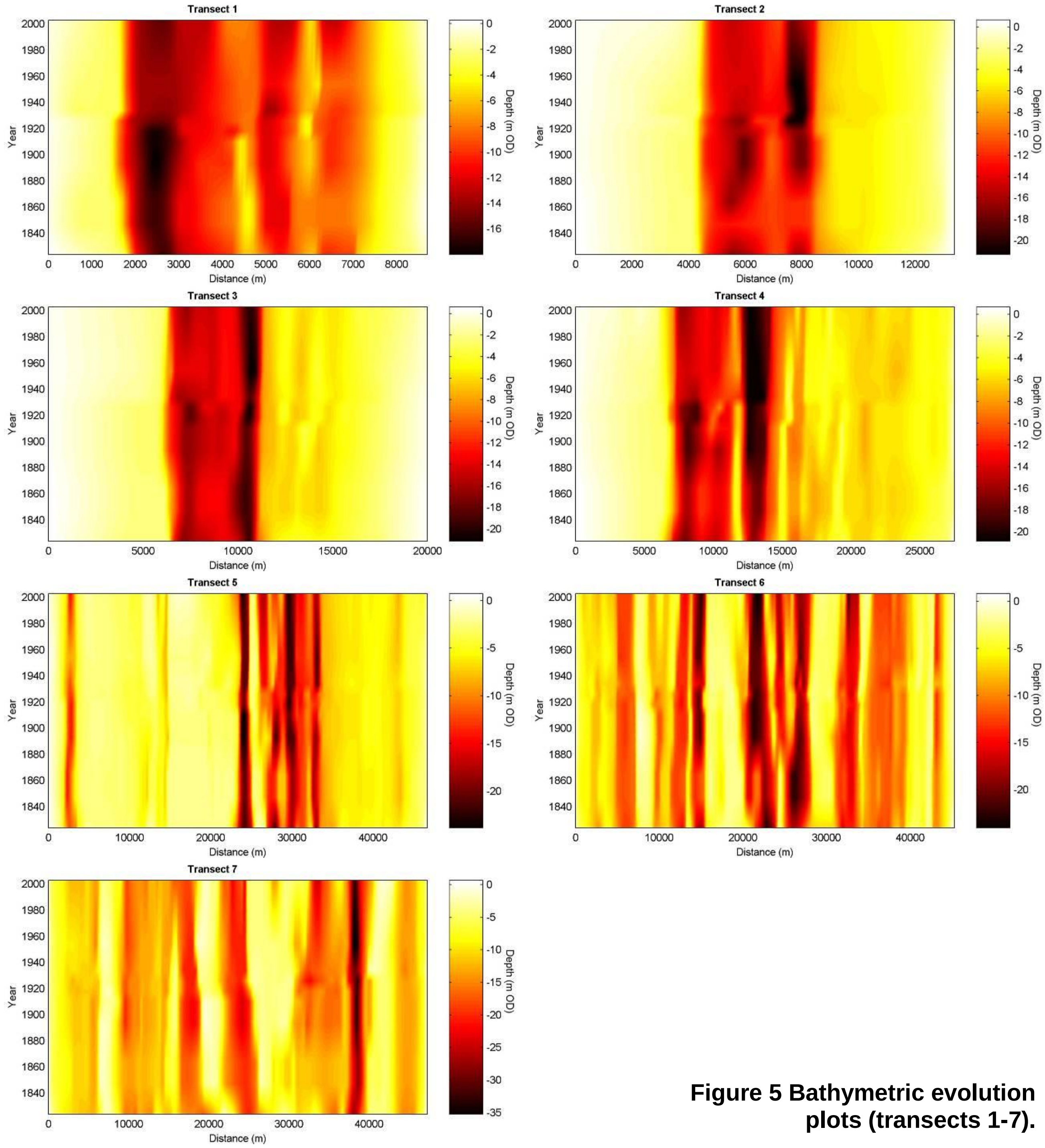


Figure 5 Bathymetric evolution plots (transects 1-7).

As these transects are cross-estuary, tidal flow is contained within the channel space illustrated in the 2D profiles. Over the period considered, accommodation space for tidal volume has increased in most parts of the broader estuary: certainly, based on a comparison of early 19th century (1824 to 1864) with the modern in-channel areas across transects 1 to 7, a small increase is evident (Figure 6A). This, and the suggestion of a cyclic change throughout the period, could simply be a reflection of the changing resolution of surveys, which peaked initially in the late 1800s and the most recent survey (Figure 6B). An increase in survey resolution appears to increase the detail of deeper areas, which would result in a relative increase in the in-channel volume.

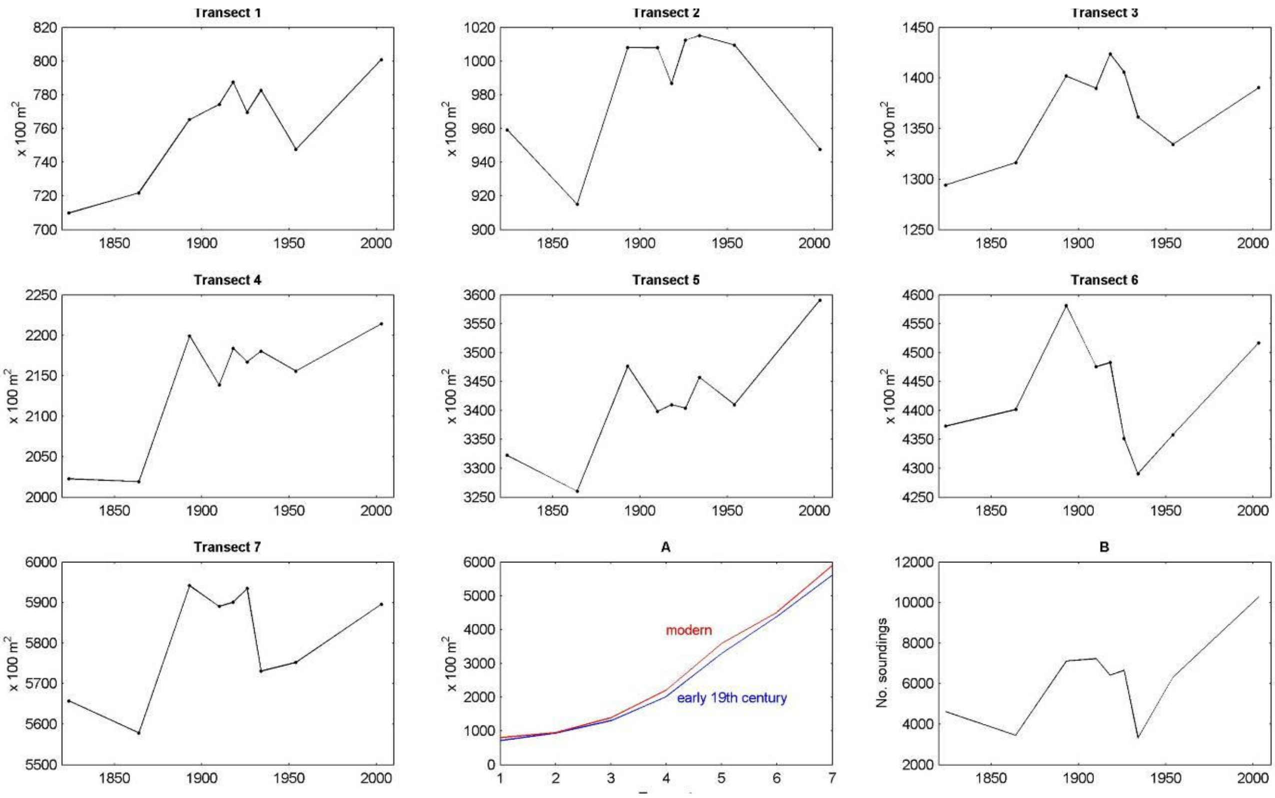


Figure 6 Changes in combined channel area (trapezoidal area per unit width) across selected transects over the timescale examined. [A: Comparison of modern with early 19th century volumes per transect. B: Number of soundings per chart (within the inner ROI).]

3.1.2. Shore-normal transects (8-20)

Shore-normal transects are depicted in Figures 7 and 8 (as bathymetric transect evolution plots) and Appendix 1b (as standard 2D profiles). Transects 8 to 17 extend across the Essex/Suffolk shoreface. Transect 8 crosses on the northern extremes of the Type 2A banks (Gunfleet, Sunk, Long Sand and Kentish Knock). It appears that all these banks have shifted seaward since 1824, and that Gunfleet has significantly broadened, but bank height and channel depth have remained relatively constant.

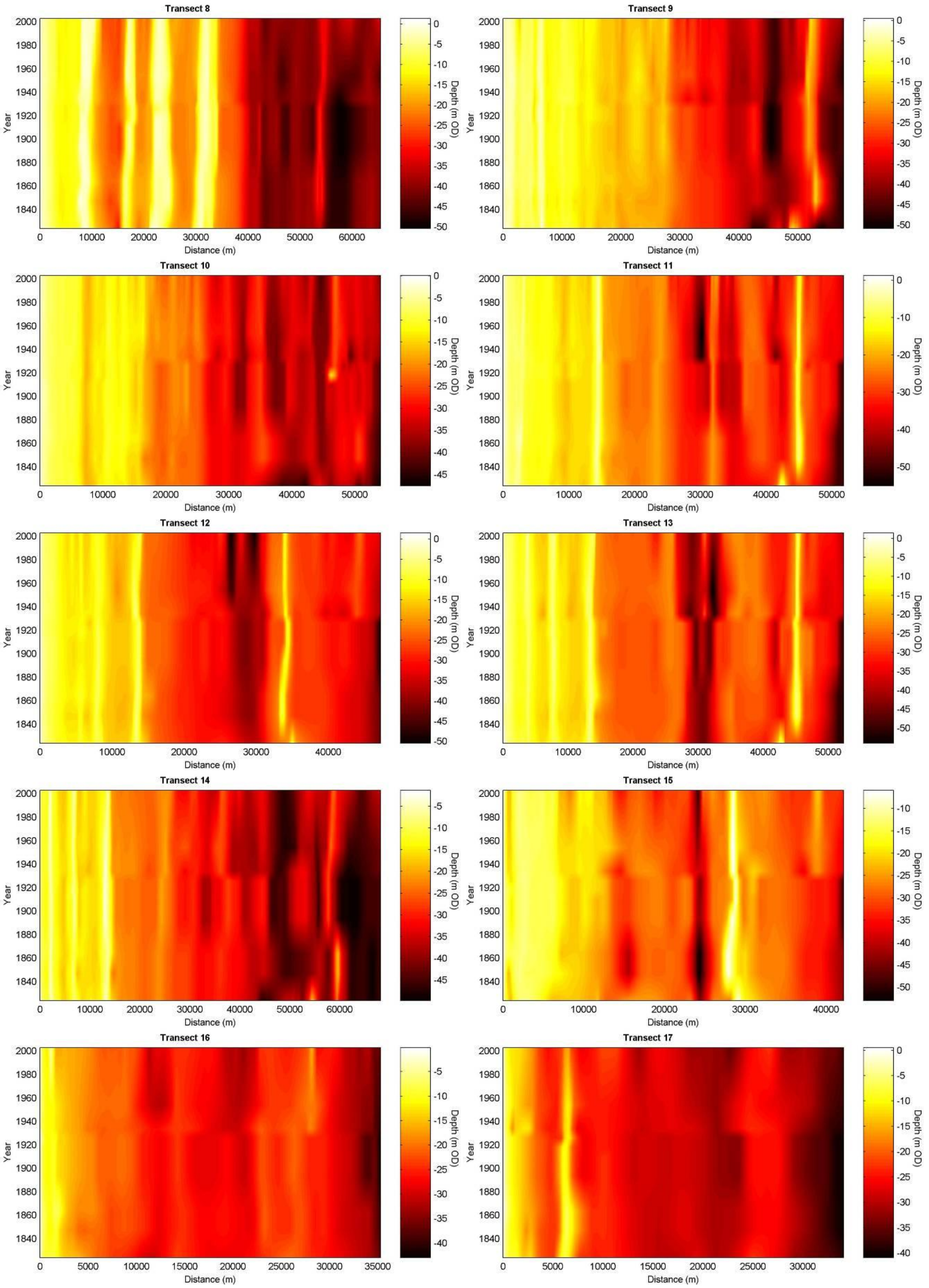


Figure 7 Bathymetric evolution plots (transects 8-17).

Transect 9 crosses the Harwich entrance region, extending over Rough Shoals, the tip of Long Sand Head across to North Falls. The shifts in position of North Falls are likely to be a result of systematic positional error in the early charts as the bank cross-section has remained notably consistent. Closer to the Suffolk shoreline, the Harwich Deep Water Channel is clearly shown as a recently introduced bathymetric low, but other changes are less clear. Transect 10 extends from Felixstowe and crosses the shoreface in between the Suffolk and Type 2A banks. The seabed is quite hummocky, but the inshore region shows only small-scale changes in depth. Further offshore, there is a bathymetric high anomaly (around the 46km mark) in the 1918 survey: this is the tail of the Galloper that was noted on the 1918 chart only. This is almost certainly a dynamic zone, and all charts since have shown an elevated seabed in this zone between the Galloper and North Falls, but it seems likely that the depths noted in the 1918 chart are an exaggeration.

Systematic errors in the positioning of the offshore banks (Galloper and Inner Gabbard) continue to be a problem on transects 11 to 15 for the 1824 and sometimes 1864 surveys. On transect 11, significant changes are evident in an area not defined by any specific bank or channel features (around the 32km mark). The bathymetric high noted in 1824 has become a more prominent feature (with a cross-section similar to nearby banks) with lowering of the seabed either side. This development is also captured on transects 12 and 13. The inshore part of transects 11 to 14, crossing Cutler, Whiting, Bawdsey, Kettle Bottom and Shipwash, show only small-scale changes across the main seabed, but increased variability around the banks. Cutler bank has migrated offshore by about 1.2km with some narrowing and lowering (transect 11). Parts of the Shipwash bank have also migrated offshore: 700m along the middle section (transect 13) and 250m to the south (transect 11), but the shifts have been changeable over the history; with some instances of onshore migration (transect 12: 1926 to 1934). Along its length, Shipwash has experienced steepening of the eastern (seaward) flank (transects 12-14). The crest of Bawdsey Bank has lowered in the south (transect 12), but has built up in the north with steepening of the eastern flank (transects 13 and 14). Whiting Bank has increased in height and has migrated shoreward by about 300m (transects 13 and 14).

Transects 15 to 17 extend from Orfordness and Sudbourne beach. Immediately seaward of Ordfordness lies a narrow bathymetric low (to at least 25m CD), and whilst there has been some variability in this, it appears to maintain a constant position with relatively consistent depths. Seaward, the seabed is hummocky with specific bathymetric highs and lows variably present, particularly around the 15km mark (possibly a reflection of changing survey resolution). Transect 16 captures the nearshore Aldeburgh Ridge and transect 17 crosses Aldeburgh Napes. Aldeburgh Ridge is a more prominent bank now than it has been in its 180 year history; its minimum vertical extent occurred during the mid-1900s and early 1800s. Conversely, Aldeburgh Napes has shown a progressive reduction in size (width and height) over this same period, shown clearly in the tapering of the bathymetric high in the transect evolution plots (Figure 7:17).

The final 3 transects extend offshore from the northeast Kent shoreline. Transect 18 shows a very stable inshore subtidal plain, and extends seaward over South Falls. Small lateral shifts here occur over the full period, suggesting that this movement is less likely a positional error and more possibly reflective of true mobility. However, the movement is not progressive along a specific direction. Transect 19 extends northeast to the tail of North Falls, where systematic positional error is again suggested by the offset in its location in the early charts. Over the last 100 years however, this tail appears to have broken down to form a broad topographic high rather than a crested bank. Transect 20 extends directly north toward the Suffolk coastline, covering the full width of the greater Thames. The features of this transect are quite consistent over time, the main changes being the slight vertical growth of Margate Sand (~6km mark); the northward shift of Knock Deep and related recession of the easterly flank of Long Sand (~20km mark); and the growth (lateral and vertical) of the Sunk (~36km mark).

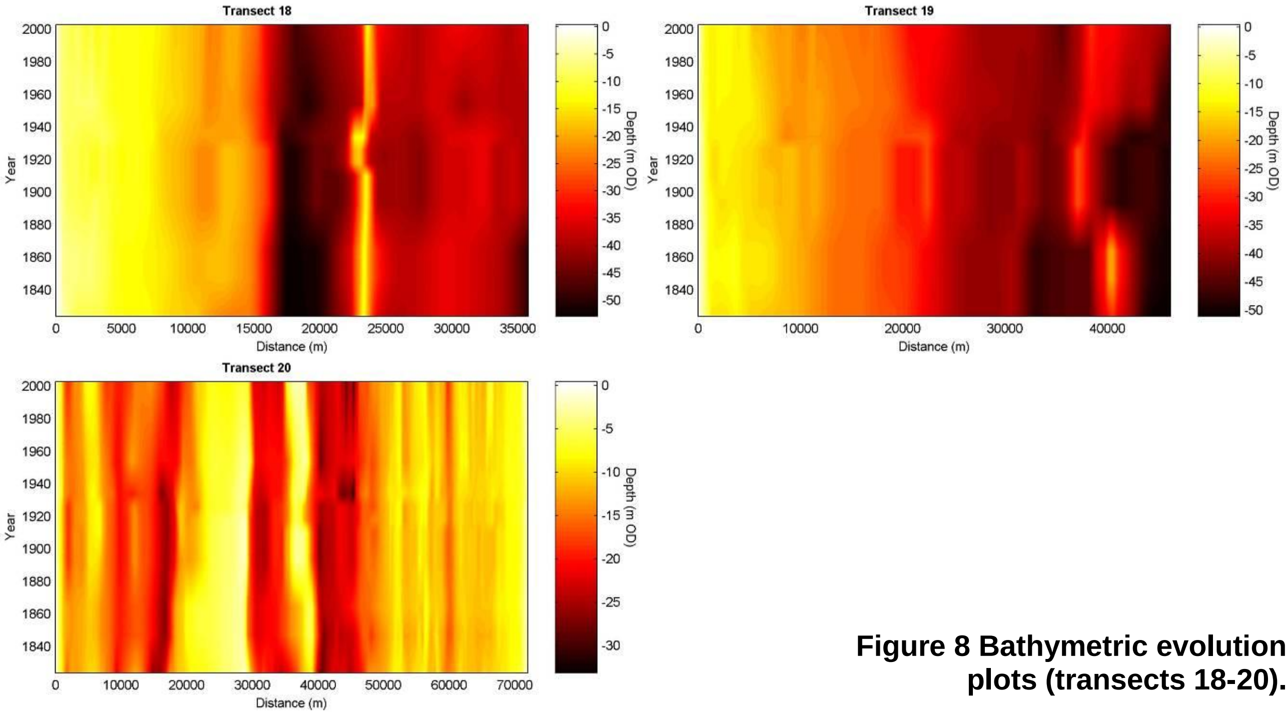


Figure 8 Bathymetric evolution plots (transects 18-20).

3.2. Bathymetric change mapping

Due to the positional error problems encountered for the outer banks, the analysis of bathymetric change was conducted within the inner region of interest only. The pattern of change in seabed depths between 1824 and 2003 is dominated by lateral shifts in the Type 2A wide estuary mouth banks (Figure 9). The margins of Gunfleet, Sunk, Long Sand and Kentish Knock (and hence Knock, Barrow, Black and Middle Deeps) are all characterised by extreme changes in depth, but the central bodies of these features show very little change. The broader Kings Channel has been less affected by lateral shifts, but there is a degree of shallowing along its southeast side, and erosion along the northwest side. Across the estuary, most patches of erosion appear to have associated patches of nearby accretion except in the vicinity of Oaze and Oaze Deep, where the seabed has lowered across bathymetric highs and lows alike.

Patterns of erosion and accretion around Gunfleet suggest offshore movement and seaward extension. The rest of the Wallet region is characterised by small-scale changes, except along the northern margin of Buxey (adjacent to Swire Hole), which appears to have significantly steepened. The greater estuary margins (Essex and Kent coastlines) show smaller scale bathymetric changes, which increase with proximity to the main channels. Margate Sands/Hook has developed into two distinct bathymetric highs, with notable erosion of the connecting seabed. There also appears to be a large area of accretion offshore to the east of Margate, not associated with any specific bank feature.

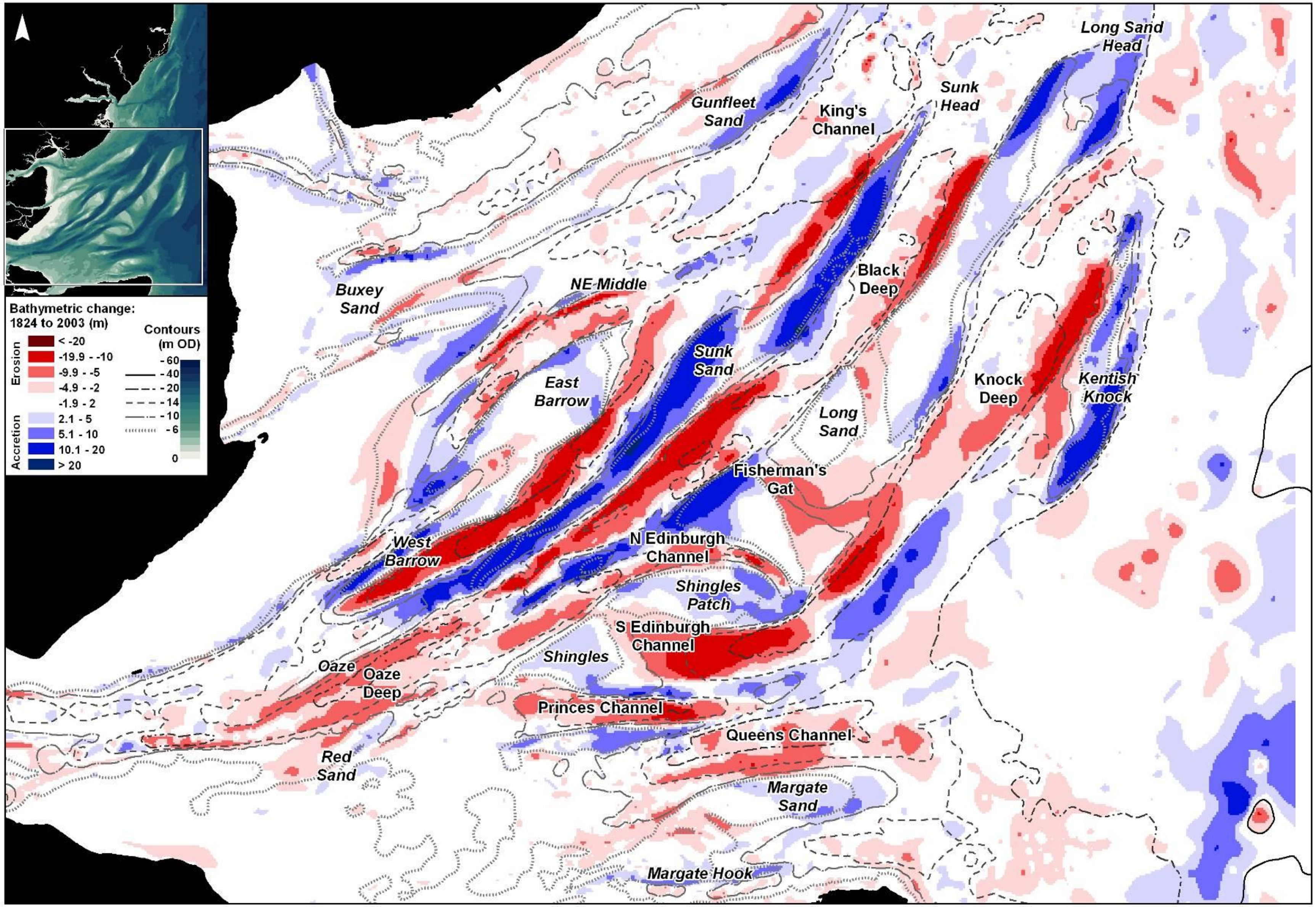


Figure 9 Total change in seabed bathymetry between 1824 and 2003 across the central region of the greater Thames estuary.

Although the central banks dominate the picture, to the north (Figure 10) a net onshore shift in Aldeburgh Ridge has caused nearshore accretion and a lowering of the seaward shoreface. South of this, the main body of Whiting has moved southwest whereas Bawdsey Bank has extended significantly to the northeast. The offshore migration of Cutler is clearly defined by associated areas of erosion (landward) and accretion (seaward). The pattern of erosion and accretion around Shipwash suggest that different parts of the bank are shifting in different directions, but that in general it has narrowed, lengthened and shallowed over the last 180 years.

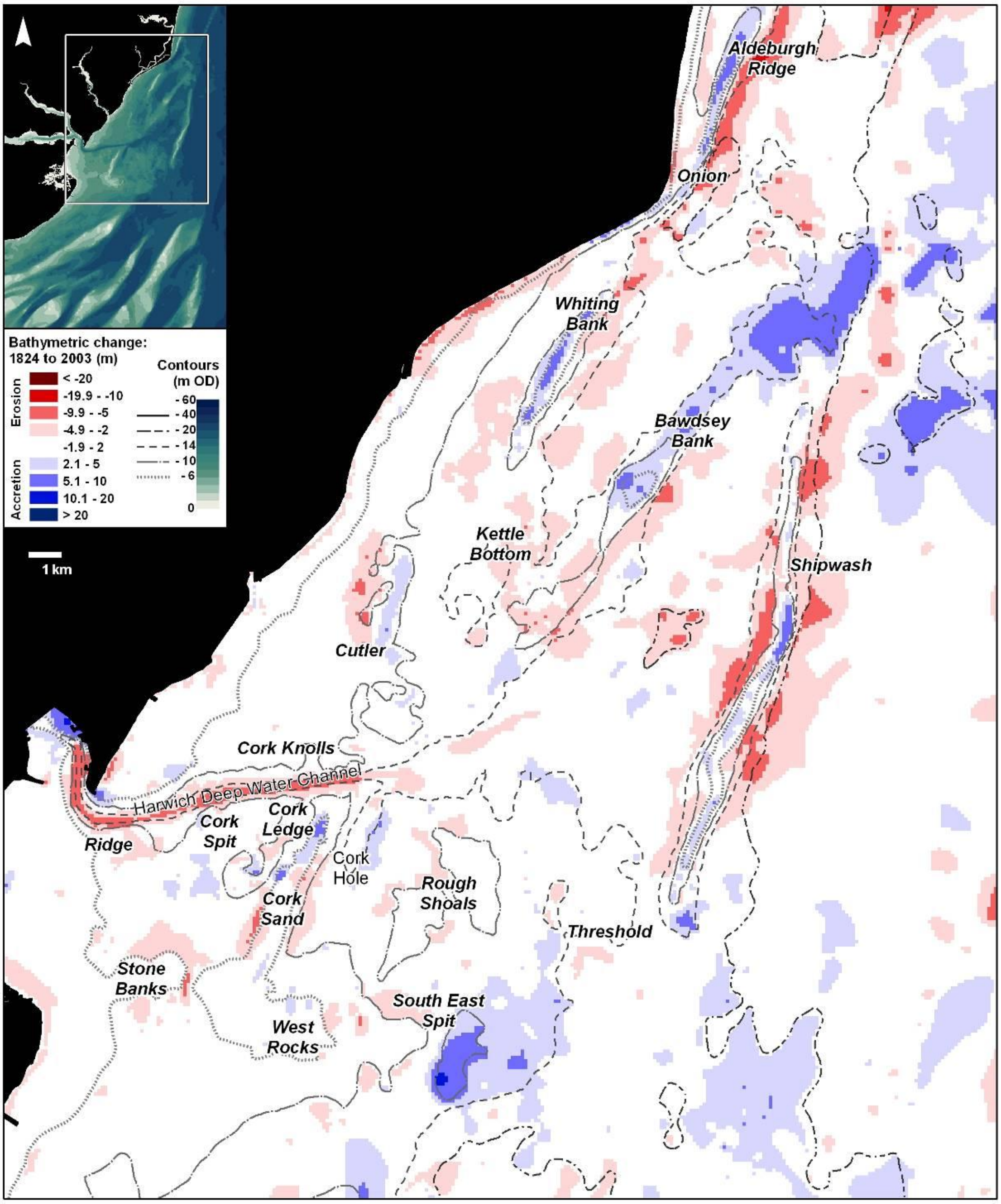


Figure 10 Total change in seabed bathymetry between 1824 and 2003 across the Suffolk shoreface.

To the south of Harwich Deep Water Channel (clearly identified as significant ‘erosion’), there is some recession around the east and west margins of Cork Sand and some growth northward. Significant accretion has occurred at South East Spit (which has been spoil ground since the 1970s), and the seabed has also built up further east (to the north of Sunk Head), in an area currently characterised by mobile sand waves. Numerous wrecks were added to the notation of this area on charts during the first half of the 20th century, but there is no indication on these earlier charts that sand waves existed and the substrate is described only as comprising sand, stones and shell. Interestingly, a review of charts 1975 and 2052 from the last 30 years (scale 1:50,000) reveals that sand wave structures were present in the soundings in the late 1970s, but were not noted as such until the late 1990s. It is possible that coarser resolution surveys in the past did not adequately capture the narrow sand waves, but comparison with a late 19th century edition of chart 1975 (scale 1:50,000) corroborates significant accretion in this area (Figure 11). It is unclear from the charts whether sand waves were present previously. This is possible, given the somewhat hummocky seabed, but there is no doubt that the volume of material contained within the sand wave area has increased over the last 100 years, causing the significant shallowing identified.

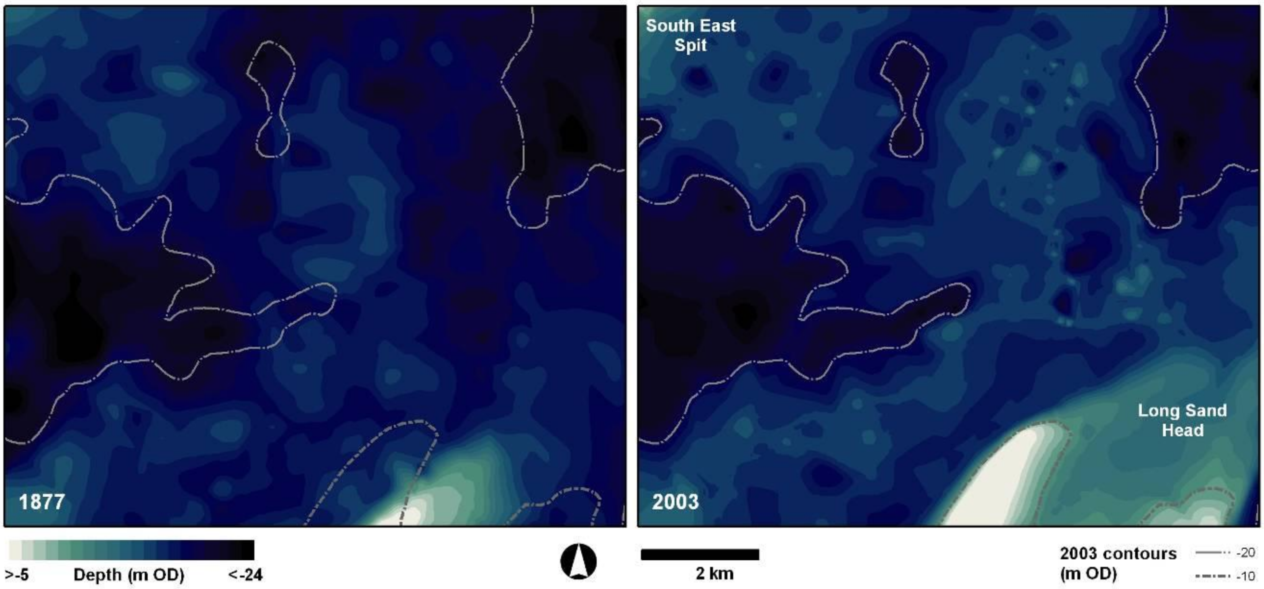


Figure 11 Seabed changes between Long Sand Head and South East Spit: comparison between the late 1880s and present, using chart 1975 (published 1877).

Localised changes in seabed bathymetry are variably associated with specific time frames, divided here on the basis of chart dates into 4 epochs (Figure 12). Much of the change around Sunk and Barrow/Black Deeps primarily takes place during the first epoch (1824 to 1864), whereas changes around Margate Sands occur mainly during the most recent epoch (1954 to 2003). Changes along the Sunk and Long Sand borders do continue to occur throughout the history, but these are quite localised patches. The surfaces of Sunk and Long Sand do not have a planed morphology, but instead comprise several discrete bathymetric highs over a broader, more continuous bank. The degree of change along bank margins here, perhaps in response to tidal scouring, is significantly enhanced in the region of bathymetric highs. Furthermore, the movement of these superimposed features contributes an additional complexity to the surface evolution over time.

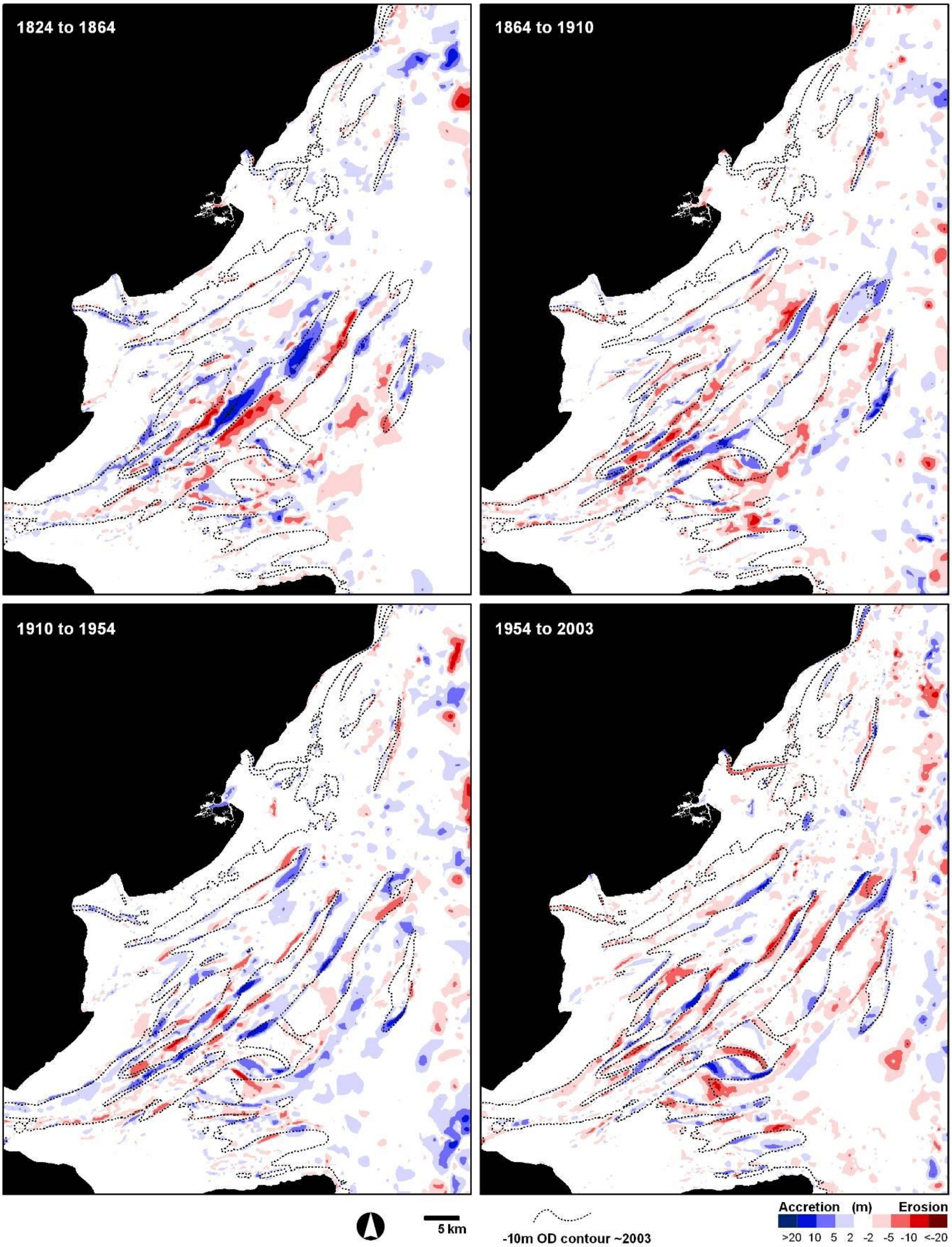


Figure 12 Bathymetric change map of the greater Thames seabed. The 180 year period is divided into 4 epochs (cut-offs determined by chart dates).

Kentish Knock appears to experience recession along its southerly extent in the initial epoch, but has subsequently prograded significantly in a southerly direction. Most of the northeasterly extension of Long Sand Head occurred between 1864 and 1954, and since then the head has broadened with raised margins and lowered in its middle. The development of channels within the Shingles region at the south end of Long Sand is also well illustrated in the bathymetric change maps, which show that formation and migration of these tidal paths occurs throughout all epochs. To the north, the pattern of change around Shipwash is relatively complex: most large-scale changes (in response to lateral shifts) took place after 1864, but the magnitude and direction is variable as the bank appears to quiver around a central mean position. The northward growth of Bawdsey Bank occurred mainly during the first half of the history presented here, whereas the shallowing around South East Spit has mostly occurred in the last 50 years.

3.3. Spatial statistics

The average seabed morphology, as determined by the mean gridded depth, highlights zones consistently deep or shallow in comparison to those that are more variable (Figure 13). In combination with the depth range, the historical variability in seabed depth is well defined, irrespective of erosion vs. accretion (Figure 13). There are few areas that exhibit no change, but the intertidal and near- intertidal environments along the Essex and Kent coastlines exhibit the least degree of change over the last 180 years. Again, this analysis shows that the general framework of banks and channels in the greater Thames estuary has remained consistent over this history, and that the greater changes are associated with shifts in bank position rather than a broader downwearing or vertical growth.

Calculation of rate of change in seabed depth is possible, and is most readily based on the assumption that site-specific changes are linear over time (e.g. Kemp & Brampton, 2007). The spatial pattern of seabed trends calculated as a linear regression across the time series of bathymetric surfaces, supported by r^2 and p-values, is presented in Figure 13. This broadly echoes the main patterns in range and net change, but importantly reflects the strength and direction of historical trends. Rates of vertical change >0.1myr^{-1} only occur where there are significant lateral shifts in bank position. Trends in areas not associated with lateral movement are generally far smaller. The region between Kentish Knock and Tongue is an exception to this: although the adjacent eastern margin of Long Sand has receded, a separate linkage between Kentish Knock and Tongue Sand appears to be developing. Where the trends have been masked to include only those that meet the 99% significance level (and r^2>0.5), it becomes clear that most of the smaller-scale, wider-seabed changes are not significant in a temporal trend context. It highlights the specific changes around Aldeburgh Ridge, Kentish Knock, Shingles/lower Long Sand, Sunk Sand and South West Reach (mid-Barrows) as environments of significant and progressive historical change. The pairing of positive and negative trends is significant, which arises due to the lateral shifts in banks causing associated regions of accretion and erosion around opposite sides of banks and channels. This suggests that the sediment budget of most banks is balanced. The region around Oaze bank and Oaze Deep, where the seabed is characterised by a strong negative (erosional) trend, stands out in this context as there are no associated positive trends in neighbouring banks, suggesting that this region has been experiencing a negative sediment budget over the last 180 years.

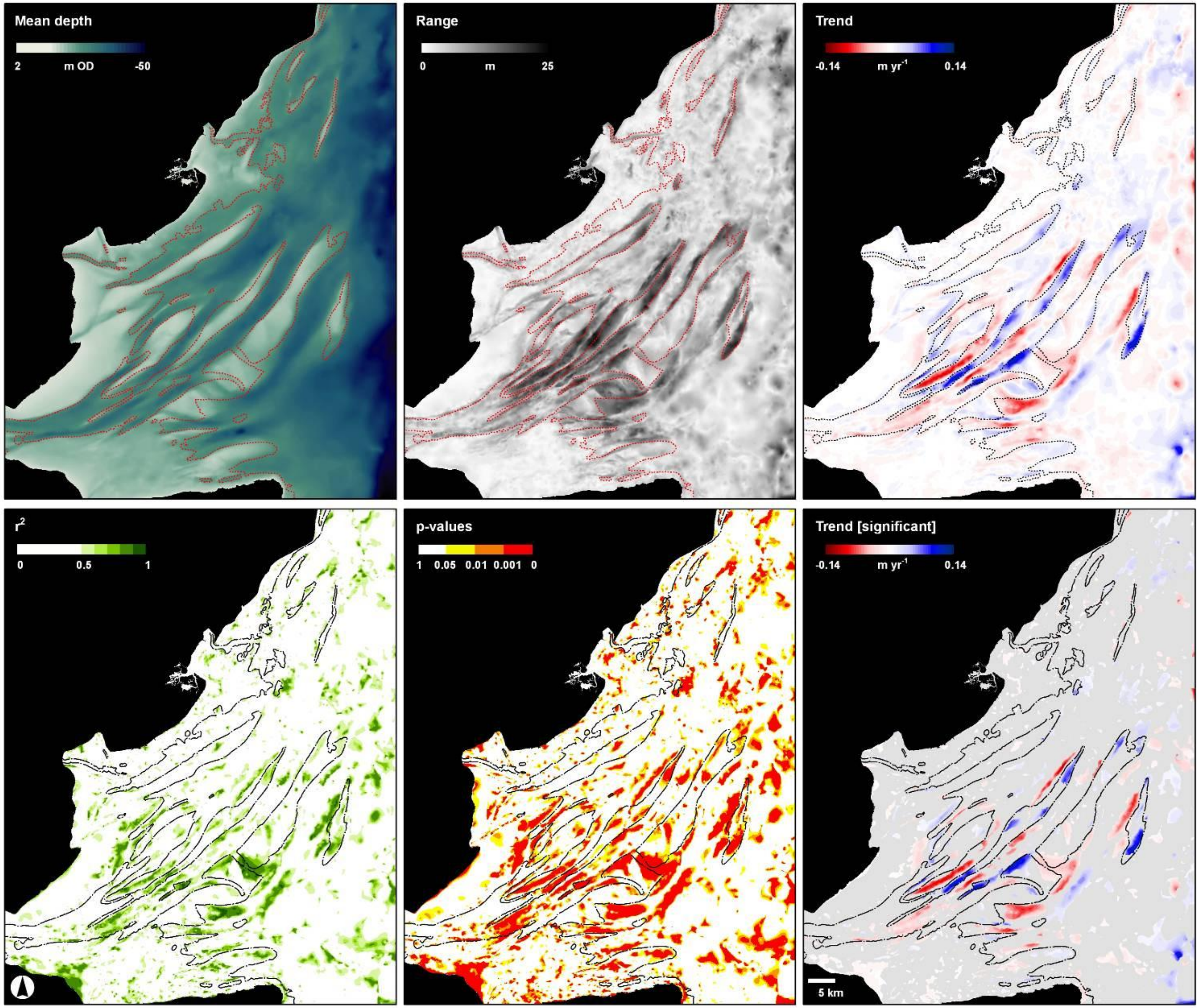
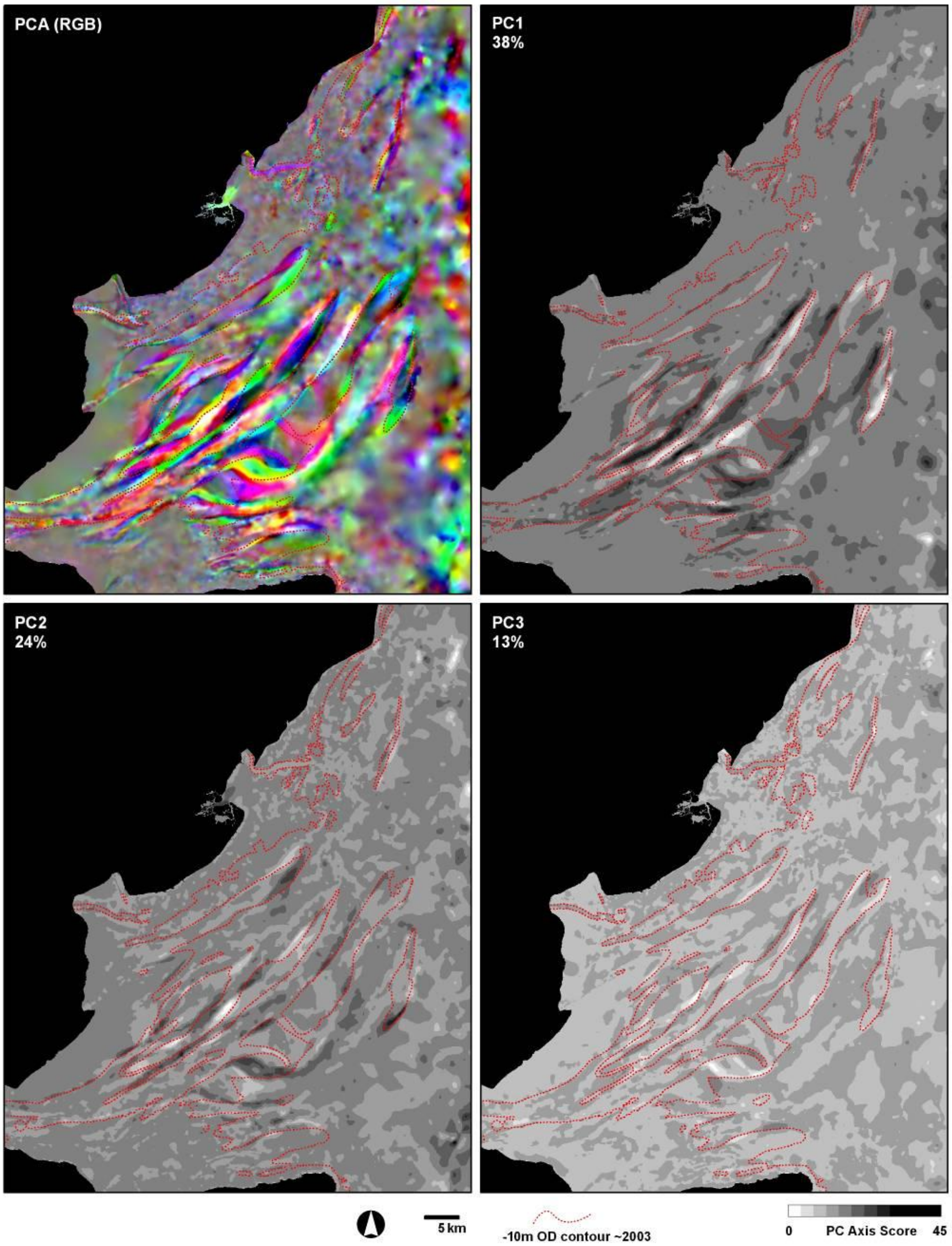


Figure 13 Seabed depth mean (proportional), range, trend (linear slope) and significance of trend (r^2 and *p*-values) in the greater Thames estuary based on a 180 year charted history (trends with r^2<0.5 and *p*>0.01 are masked in grey in the last plot).

A PCA of the seabed surfaces (transformed to remove the mean surface) provides a further means of assessing seabed changes. The PCA organises the variance in the dataset using a reduced number of independent variables (components), which are described by a gradient of scores. Those areas with high scores represent the opposite end of the gradient to those with low scores: mid-scores represent the midpoint of the gradient. Here, the first three components explain 75% of the variance in seabed bathymetry (Figure 14). PC1, which accounts for 38% of the total variance in the data, appears to reflect the net effect of historic changes, and is well correlated with the 1824 to 2003 bathymetric change map (correlated with net change R = -0.85). The gradient of PC1 eigenvectors is evenly distributed across the 1824 to 2003 bathymetries (Figure 15), suggesting that the dominant aspect of variance in seabed morphology follows a clear progressive evolution.



	Eigenvalues	Variance (%)	Cumulative variance (%)
PC1	7.03	38	38
PC2	4.46	24	62
PC3	2.38	13	75
Total	18.62		

Figure 14 Principal Component Analysis (PCA) of seabed mobility: composite RGB image of components 1 to 3, the individual components and table of eigenvalues.

PC2, which explains 24% of the total variance, is more closely associated with the early 20th century and is well correlated with changes over the 1910 to 1954 epoch (R = 0.82). PC3 explains a further 13%, and is best correlated with late 20th century changes (correlated with the 1954 to 2003 epoch R = -0.91). Eigenvectors on PC2 show the maximum gradient is between the early 1900s and mid- to late 1900s, whilst on PC3 the gradient is dominated by the difference between 1954 and 2003 (Figure 15). This third component possibly represents the increased time interval between these latter datasets where bathymetric change is not captured at a high enough temporal resolution.

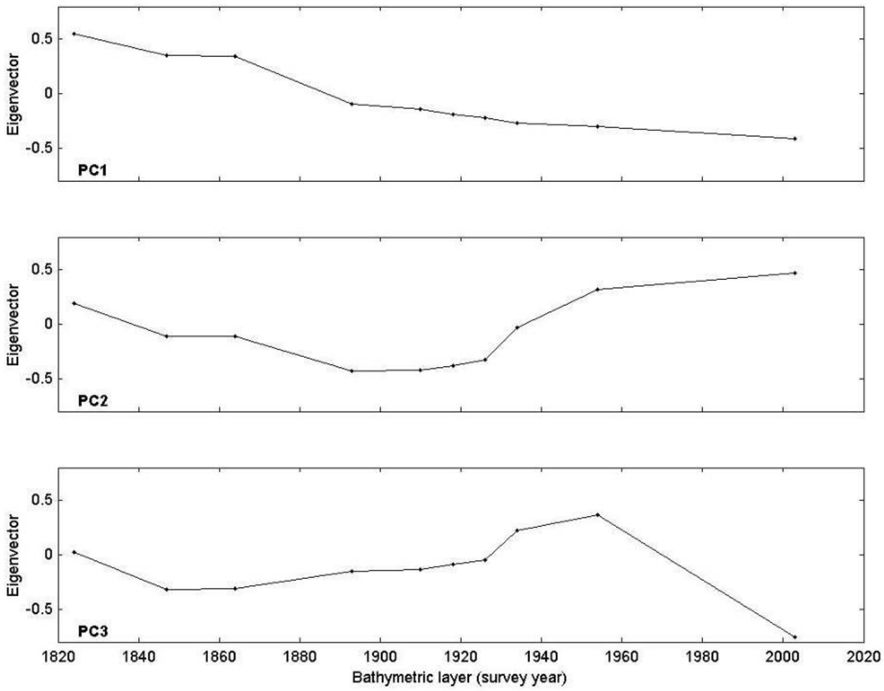


Figure 15 Eigenvectors of each bathymetric layer (survey) for principal components 1 to 3.

Whilst the PCA seems to reiterate most of the patterns acknowledged using other measures of change and trend, it does confirm that progressive change is the dominant behaviour identified from the changes in seabed morphology. The variance explained by the first three non-mean components is similar to that quoted by Reeve *et al*. (2008) in their analysis of the Great Yarmouth banks, Norfolk. Interestingly however, Reeve *et al*. (2008) found that the temporal behaviour of eigenvectors of all non-mean components was quasi-oscillatory, similar to the eigenvectors of PC2 and PC3 derived for the Thames. The near-linear trend in the eigenvectors of PC1 is notably different and indicates that the dominant characteristic of morphological evolution in the greater Thames estuary is significantly different to that of the Norfolk banks.

3.4. Geomorphological assessment

Comparison of bathymetric contours from selected surveys focuses on the gross shifts in seabed features (Figure 16). Overall, the offshore 30m and 20m OD contours have remained relatively stable over the last 180 years, following an almost north-south trend in comparison to the northeast-southwest trending coastline. The Long Sand and Kentish

Knock 'bulge' has remained, as has the closer alignment between the 20m OD contour and the Kent coast to the south. These contours show some association with the D'Olier's reconstructed Holocene shorelines (D'Olier, 1972), particularly between Kentish Knock and north Kent, the location of the palaeo-Thames channel (Figure 17). The 20m OD channel contours indicate that the Deeps (Knock, Middle, Barrow and Black) have become more continuous in along-channel depth.

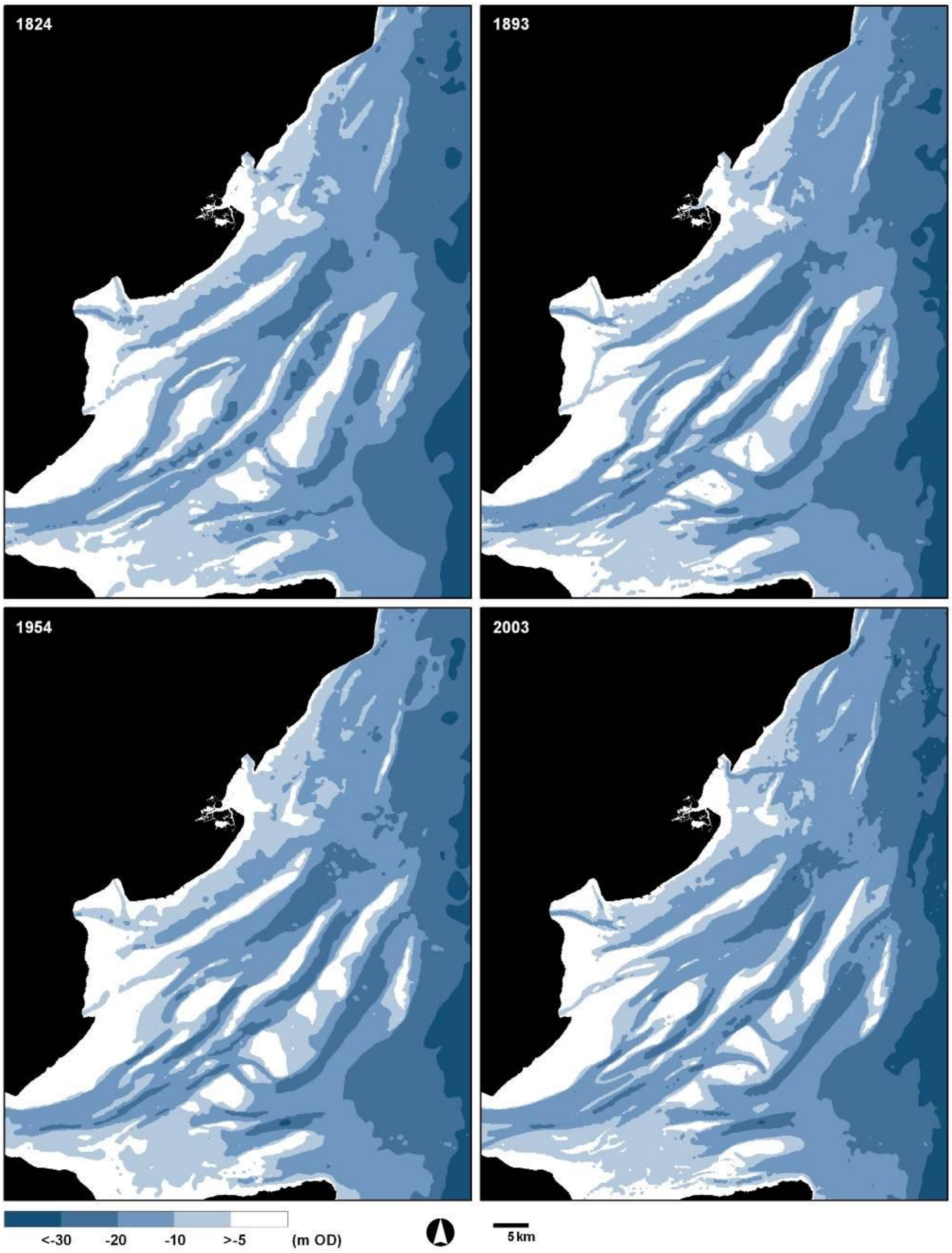


Figure 16 Simplified contour map of selected bathymetric surfaces.

The 10m OD contours draw out the main bank features, where movement is closely associated with the patterns of change in depth. Long Sand Head is dominated by progressive extension, although again there is evidence of localised sculpting. Changes around the headland-associated banks to the north are comparatively small, and it seems that landward of the 10m OD contour, the shoreface has been significantly stable.

The organisation of these sedimentary features and the shallower contours, seem far removed from the physiography of the palaeo-shorelines (Figure 17). Kentish Knock is likely to be associated with a topographic high that existed to the northwest of its current position. Hindcasting the historic behaviour into the Holocene past would suggest that the contemporary Kentish Knock has evolved from the topographic high through processes of wave and tidal reworking. Beyond the obvious shoreline associations between contemporary bathymetric and Holocene topographic highs, it is likely that Girdler/Shingles and Shipwash owe their origins to palaeo-landscape.

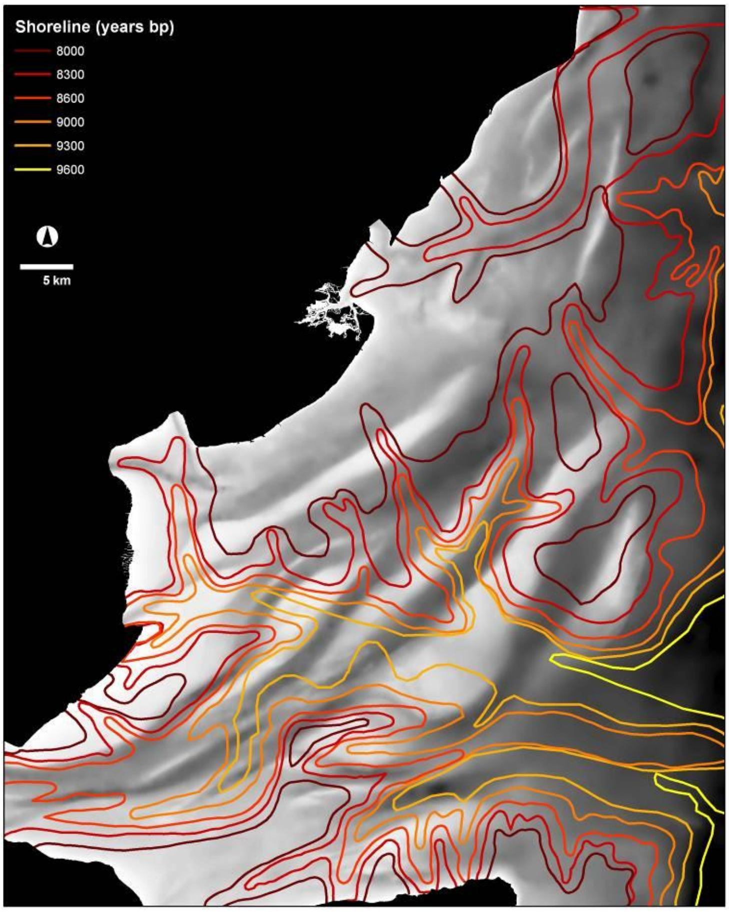


Figure 17 Summary of mid-Holocene shoreline evolution in the greater Thames (modified from D'Olier (1972)), superimposed on the 180 year mean bathymetry.

Morphological maps showing the 3D character of specific bank areas are provided in Appendix 2. These illustrate the nature of morphological evolution over the last 180 years. As previously shown, the gross framework of seabed features in the greater Thames estuary has remained relatively consistent over the history considered (Appendix 2a). At this scale it is difficult to account specifically for some of the growth/decay behaviour identified, but the view is useful to put the bank types in context.

Focusing in on the Suffolk coast, the 3D view emphasizes the tidal-stream aligned banks of Whiting, Bawdsey and Shipwash (Appendix 2b). The morphology is indicative of mutually evasive ebb and flood tidal channels. Shipwash and Bawdsey Bank almost join at their northern extremes, and the presence of northerly skewed sandwaves in the Shipway (HR Wallingford, 2002) indicates that this system is ebb-aligned. Similarly, the Sledway between Whiting and Bawdsey Bank is flood-aligned, shallowing at Kettle Bottom to the south. The position and orientation of these banks has changed over the 180 year period. Shipwash has shifted by up to 800m (mainly in an offshore direction) and has developed a distinct kink about two-thirds distance along the bank, where orientation changes by 25°. There is some suggestion that Shipwash has increased in size. Seller's Coastal Pilot of 1671 provides dimensions of 14.5km long and 0.4km wide, and by the 1800s this had increased to an average of 15km and 1.5km respectively. The current dimensions are 16km long and 1.25km wide, and part of the length increase is certainly associated with the development of a recurve extension (eastward) at South Ship Head. The bathymetric high of Bawdsey Bank has shifted northward: historically, the main body of sediment occupied the zone closer to Kettle Bottom, but now occupies a central zone. Also, the length has increase: Seller (1671) noted a length of 7.25km which has increased to about 10km, with a greater tail to the north. Conversely, the main body of Whiting Bank has shifted to the southwest.

As previously noted, Long Sand Head has progressively extended northward over the last 180 years by about 4.5km. This growth appears to be supplied by northward migration of the discrete bathymetric highs that make up the surface of Long Sand (Appendix 2c). These superimposed features are asymmetric (landward skewed), as is the majority of Long Sand. It is therefore likely that waves play a significant role in transporting sediment across the bank, whilst tidal currents are responsible for reshaping the margins, particularly in the ebb direction. Interestingly though, Long Sand Head appears to accommodate the beginnings of a flood-oriented channel which may cause the east wing of Long Sand Head to be explicitly divided from Long Sand.

The view of Long Sand Head also illustrates some of the main changes in Kentish Knock. In the 1800s, Kentish Knock was about 13km by 3.3km and oval in planform, formed of two ebb-directed wings around a flood-oriented blind channel, whereas earlier charts and pilots suggest that this shape had evolved from a more equidimensional bank: Seller (1671) records a length of 4.8km and a width of 3.2km. The bank has been progressively eroded on its northwest aspect causing the eastern wing to be almost removed, whilst the western wing have become tapered into a point. From the south (Appendix 2d), it seems that the material removed from the eastern wing has contributed to a southerly extension of the overall bank, and it now takes the form of a crescentic bank 16km long and 4.2km at its widest. In addition, Knock Deep has broadened significantly between north Kentish Knock and Long Sand, which appears to be facilitating the development of separate flood (following the Long Sand margin) and ebb (forming against the Kentish Knock margin) channels. Tidal circulation around these banks is clockwise around (HR Wallingford, 2002), which is consistent with the observed morphological evolution of Knock Deep. Over this history, a low broad ridge connecting southwest Kentish Knock to the Tongue-Ridge bank has become increasingly well developed. One of the main consequences of this is the consolidation of a broad bathymetric high at Tongue Sand (west-northwest of the original Tongue-Ridge bank).

The east facing margin of Long Sand has also been reshaped, primarily in terms of recession of the southeast face. In the 17th and 18th centuries, a small bank was present to the east of south Long Sand. By the late 18th century, it was noted as Albion Knowl, presumably due to the fact that the *Albion* (East India Company ship, bound for China) sank after colliding with a sand bank on the 16th January 1765 (Redknap, 1990). By the early 1800s, Albion Knowl is shown as being attached to the southeast of Long Sand: Heather (1801) identifies the feature and name, but Norie (1817) only recognises a sliver of bank attached to Long Sand. By the mid 1800s, Albion Knowl appears to have been fully integrated within a broad south end of Long Sand, and this material has been reworked (most probably southward) resulting in some recession of this margin.

The southerly margin of Long Sand has changed significantly in terms of the presence and position of cross-bank channels, referred to historically as *swatchways* (Appendix 2e). Pre-1800 charts and pilots note numerous channels crossing Long Sand, but the naming of such features seems to only start in the early 19th century well after the advent of Admiralty surveys. The largest channel at that time (dividing Long Sand from Girdler) was noted by Norie (1817) as Thomas's Channel (after the hydrographer George Thomas (Ritchie, 1995)). Even by 1824, there was evidence to suggest a new channel was developing to the south of this, with deeper water pushing in to the east aspect of Girdler. Laurie (1857) shows the presence of Thomas Channel (north) and Bullocks Channel (south), although the northerly route was already diminishing at that stage and only the southerly route was identified on the 1864 chart. Bullocks Channel (after the hydrographer Frederick Bullock (Ritchie, 1995)) was renamed in the 1880s as Duke of Edinburgh Channel: at this stage, Thomas's Channel had completely gone, and the Duke of Edinburgh Channel was well established. By the 1890s this channel had broadened sufficiently to allow some mid-channel shoaling, and this initial division of the channel was the start of the split into the North and South Edinburgh Channels, and the exceptional growth of Shingles Patch.

Robinson (1960) presented a detailed account of the development of Shingles Patch over the period 1926 to 1958, which compared the evolving bank form to a double-hydrofoil. This association helps to explain the continued growth of the bank, which benefits from positive feedback: the shoal acts as an obstacle to flood and ebb tidal currents, causing deflection and concentration of forces on the leading edge - outer bank (Long Sand for North Edinburgh Channel and Shingles for South Edinburgh Channel) and a pressure void on the inner banks (Shingles Patch). Hence, while tidal flow is constrained and deflected through the Edinburgh Channels, Shingles Patch will continue to grow. Changes in its development can be effected through bank and channel shifts across a broader area, which could reduce or change the importance of these routes for ebb and flood tidal flow.

The Long Sand swatchways are predominantly formed from the east, and therefore forced by the flooding tide. North Edinburgh Channel is the only charted evidence of a strongly ebb-directed channel across the Long Sand - Girdler bank. Certainly, the channels depicted in the 19th century all maintained deeper regions to the east than west, and yet in recent decades, North Edinburgh Channel has developed, with support from an increasingly established Knob Channel, as a dominant ebb-directed connection to the North Sea. Over the same timescale, South Edinburgh Channel has diminished in importance, but this may be related to the increased size and depth of Fishermans Gat to the north. This feature was first named Fishermans Gat in the 1850s, and appears to be relatively unchanged over the mid 1800s to mid 1900s, but has clearly deepened over the last 50 years. Given the current bathymetry, where Fishermans Gat is deeper than South Edinburgh channel, it seems likely that this northerly channel may continue to develop at the expense of South Edinburgh Channel.

Further south, Princes and Queens Channels have remained comparatively stable (Appendix 2f): there is evidence of modification to channel margins, but their position has not changed over the last 180 years. Additionally, the Pan Sand - Ridge - Tongue bank group have also maintained their position, despite quite significant changes in planform and size. Closer to the Kent shoreline, it is Margate Sands that exhibits a greater degree of change over the historical timescale. The main bathymetric high of Margate Sands has moved northeast, and one of the small westward tails (Last) has developed into a larger bank in the location of the former Margate high. A further development related to this growth is the formation of NE Spit, which represents the prograding eastern front of this broad complex of banks.

The Oaze region was indentified has having experienced sustained breakdown over the last 180 years, with little evidence of an associated balance in sediment budgets with adjacent accretion. The Thames estuary at this location is narrow, and tidal flow is essentially constrained between the flats of Maplin Sands and The Cant (Appendix 2g). The sequence of changes in banks and channels in this region is quite complicated, with banks such as Mouse migrating across channels. In the early 1800s, Mouse formed a small bank at the southwest extent of West Barrow: these were divided from Oaze and Knock John by Barrow Deep. Through the 19th century Mouse expanded, mainly into Barrow Deep. As the feature broadened, it started to divide in the early 1900s, probably driven by the tidal flow through an increasingly obstructed Barrow Deep. By the 1930s, Mouse was developing as a separate bank on the east margin of Barrow Deep, and over the last 70 years, it has progressively become aligned with, and integrated into the Knock John - Oaze bank complex. In addition, a small spur (North Mouse) now extends southeast from Mouse across to the end of West Barrow. The resulting formation is indicative of evading flood and ebb channels: Barrow Deep appears to be flood-aligned and shallows at North Mouse, whereas The Warp shallows toward North Mouse and appears to be ebb-aligned.

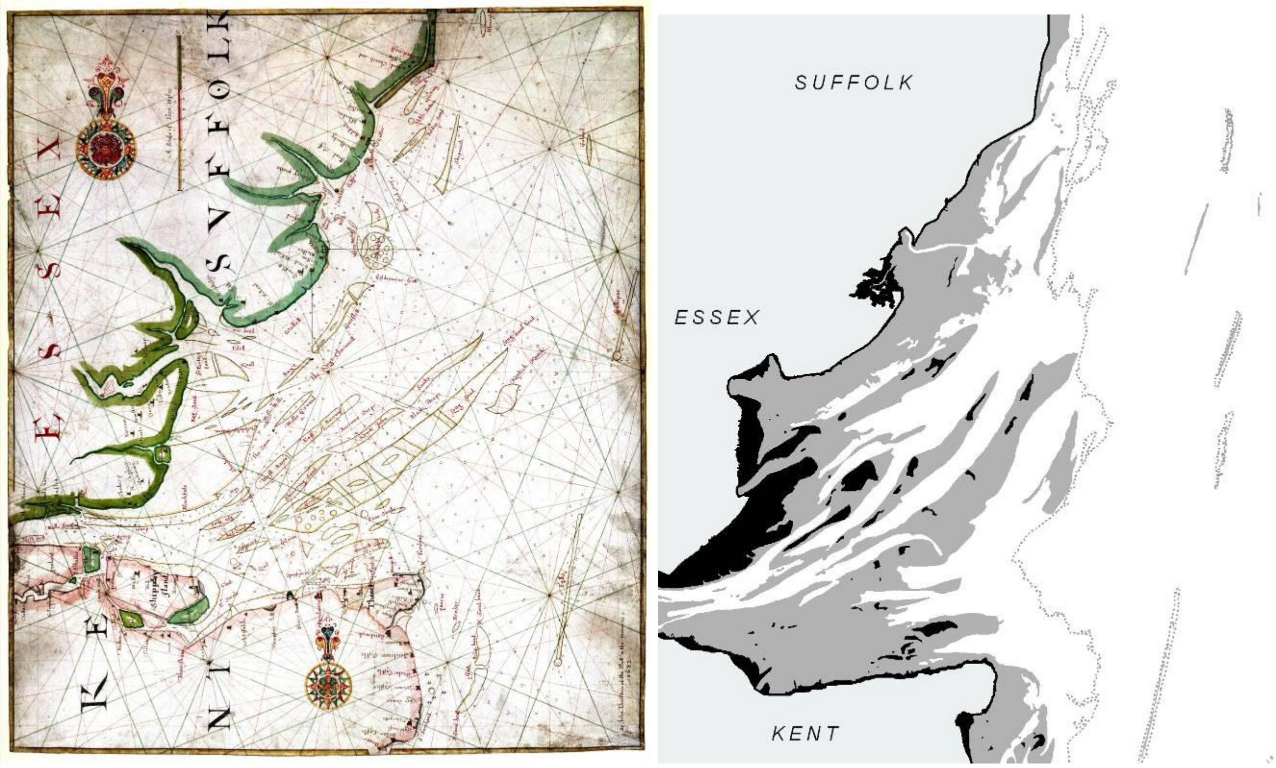
One of the most significant changes in this region is the gradual demise of Shivering Sand. Seventeenth century charts and pilots suggest that Shivering Sand was once a very significant feature in the estuary: Seller (1671) noted dimensions of 11.25km long (it is now less than half this) and 1.6km broad and it is depicted as a prominent bank on Thornton’s 1682 chart. But by the end of the 18th century, it had merged with the north end of Red Sand, with an associated ambiguity over where Shivering Sand stopped and Red Sand started. What is clear though is that the northern end of Red-Shivering Sands has been progressively denuded over the last 180 years, as have most of the bathymetric highs that occupy this margin of The Cant. There is some degree of sediment reworking - East Middle Sand has built up to the east of Middle and Red Sands - but on the whole The Cant is becoming increasingly featureless.

The movement of Mouse is the most dynamic element of West Barrows, which has occupied a very stable position in comparison. East Barrows has equally maintained its position over the last 180 years, although like Mouse, various features loosely connected to the Barrows are much more mobile (Appendix 2h). East Barrow invariably comprises an ebb-directed blind channel (originating from West Swin), which also plays a role in maintaining a small swatchway across the Barrows into Barrow Deep. These components move around, but there does not appear to be a specific pattern to this at the temporal resolution and timescale considered here. It is likely that shifts in these channel features have been affected by the migration of Maplin Spit, and associated changes in the connection between West Swin and Middle Deep (through South West Reach). Maplin Spit originally developed as a northeast extending spur from Maplin Sands during the early 1900s. Growth was not continuous, but by the 1950s South West Reach and Maplin Spit had moved about 1.5km to the northeast. Since then, Maplin Spit has attached to East Barrow, and South West Reach leads into the ebb-aligned blind channel and Barrow Swatchway along the south end of East Barrow. Middle Deep now shallows toward Maplin Spit (suggesting a flood-dominance) and the connection between this and South West Reach has significantly shallowed.

Throughout this history, the Middle bank to the west of East Barrow has maintained a very clear position along the margin of Middle Deep. There appears to have been some reworking of material and a shift in the main bathymetric highs, but perhaps most interesting is the development of features to the northeast of this (NE Middle and an unnamed spur), not least because 17^{th} and 18^{th} century charts note the presence of Middle Ground and Saverold banks in this region, which appear to have disappeared by the early 1800s. Given the historical evolution, the extension of the northern tip of East Barrows could be instrumental in supplying sediment to northeast of NE Middle, perhaps facilitating the occasional development of these features.

4. Conclusions

This comprehensive analysis of the morphology of the greater Thames seabed shows that the gross organisation of banks, ridges and channels has changed very little over the 180 year history examined. Furthermore, the presence and distribution of features is remarkably similar to that depicted in 17th century charts (Figure 18), suggesting an inherent and significant long-term stability.



1682: Thornton 2003: UK Hydrographic Office

Figure 18 Visual comparison of 17th and 21st century charts of the greater Thames estuary.

Beyond the organisational stability however, the seabed is locally dynamic. Banks and channels display progressive but significant lateral shifts which can account for depth changes of the order of 10s metres over the course of a century. This is specifically true for the central Type 2A banks (wide estuary mouth banks) where margins of Sunk Sand, the Barrows, Long Sand and Kentish Knock and associated channels have moved by 2km. Further significant changes occur where cross-bank swatchways proceed through a sequence of initial development, expansion, migration and closure, as experienced around the Edinburgh Channels and Shingles Patch area.

There is some evidence to suggest that the outer Type 1 ridges comprise mobile surficial features which cause some along-bank changes in depth and small-scale variations in planform, particularly at the heads and tails of the ridges. It does appear that the relative position of these ridges on the greater Thames - southern North Sea seabed is stable over the historical time scale. But at the spatial resolution considered here, and given the positional problems associated with the offshore region of early 19th century charts, it is not possible to describe with any greater accuracy the nature of changes around these banks.

The dynamics of Type 3A ridges - headland associated banks - on the Suffolk shoreface are appreciably different. These features exhibit smaller scale changes, mainly attributed to subtle changes in orientation and position relative to the shoreline. Interestingly, each bank has moved position in a different way to each other: Cutler has moved offshore, Whiting has moved onshore, the bathymetric highs of Bawdsey Bank moved along-bank in a northeasterly direction, and Shipwash is bending in the middle. Meanwhile, to the north Aldeburgh Ridge has moved onshore whilst Aldeburgh Napes has moved slightly offshore.

The potential for links between bank/channel morphodynamics and shoreline change is unclear. Certainly, there is very little evidence to suggest that there is any broader connection between seabed dynamics and the regional picture of foreshore steepening, as presented by Taylor *et al*. (2004).

5. References

Buonaiuto F.S., Bokuniewicz H.J., Fitzgerald D.M. 2008. Principal component analysis of morphology change at a tidal inlet: Shinnecock Inlet, NY. *Journal of Coastal Research*, **24** (4), 867-875.

Burningham H., French J.R. 2008. *Historical changes in the seabed of the greater Thames estuary*. The Crown Estate, 54pp.

Cuadradoa D.G., Perillo G.M.E. 1997. Principal component analysis applied to geomorphologic evolution. *Estuarine, Coastal and Shelf Science*, **44**, 411-419.

D'Olier B. 1972. Subsidence and sea-level rise in the Thames Estuary. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, **272** (1221), 121-130.

Dyer K.R., Huntley D.A. 1999. The origin, classification and modelling of sand banks and ridges. *Continental Shelf Research*, **19**, 1285-1330.

HR Wallingford. 2002. *Southern North Sea Sediment Transport Study (Phase 2)*. HR Wallingford Report, EX 4526.

Kemp J.A., Brampton A. 2007. The development of a time trend analysis tool for GIS and its application in the assessment of Nash Bank, South Wales. *Journal of Hydroinformatics*, **9** (3), 193-201.

Maron P.P., Reeve D.E., Rihouey D., Dubranna J. 2008. Transverse and longitudinal eigenfunction analysis of a navigation channel subject to regular dredging: the Adour River Mouth, France. *Journal of Coastal Research*, **24** (1), 206-215.

Redknap M. 1990. The *Albion* and *Hindostan*: the fate of two outward-bound East Indiamen. *The International Journal of Nautical Archaeology and Underwater Exploration*, **19** (1), 23-30.

Reeve D.E., Horrillo-Caraballo J.M., Magar V. 2008. Statistical analysis and forecasts of long-term sandbank evolution at Great Yarmouth, UK. *Estuarine, Coastal and Shelf Science*, **79** (3), 387-399.

Ritchie G.S. 1995. *The Admiralty Chart: British Naval Hydrography in the Nineteenth Century*. Pentland Press, Edinburgh, (New Edition), 444pp.

Robinson A.H.W. 1960. Ebb-flood channel systems in sandy bays and estuaries. *Geography*, **45**, 183-199.

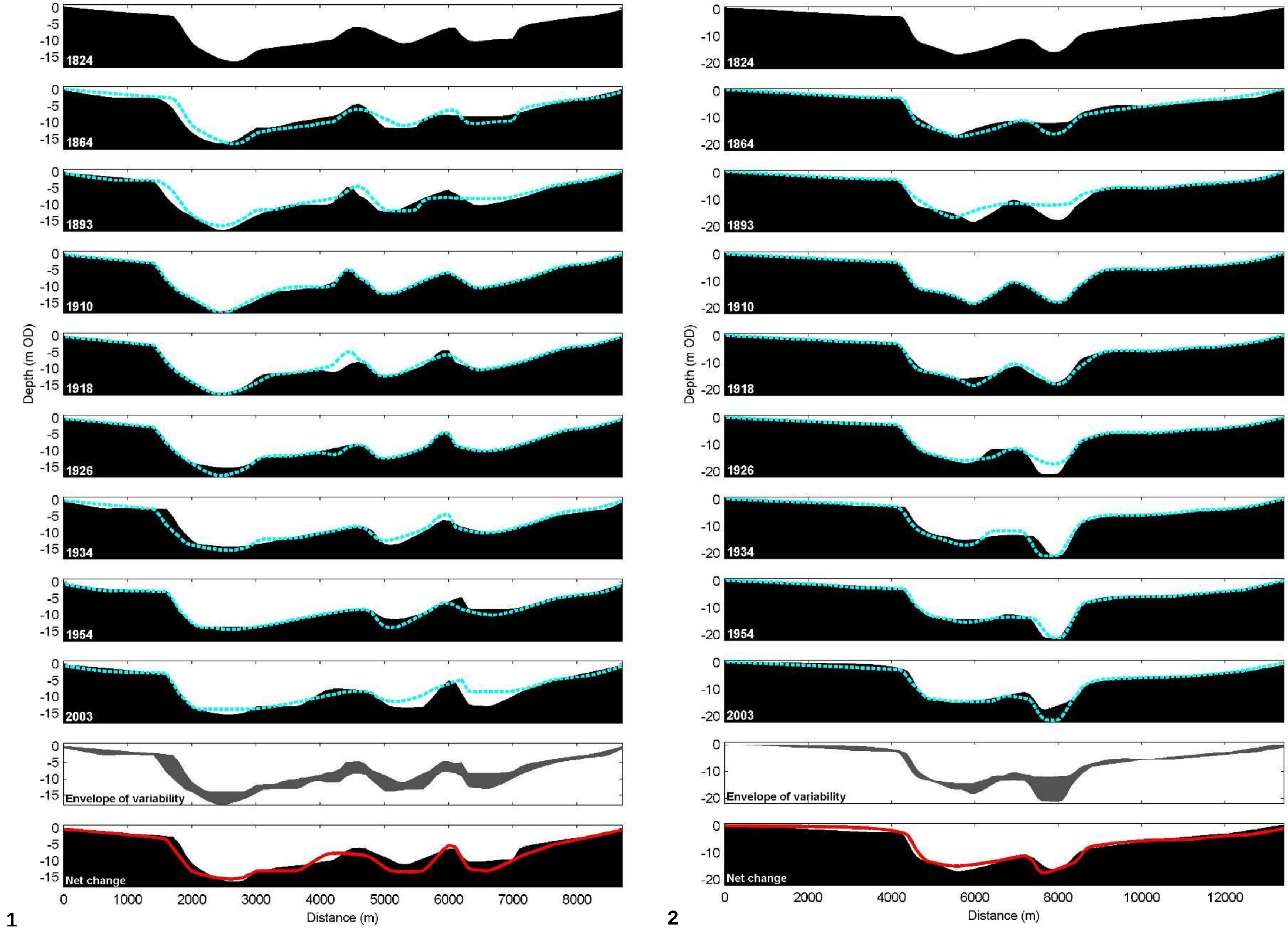
Seller J. 1671. *The English Pilot: Describing the sea-coasts, channels, soundings, sands, shoals, rocks, & dangers … upon the coasts of England Flanders and Holland with directions to bring a shipp into any harbour on the said coasts.* John Seller, London.

Taylor, J.A., Murdock A.P., Pontee N.I. 2004. A macroscale analysis of coastal steepening around the coast of England and Wales. *The Geographical Journal*, **170** (3), 179-188.

Appendices

Appendix 1: Bathymetric transects.

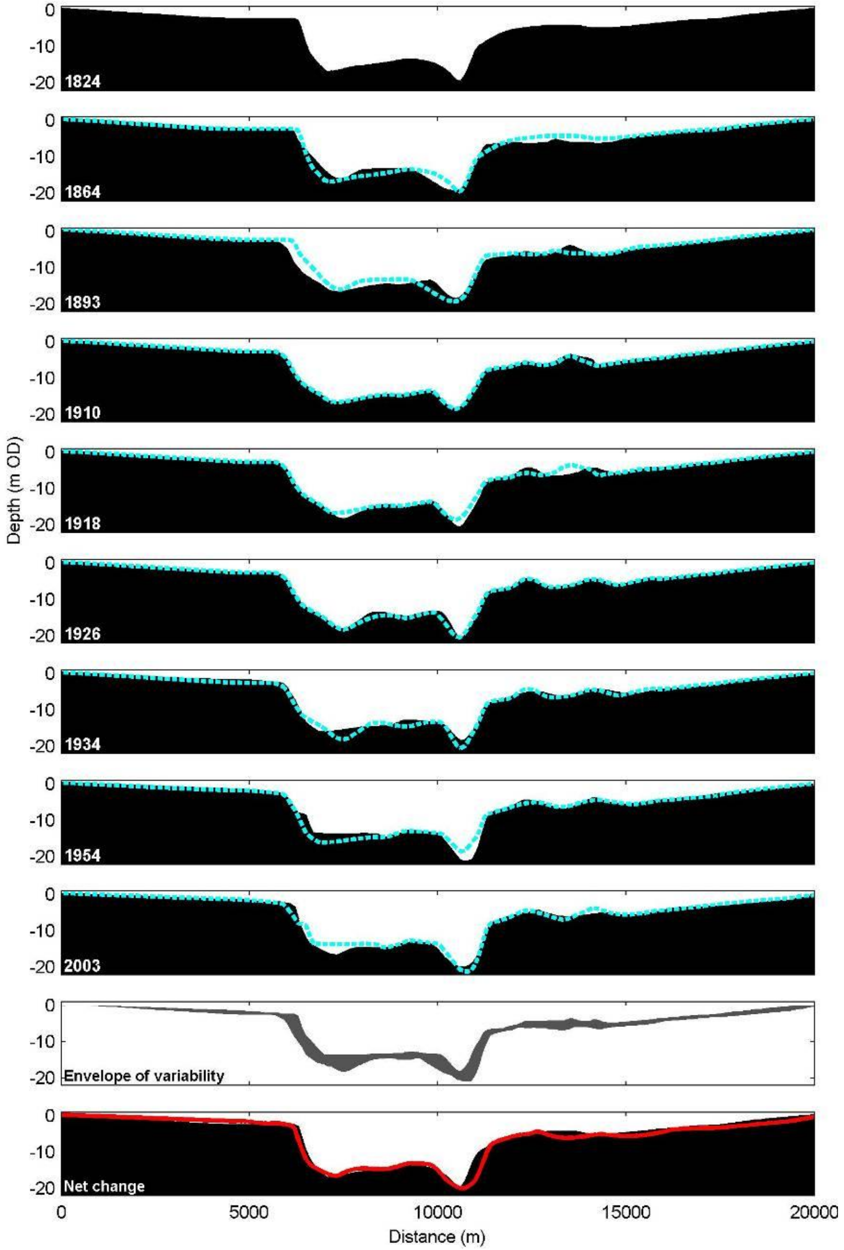
Appendix 1a: Cross-estuary transects (1 and 2).



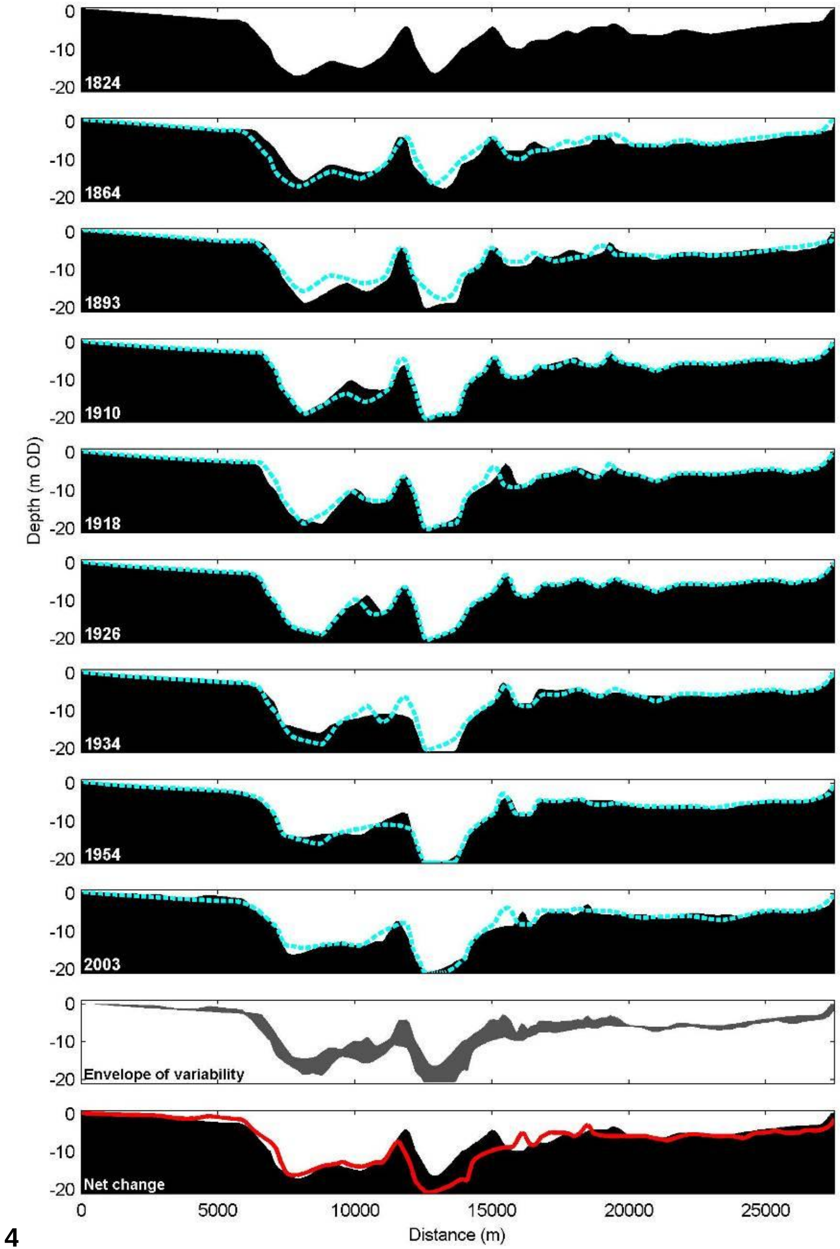
[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

Appendix 1a: Cross-estuary transects (3 and 4).



3

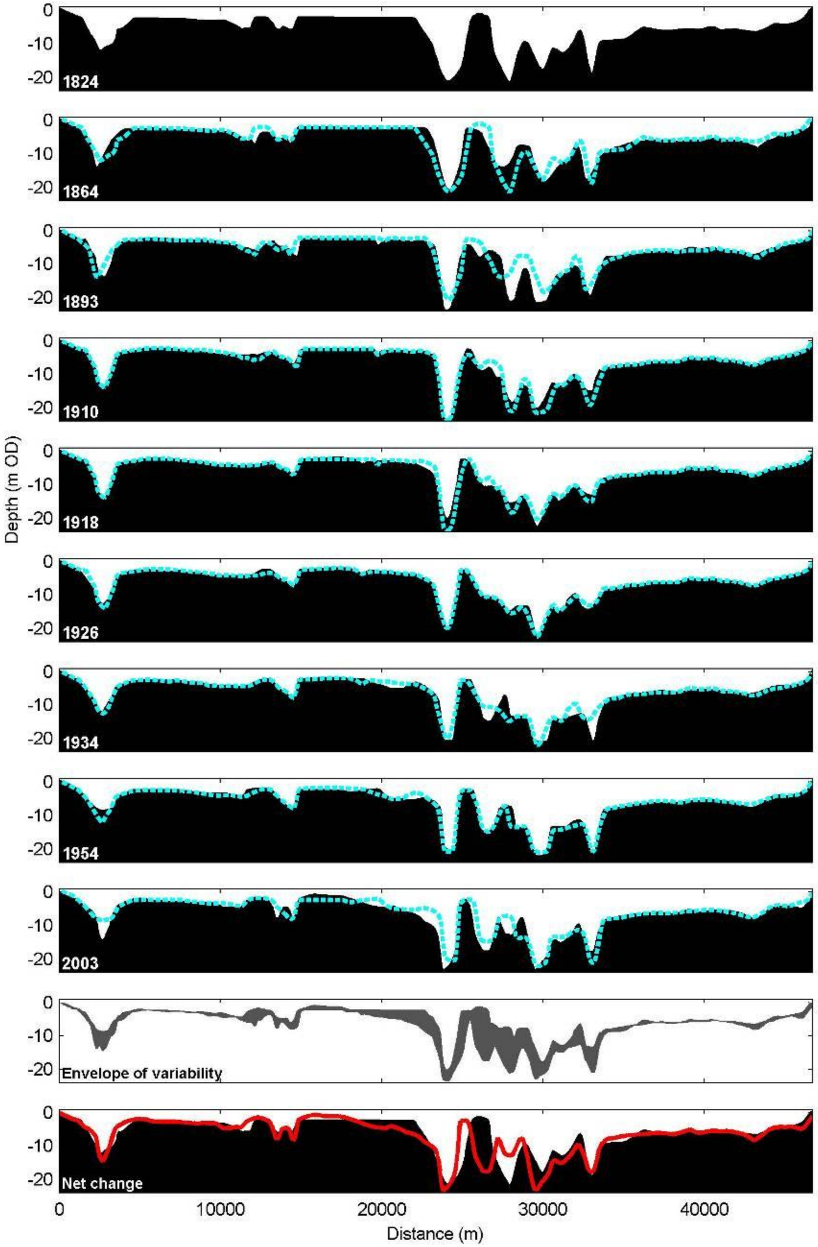


4

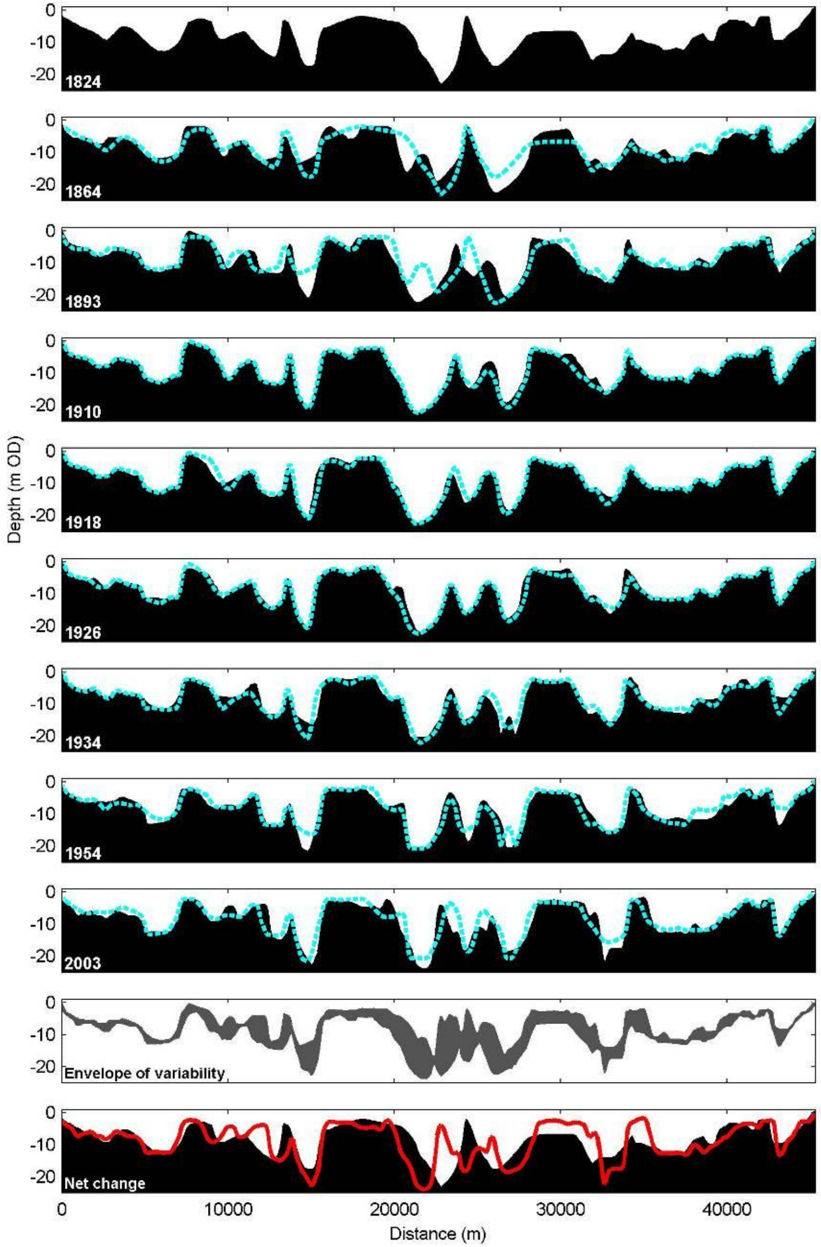
[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

Appendix 1a: Cross-estuary transects (5 and 6).



5

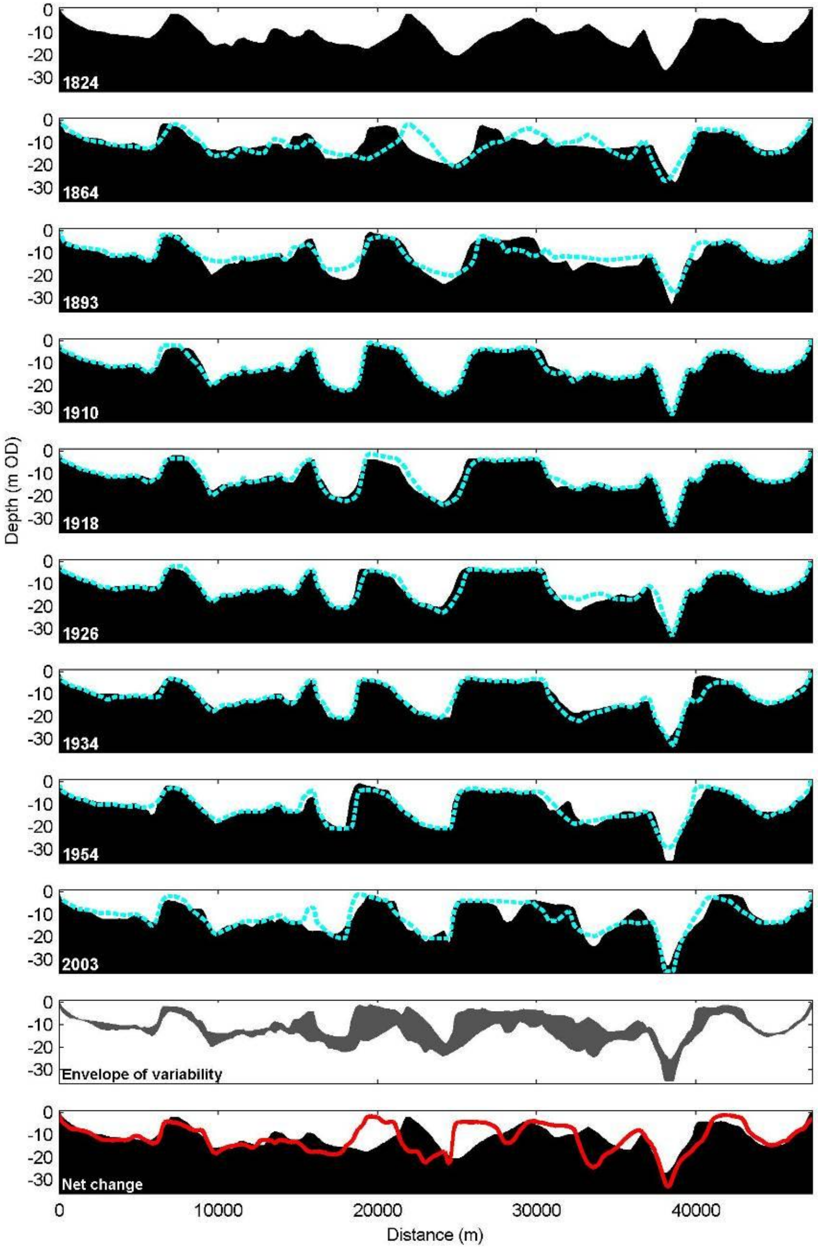


6

[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

Appendix 1a: Cross-estuary transect 7.



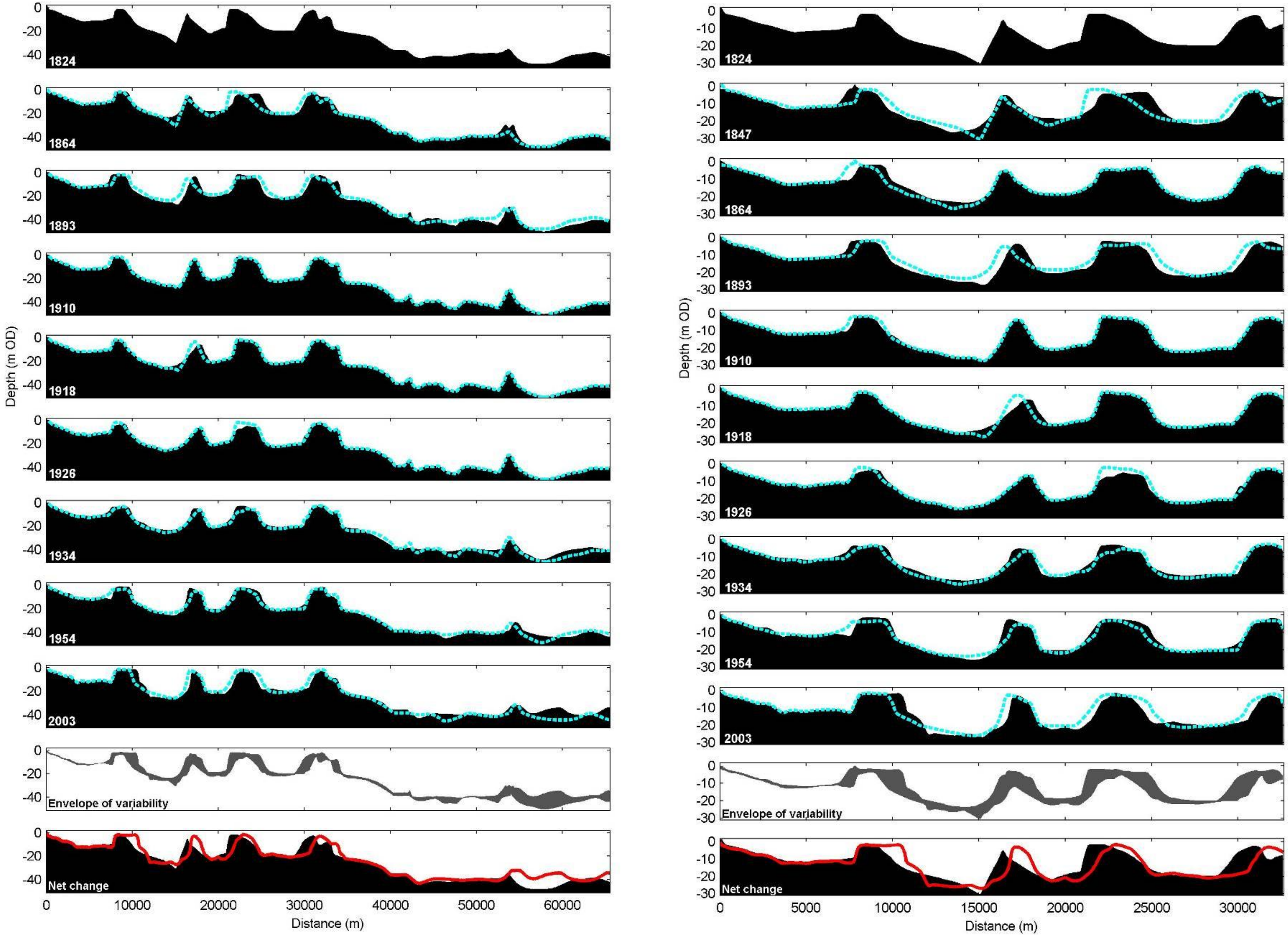
7

[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

Appendix 1b: Shore-normal transect 8 (left: full extent, right: inshore zoomed in).

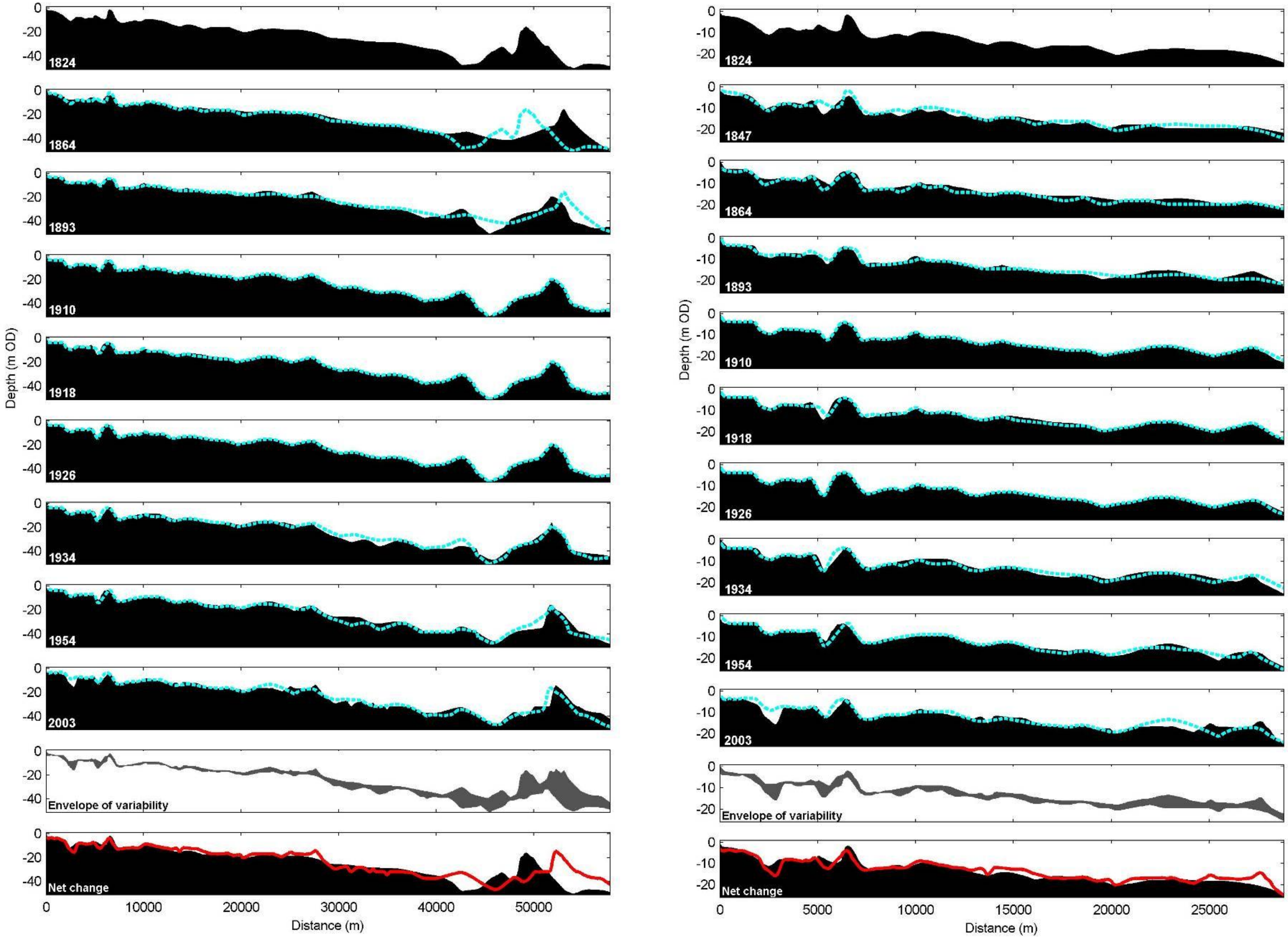
8



[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

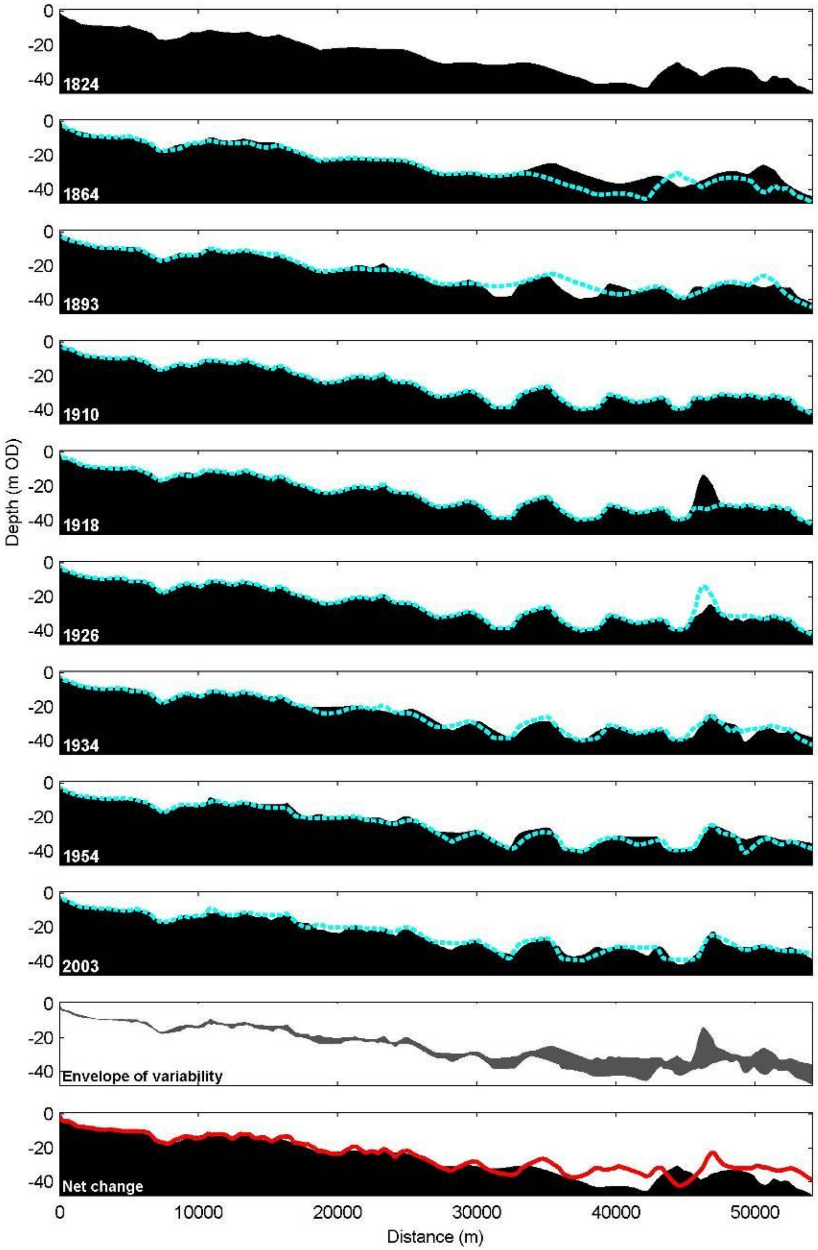
Appendix 1b: Shore-normal transect 9 (left: full extent, right: inshore zoomed in).

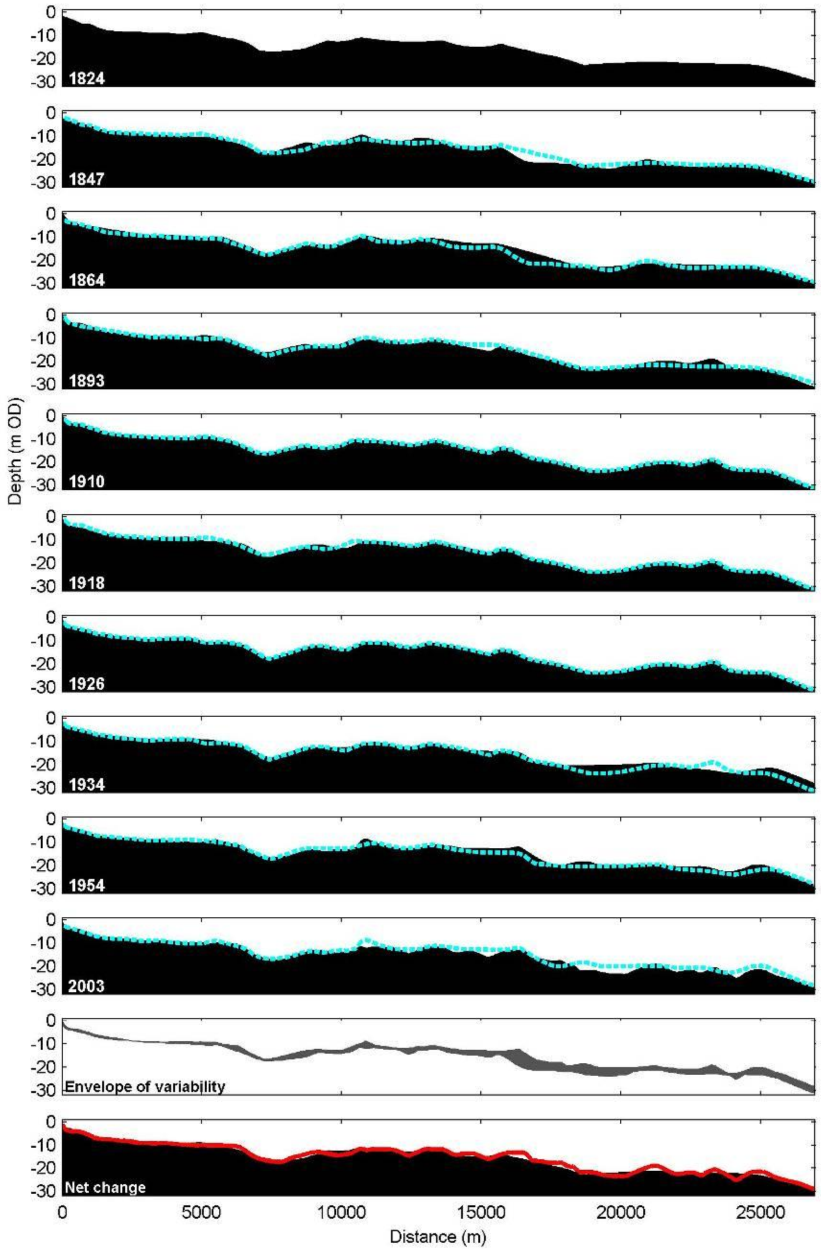


9

[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.





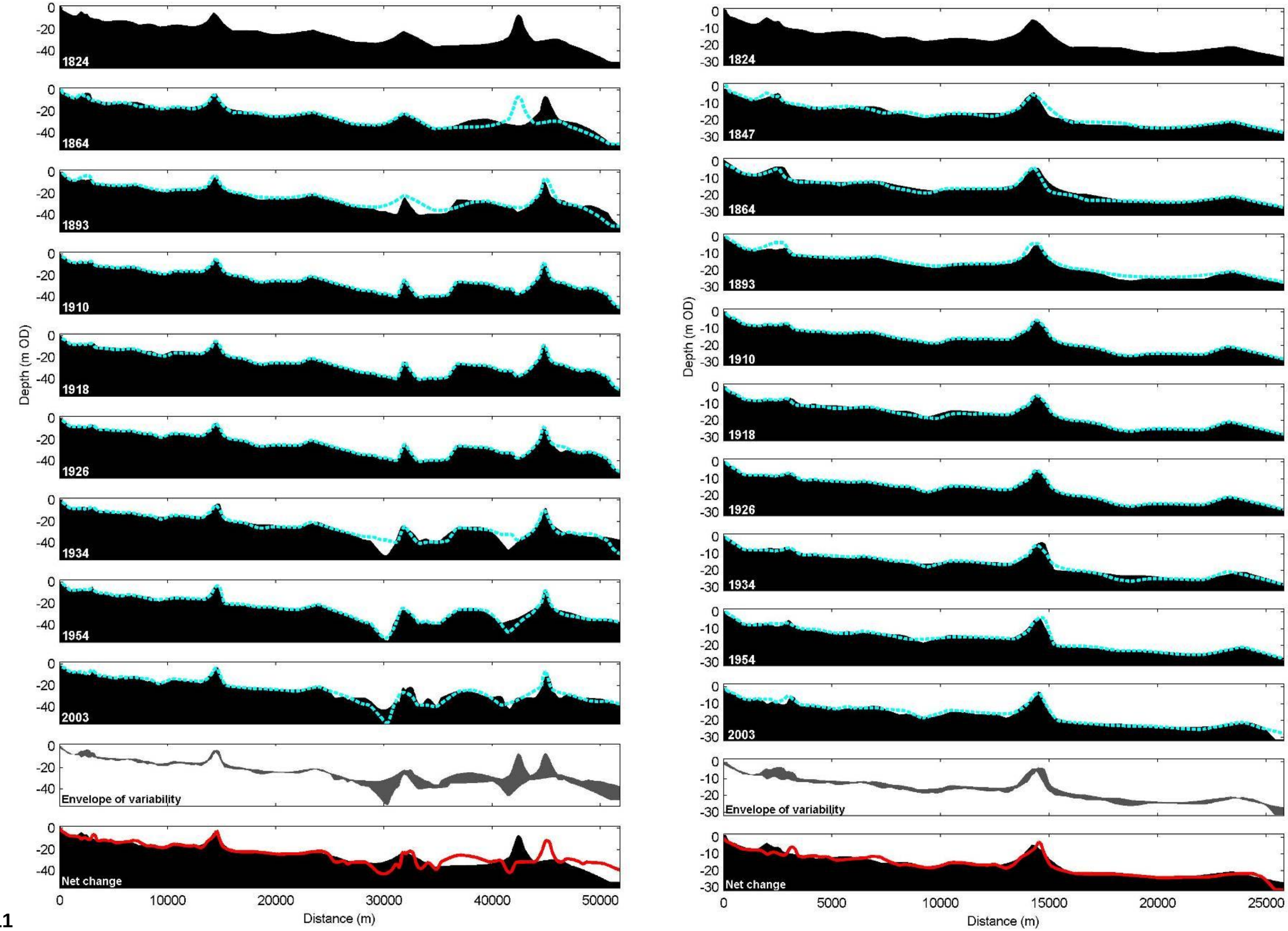
Appendix 1b: Shore-normal transect 10 (left: full extent, right: inshore zoomed in).

10

[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

Appendix 1b: Shore-normal transect 11 (left: full extent, right: inshore zoomed in).

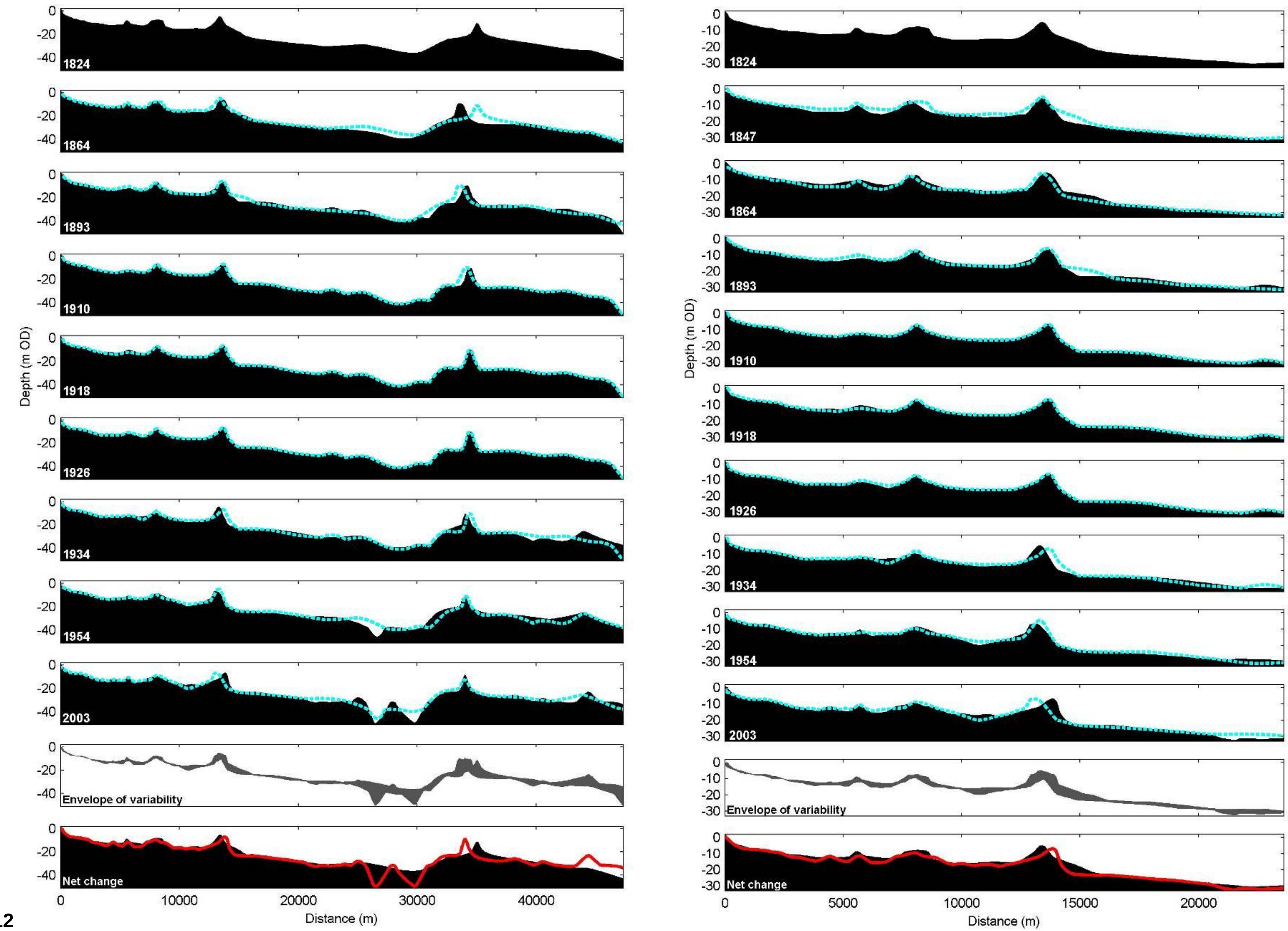


11

[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

Appendix 1b: Shore-normal transect 12 (left: full extent, right: inshore zoomed in).

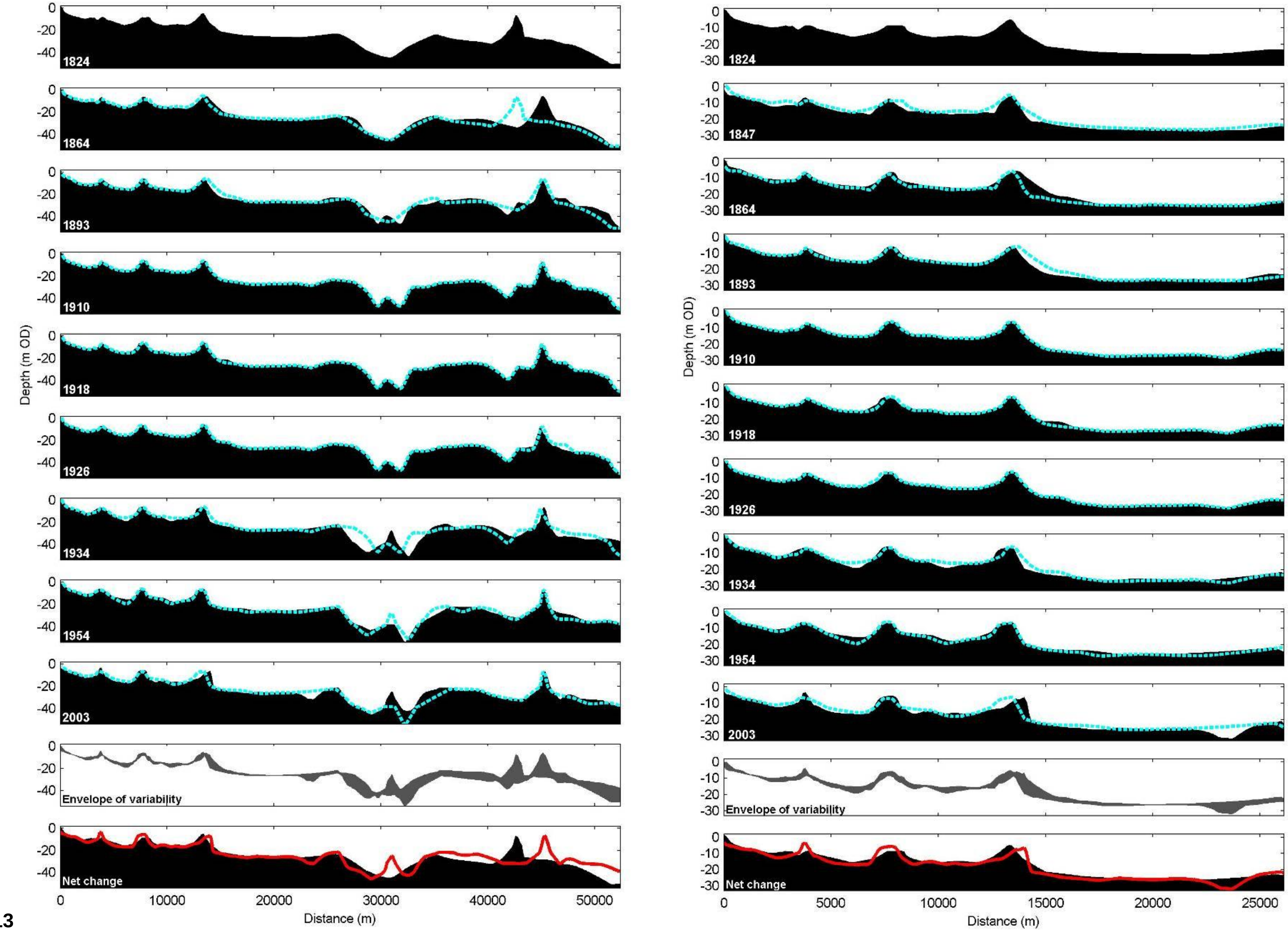


12

[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

Appendix 1b: Shore-normal transect 13 (left: full extent, right: inshore zoomed in).

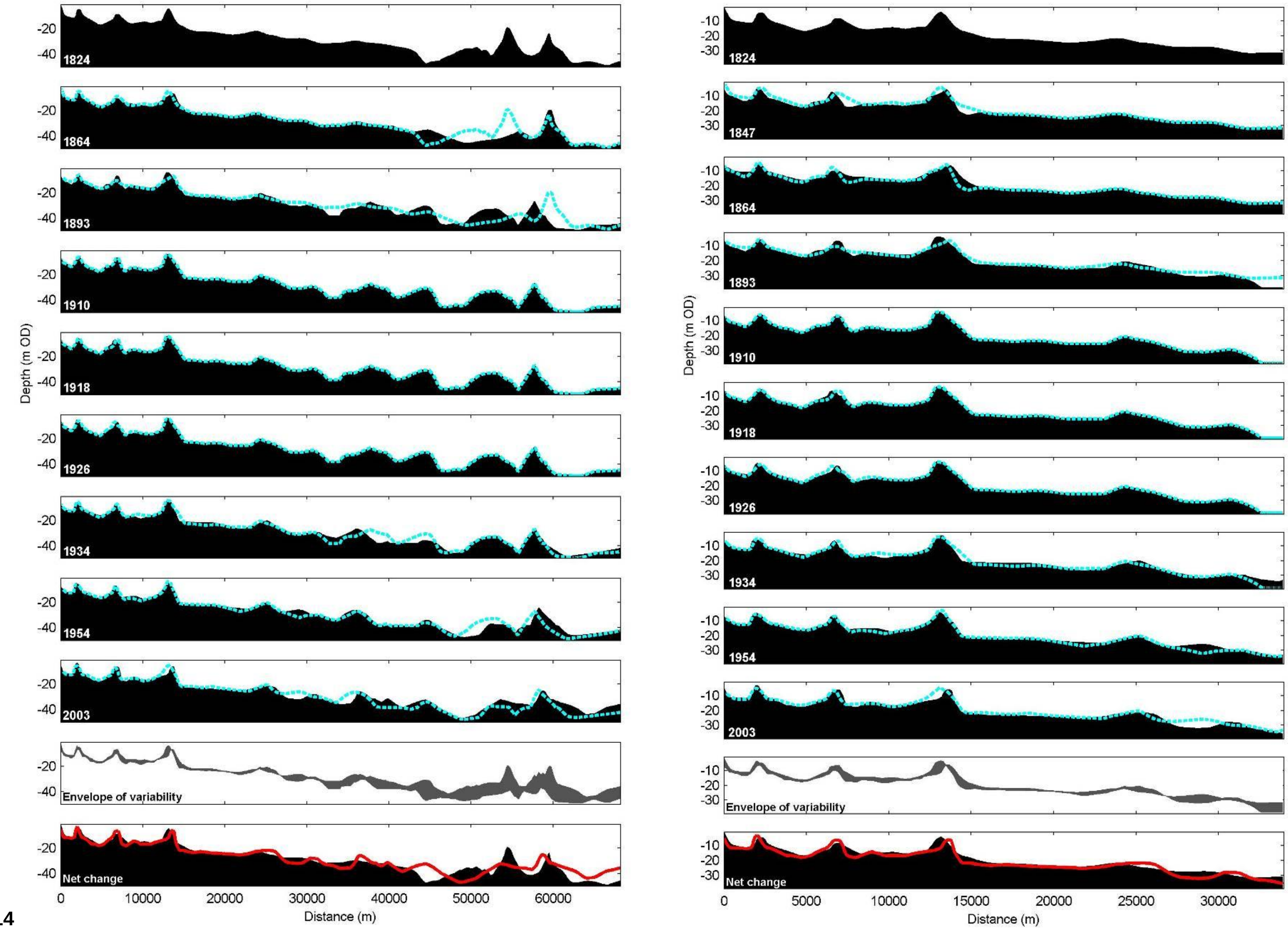


13

[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

Appendix 1b: Shore-normal transect 14 (left: full extent, right: inshore zoomed in).



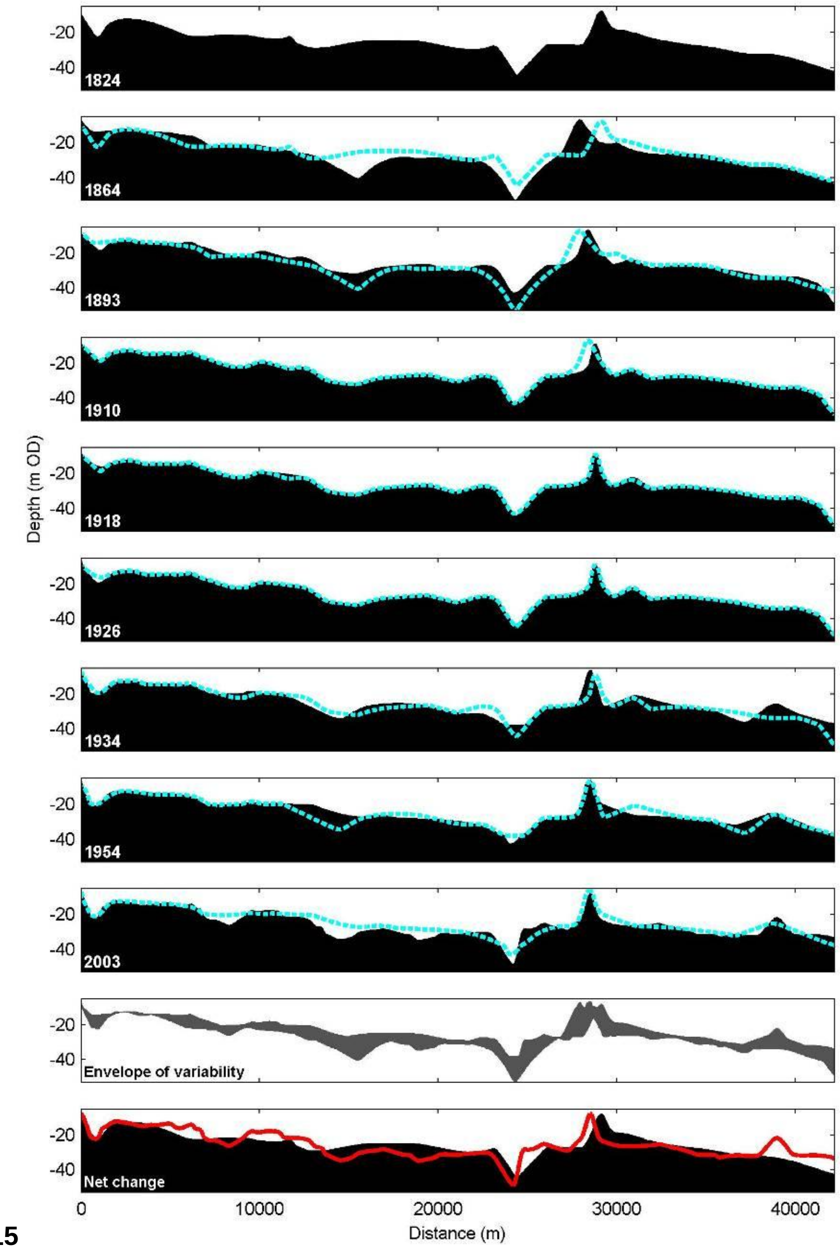
14

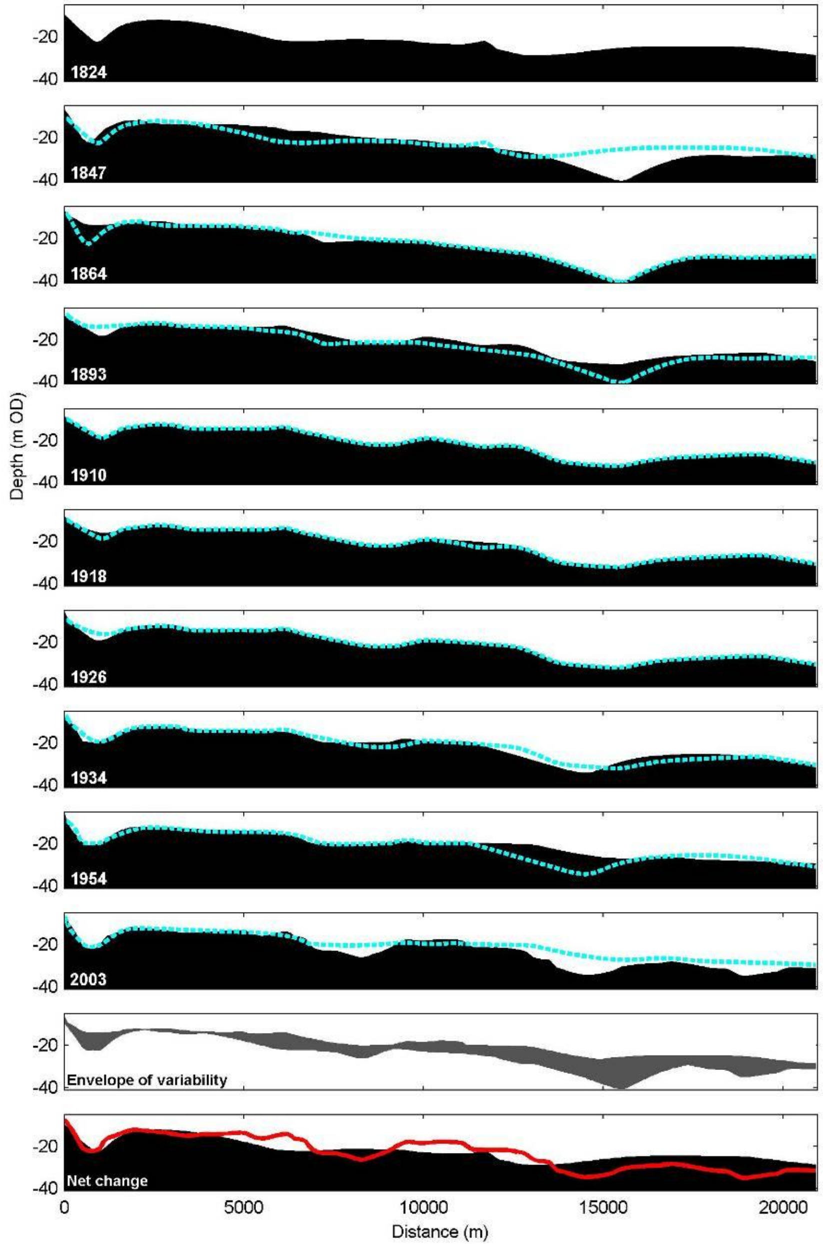
[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

Appendix 1b: Shore-normal transect 15 (left: full extent, right: inshore zoomed in).

15

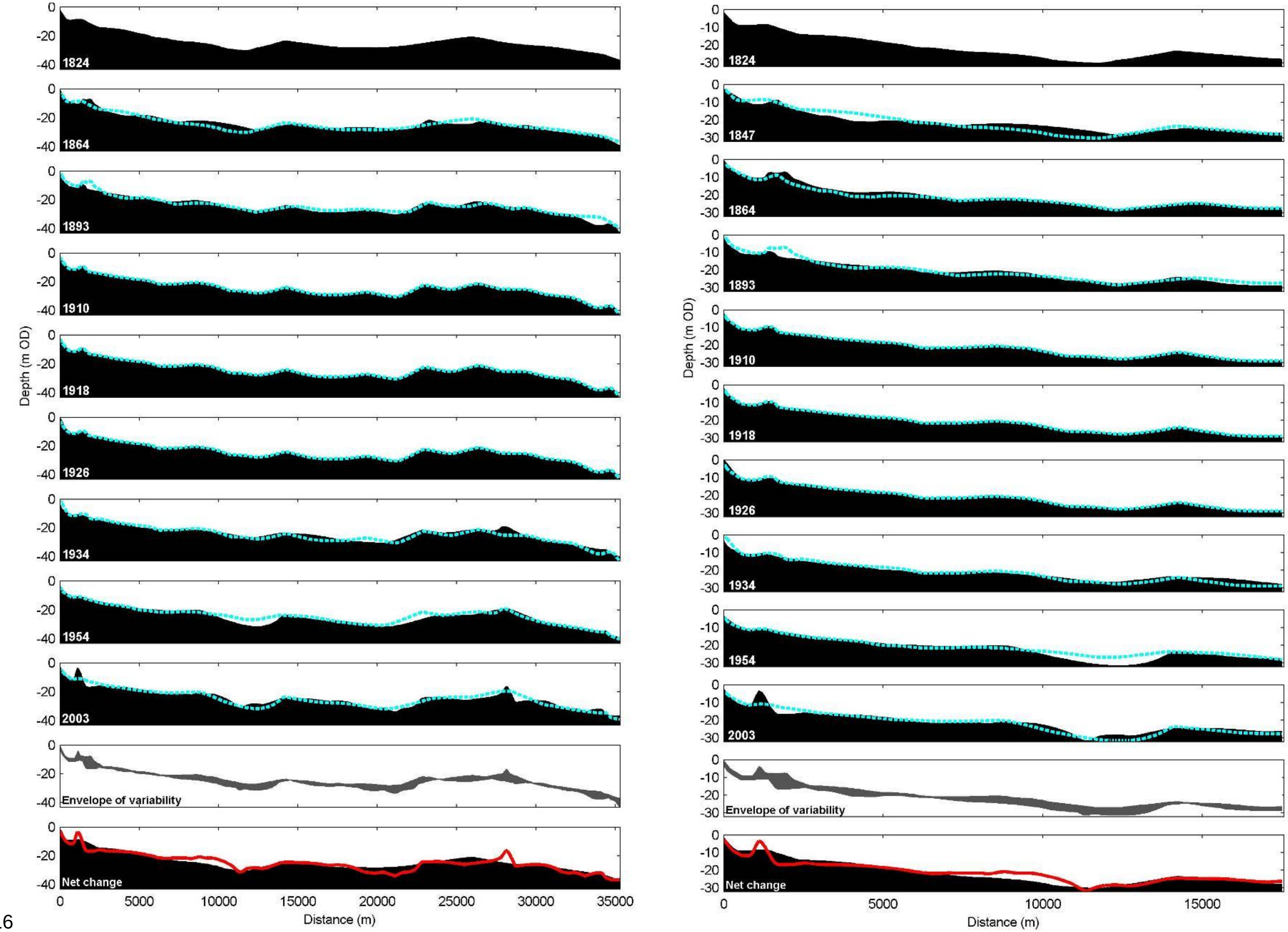




[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

Appendix 1b: Shore-normal transect 16 (left: full extent, right: inshore zoomed in).

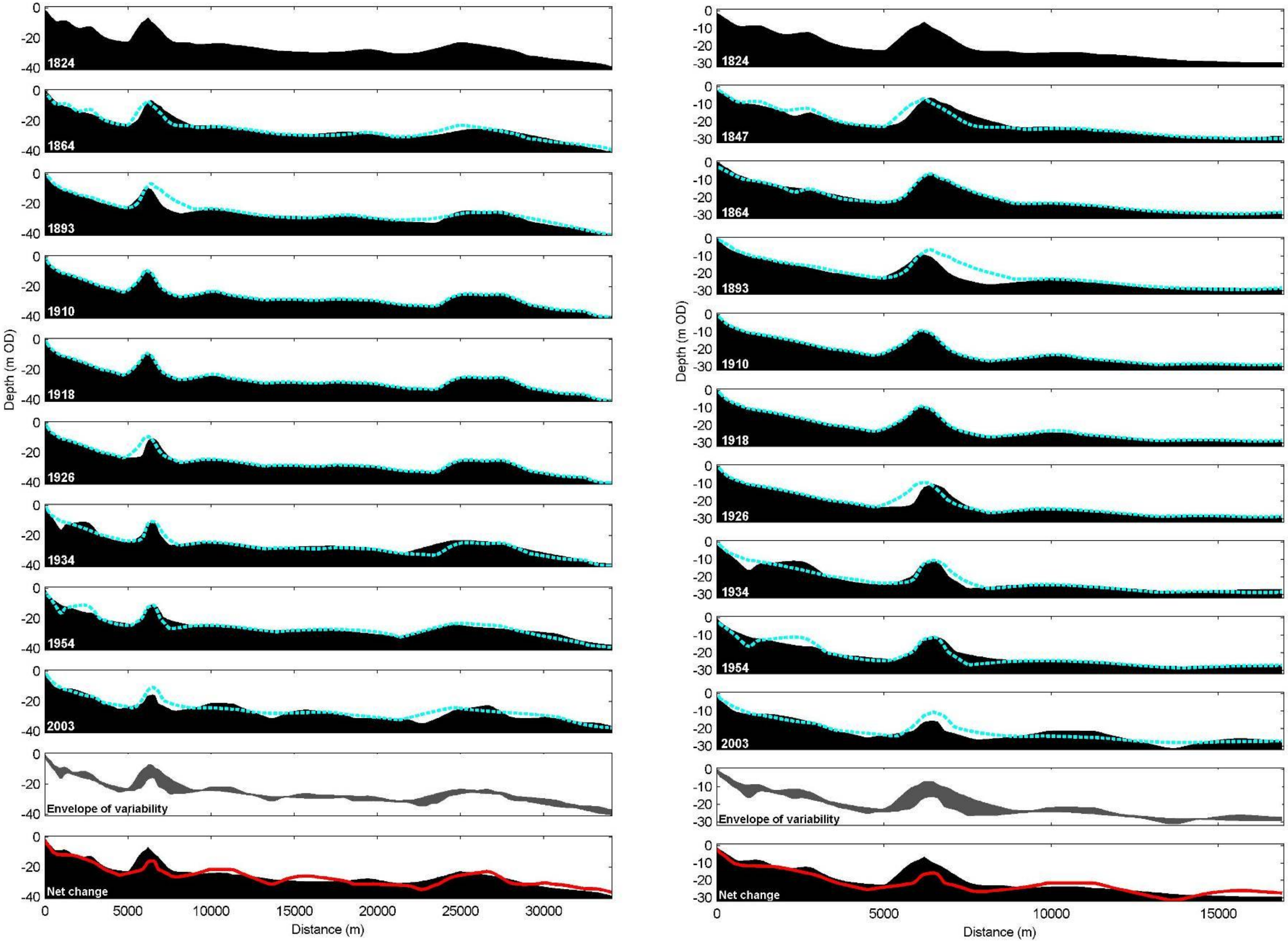


[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

16

Appendix 1: Bathymetric transects.

Appendix 1b: Shore-normal transect 17 (left: full extent, right: inshore zoomed in).

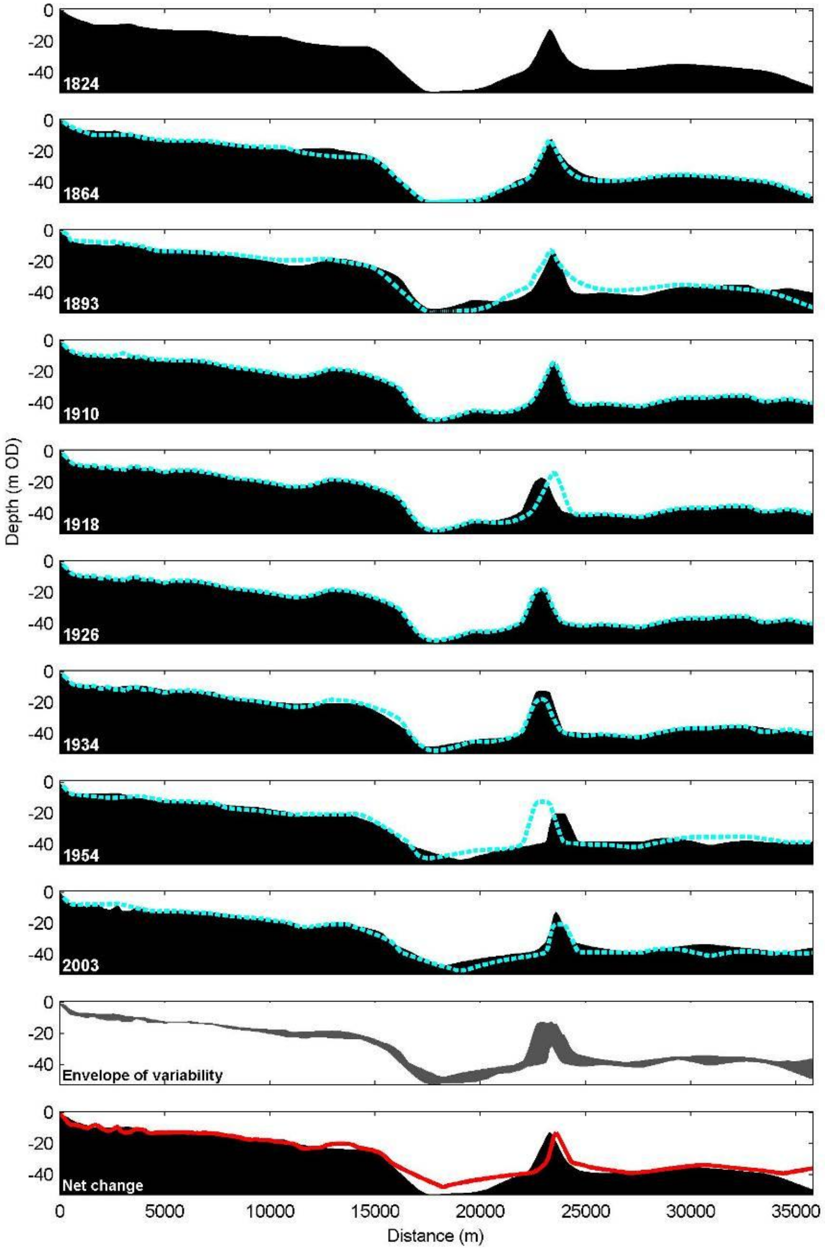


17

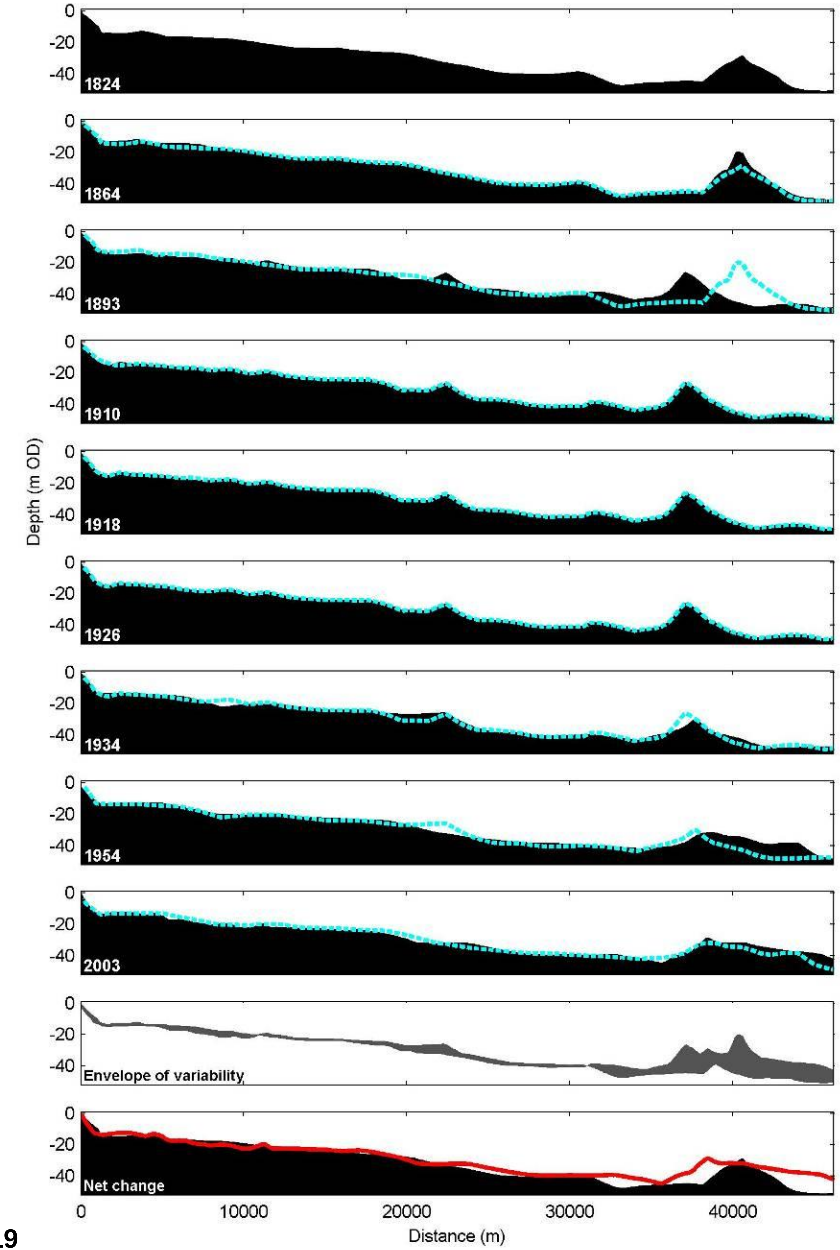
[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

Appendix 1b: Shore-normal transects (18 and 19).



18

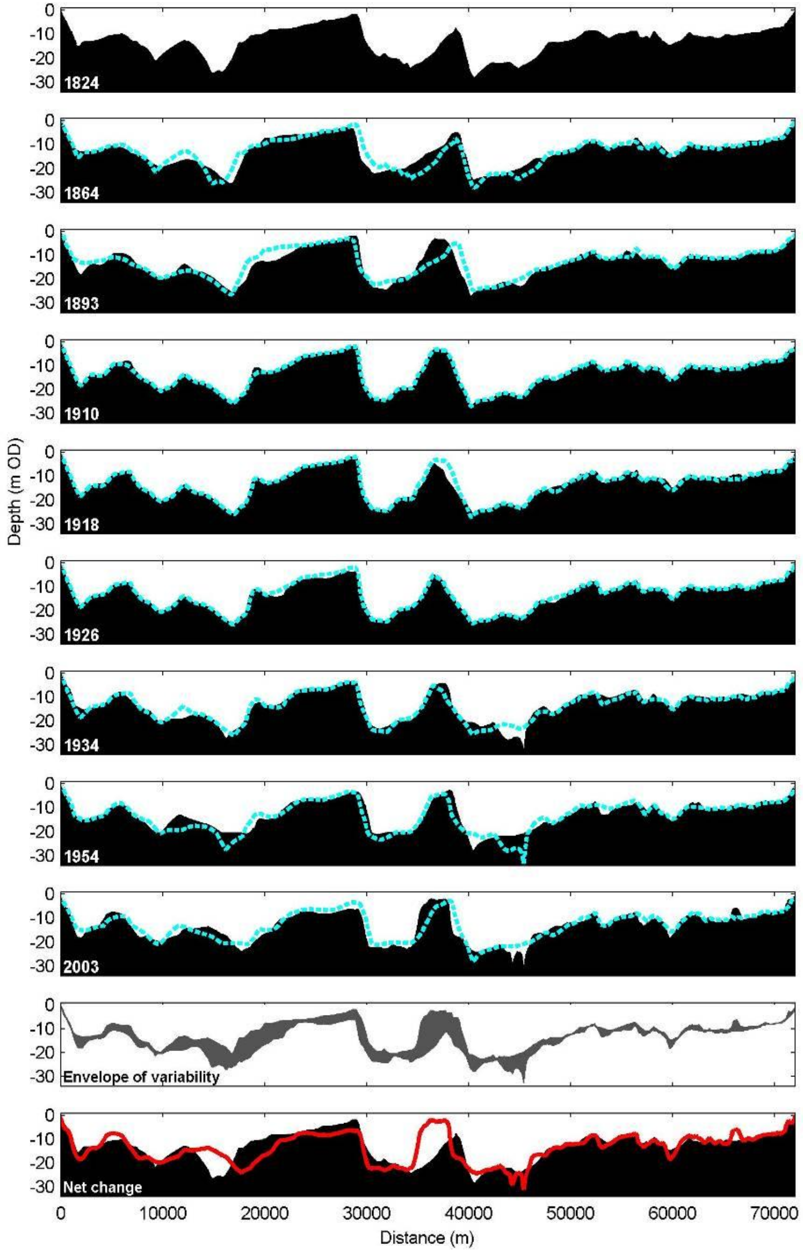


19

[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

Appendix 1: Bathymetric transects.

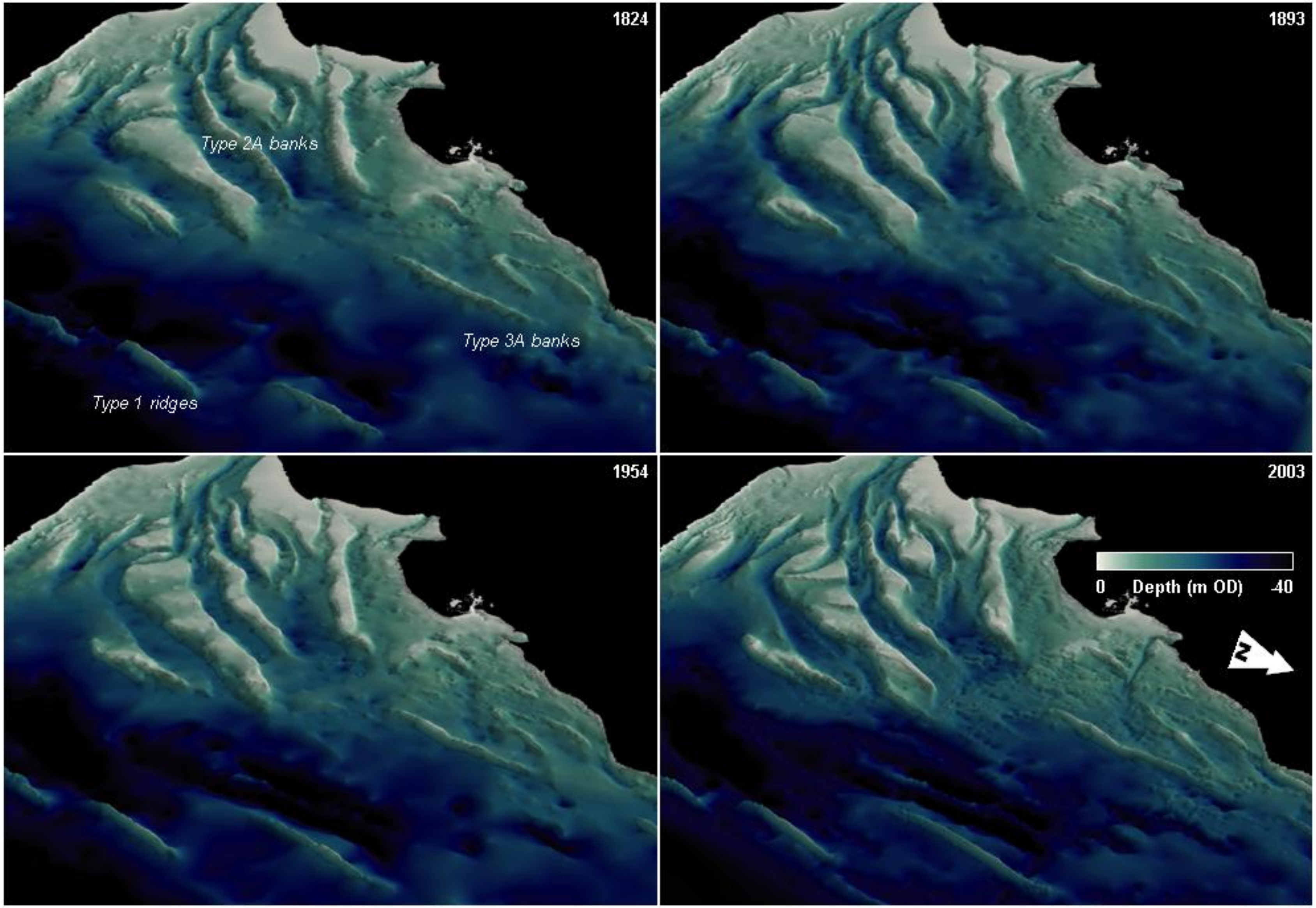
Appendix 1b: Shore-normal transect 20.



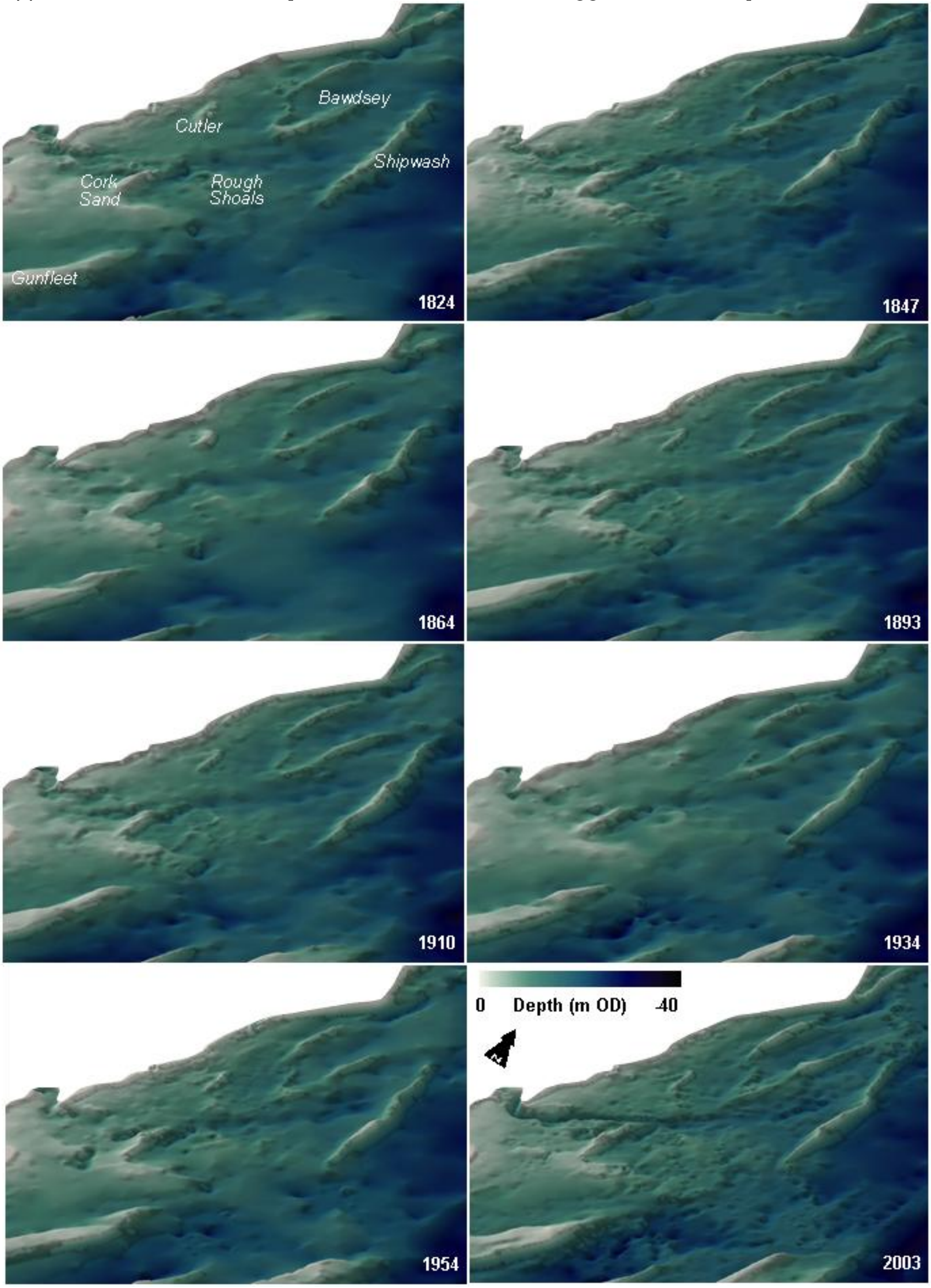
20

[Blue dashed lines show the profile of the preceding survey. Net change: the most recent survey is superimposed on the earliest survey as a red line.]

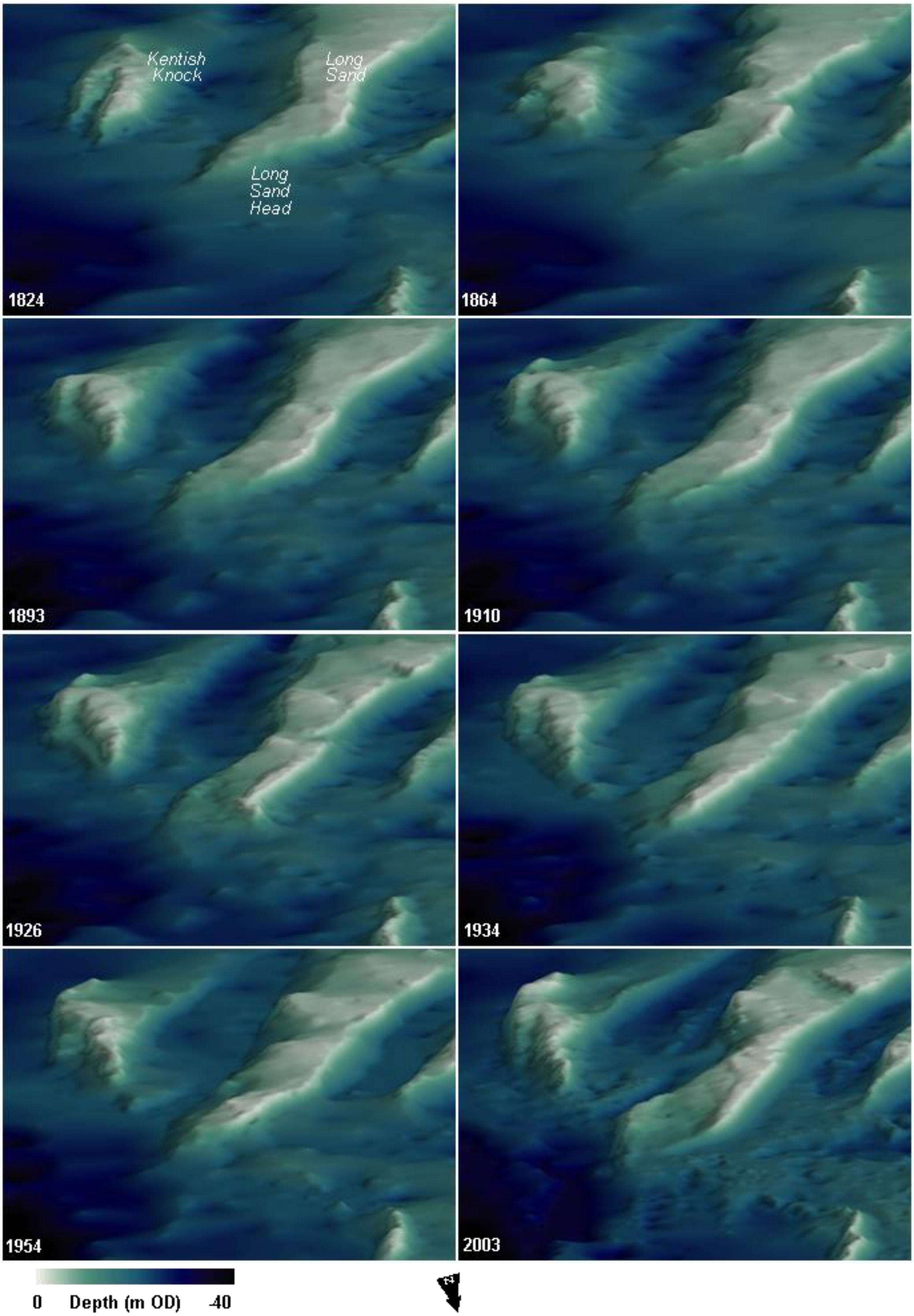
Appendix 2a: Greater Thames estuary. [3D view uses a vertical exaggeration of 50x.]



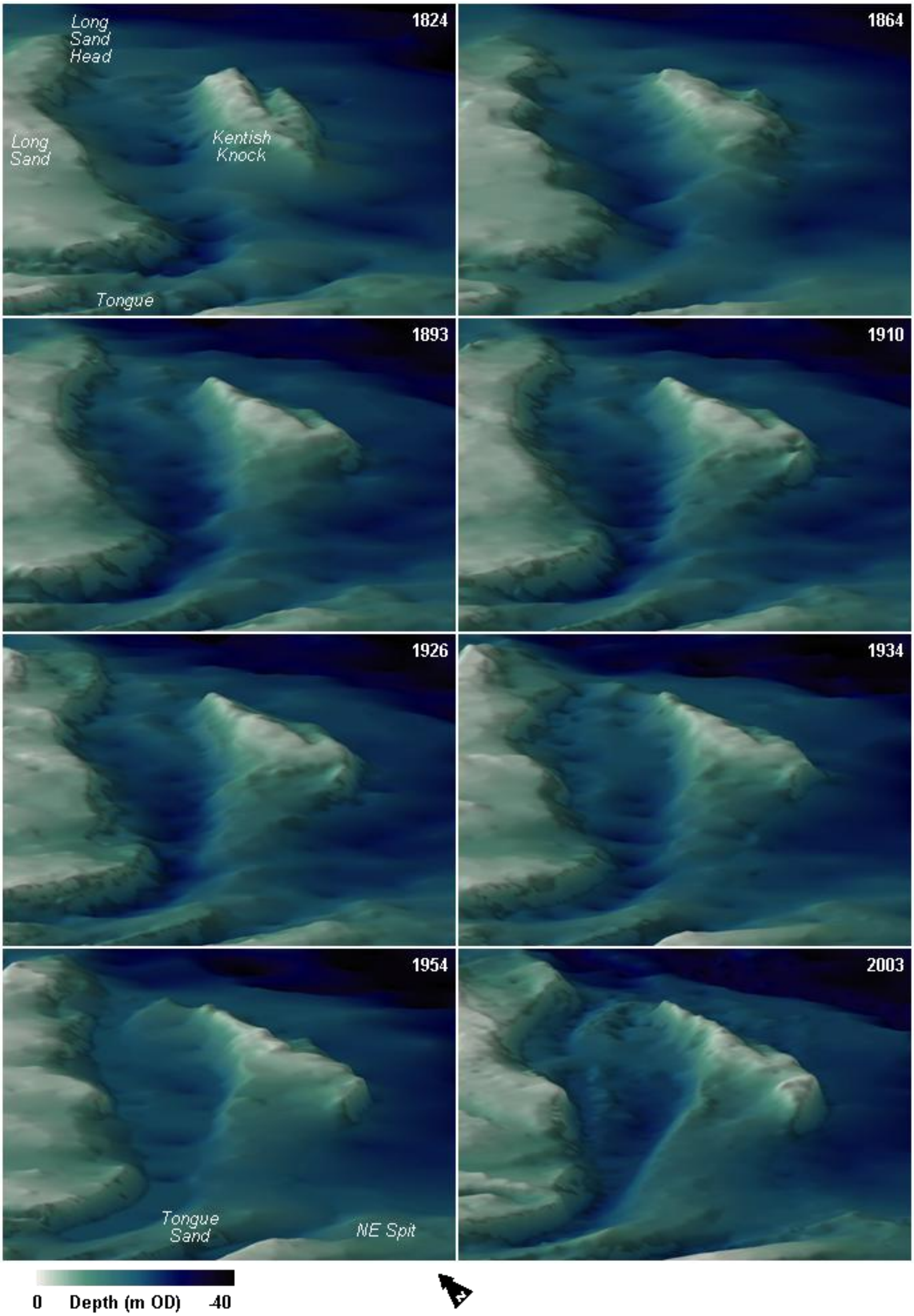
Appendix 2b: Suffolk coast. [3D view uses a vertical exaggeration of 50x.]



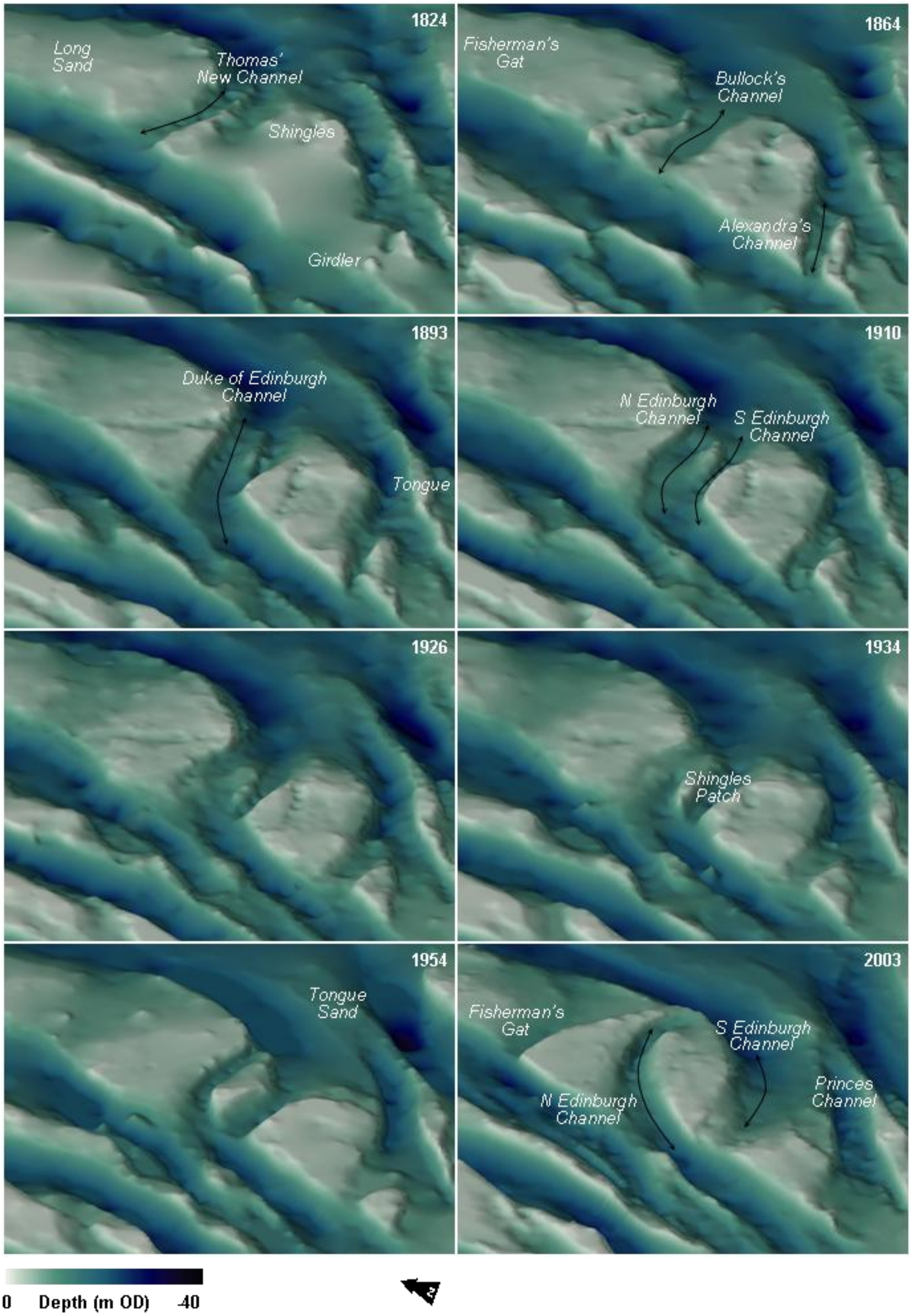
Appendix 2c: Long Sand Head. [3D view uses a vertical exaggeration of 50x.]



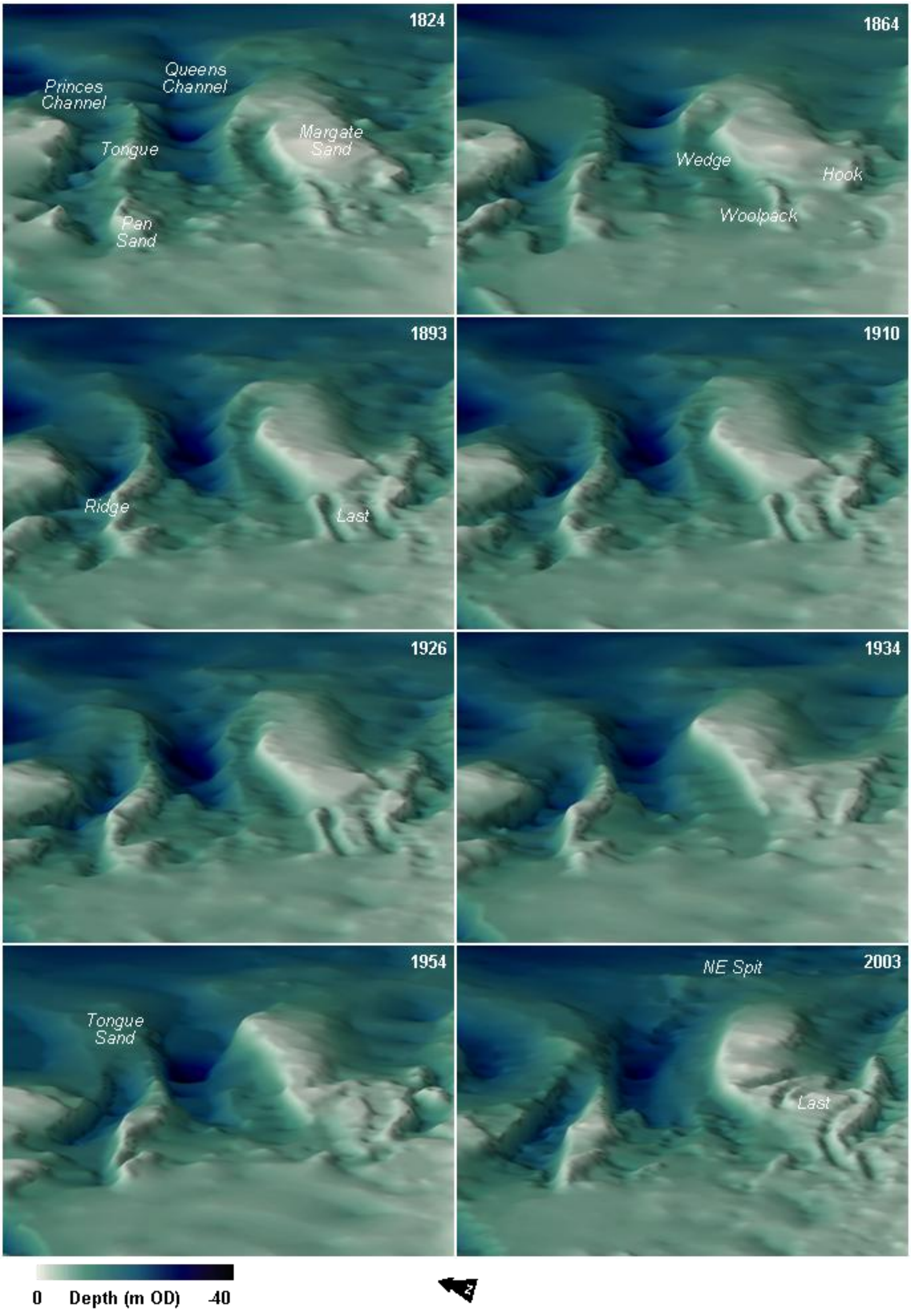
Appendix 2d: Kentish Knock. [3D view uses a vertical exaggeration of 50x.]



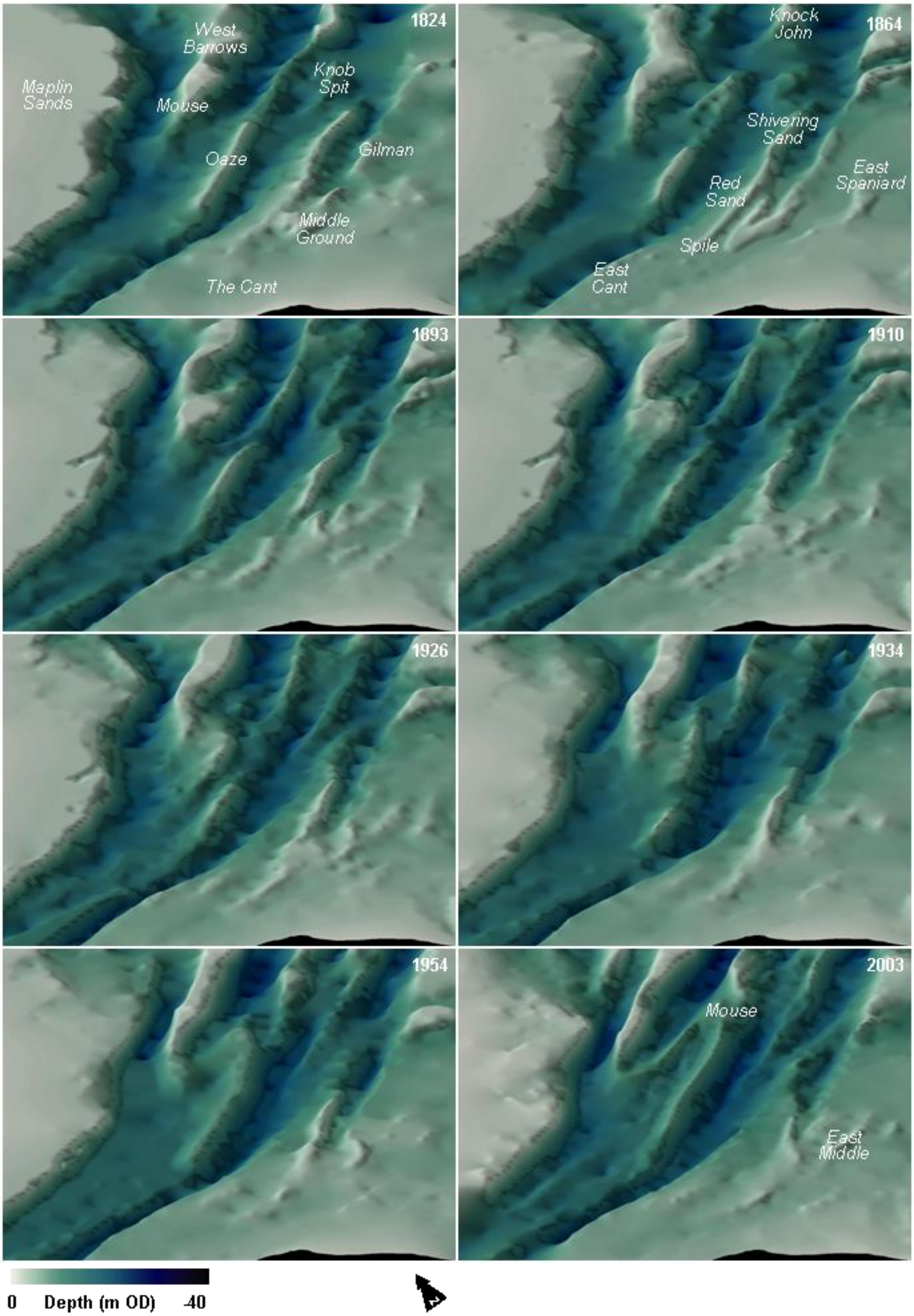
Appendix 2e: Edinburgh Channels. [3D view uses a vertical exaggeration of 50x.]



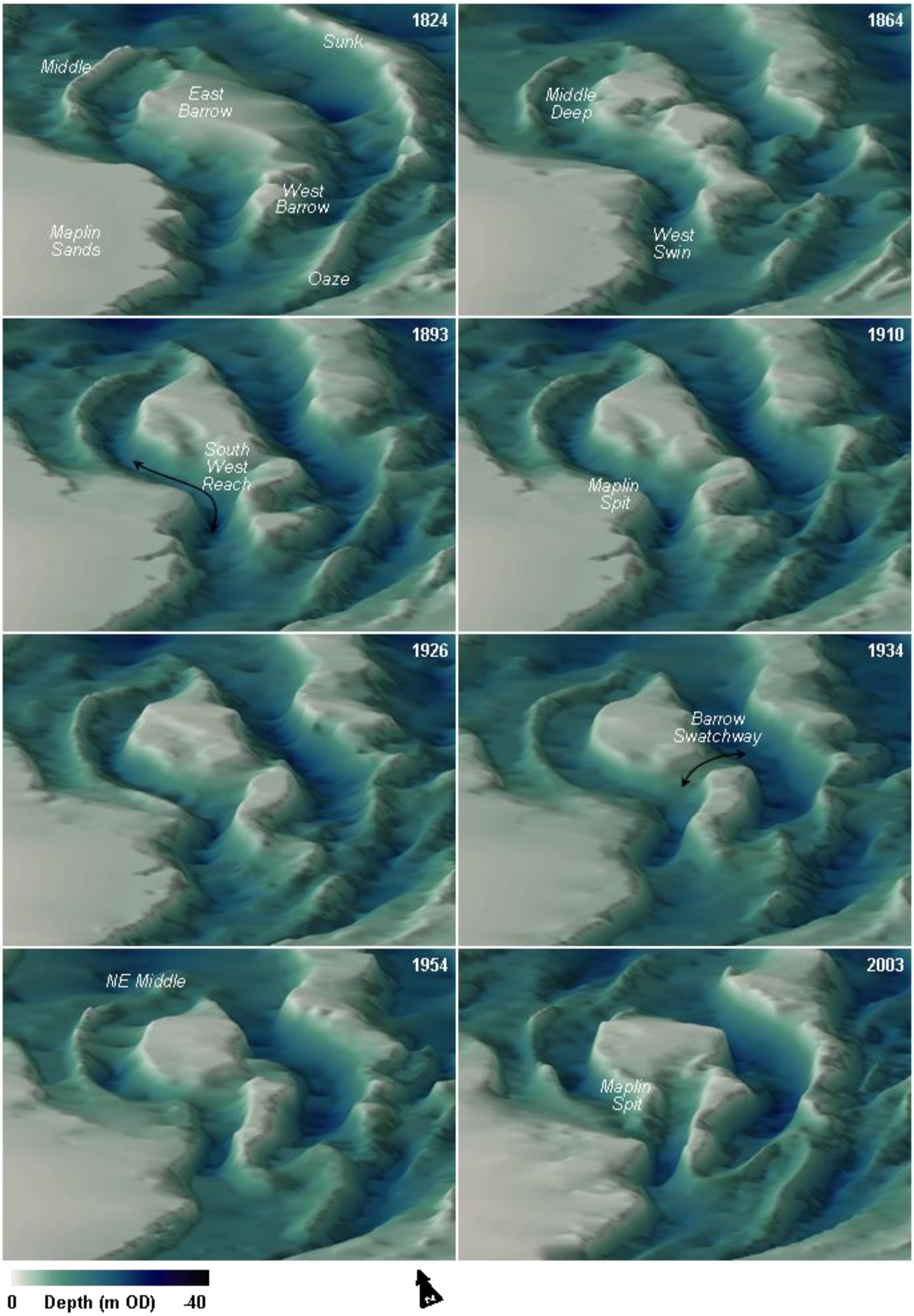
Appendix 2f: Margate Sand. [3D view uses a vertical exaggeration of 50x.]



Appendix 2g: Cant Edge. [3D view uses a vertical exaggeration of 50x.]



Appendix 2h: The Barrows. [3D view uses a vertical exaggeration of 50x.]



The Crown Estate
16 New Burlington Place
London W1S 2HX
Tel: 020 7851 5080
www.thecrownestate.co.uk
ISBN: 978-1-906410-09-4