Late Holocene Relative Sea-Level Change and the Implications for the Groundwater Resource, Humber Estuary, UK

Two Volumes

Volume Two:

Figures & Tables

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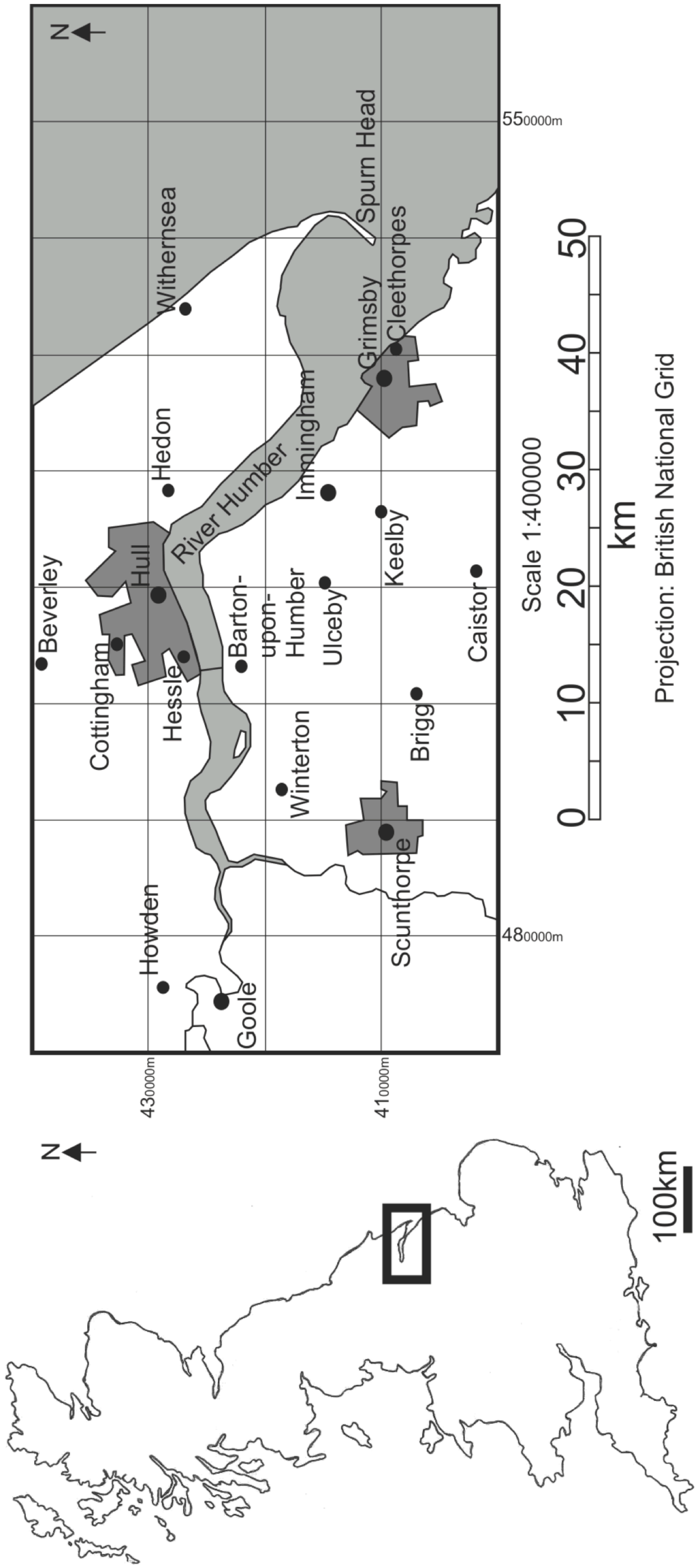

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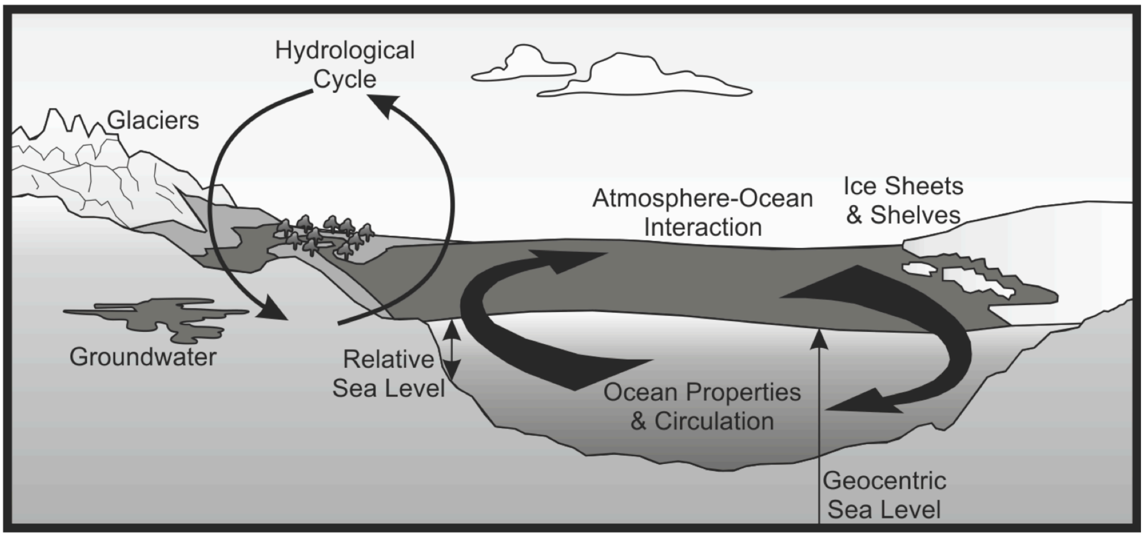

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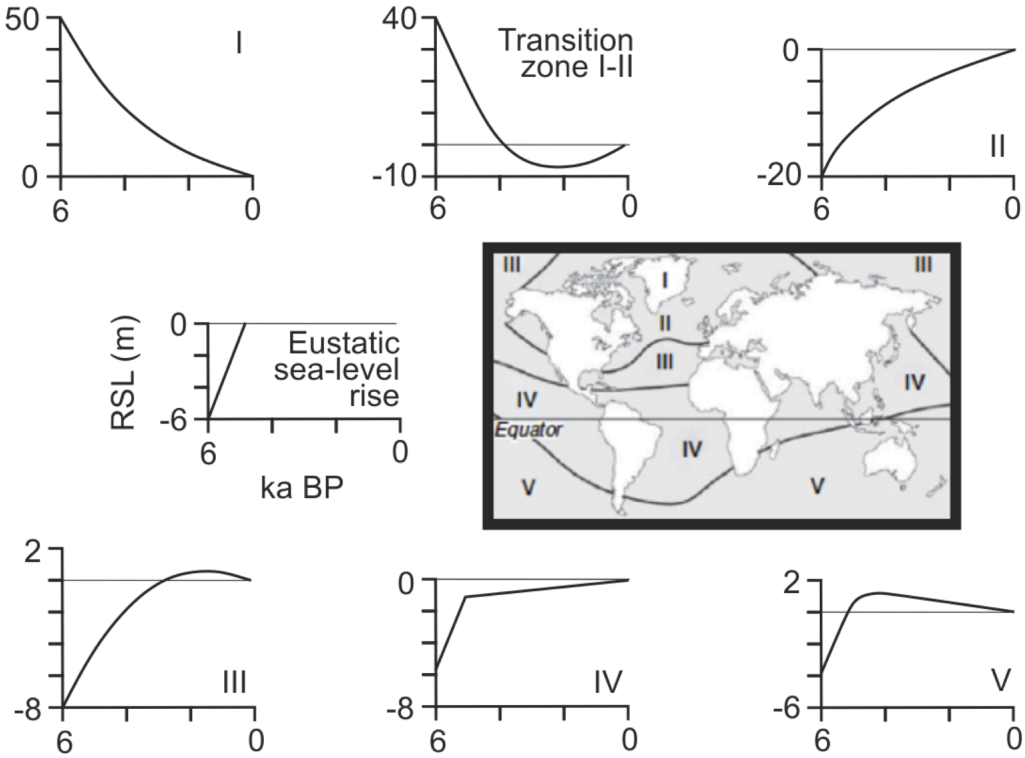

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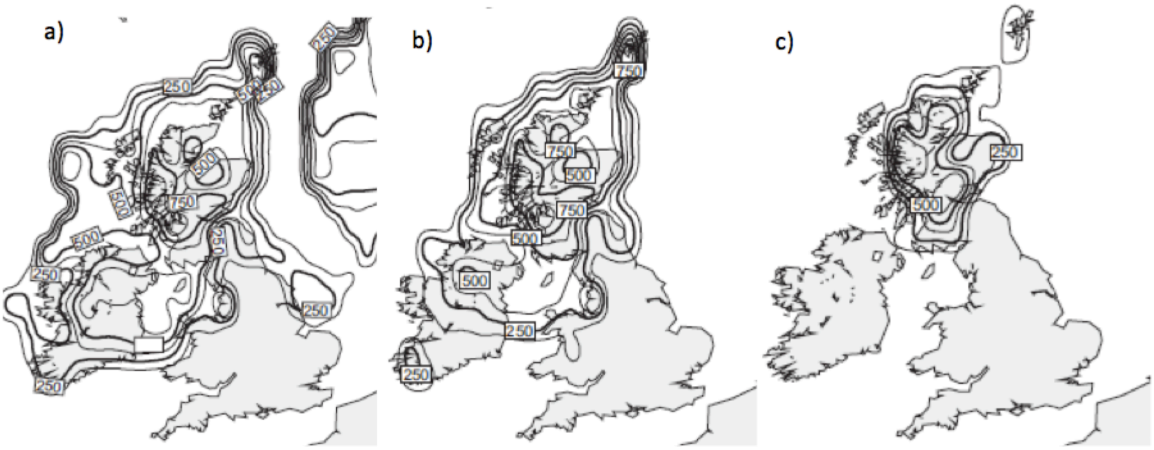

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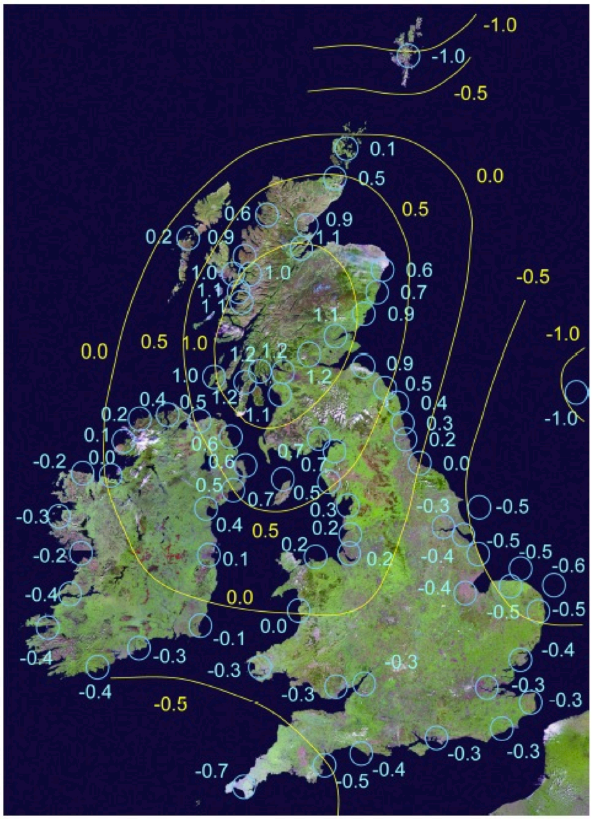

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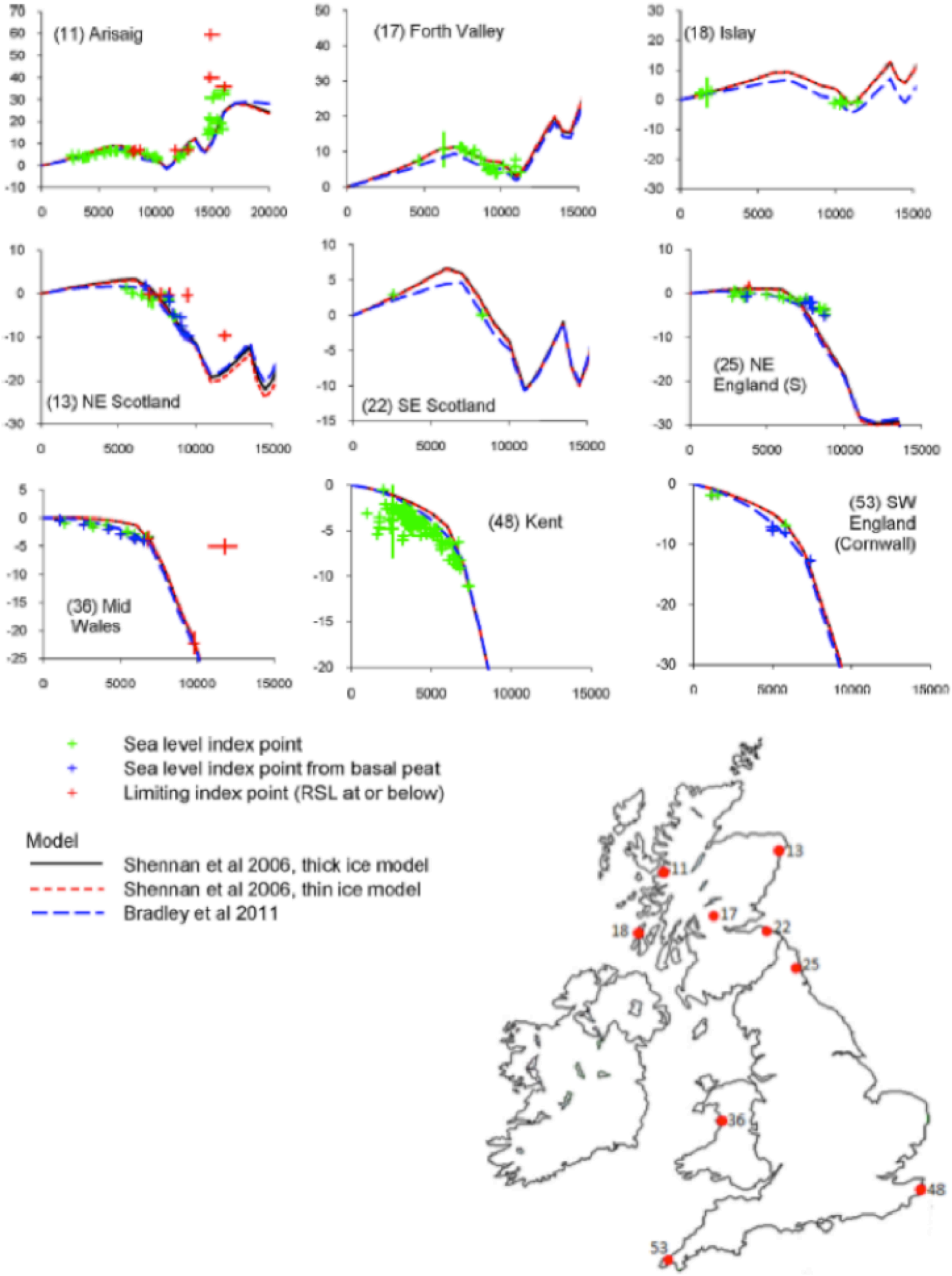

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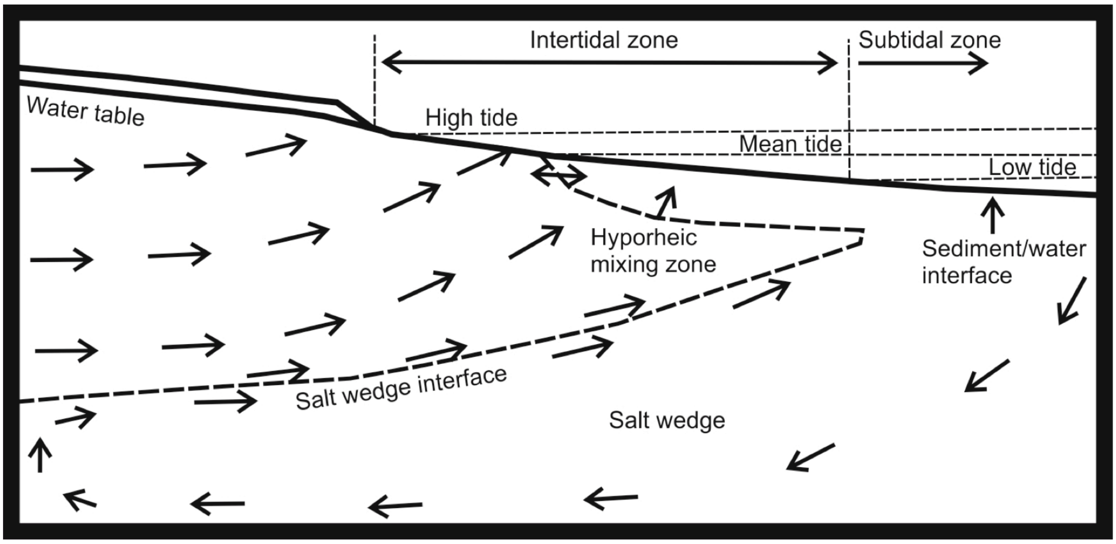

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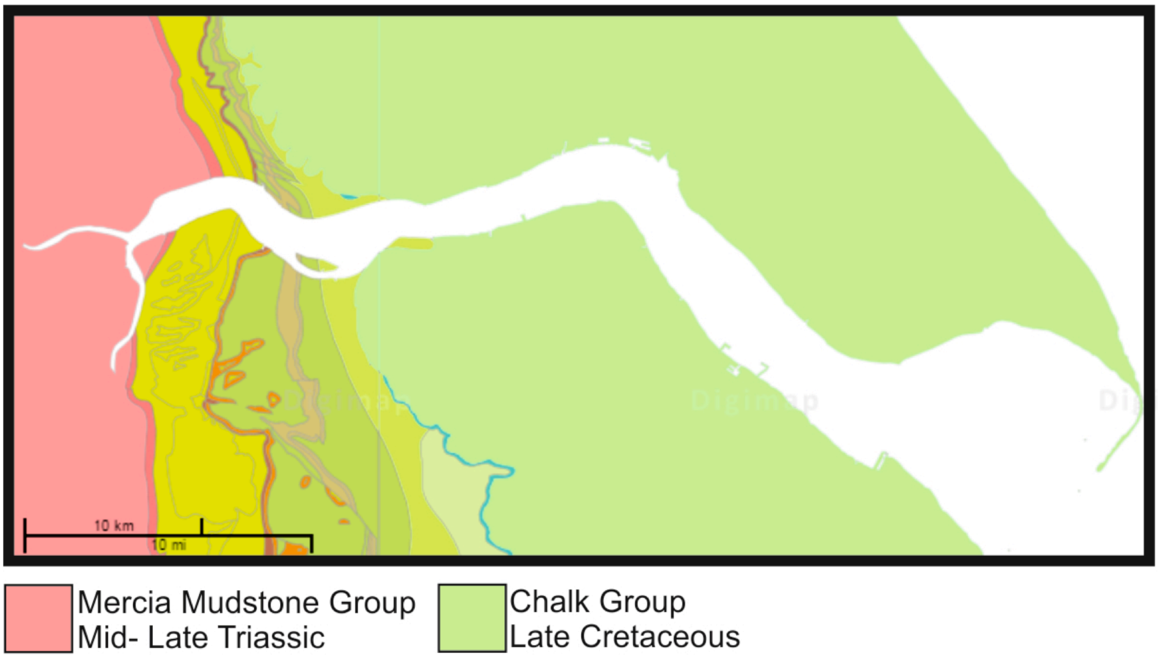

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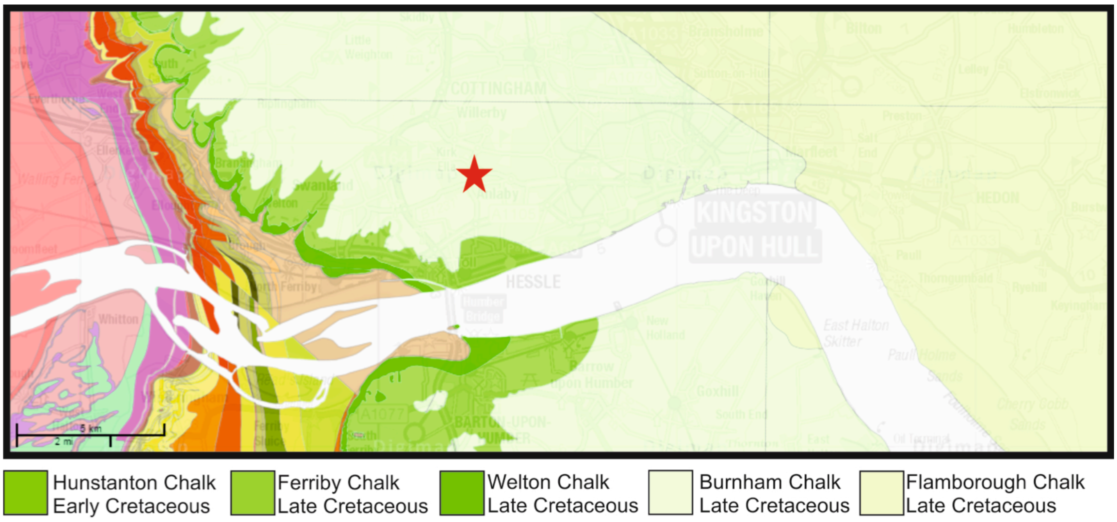

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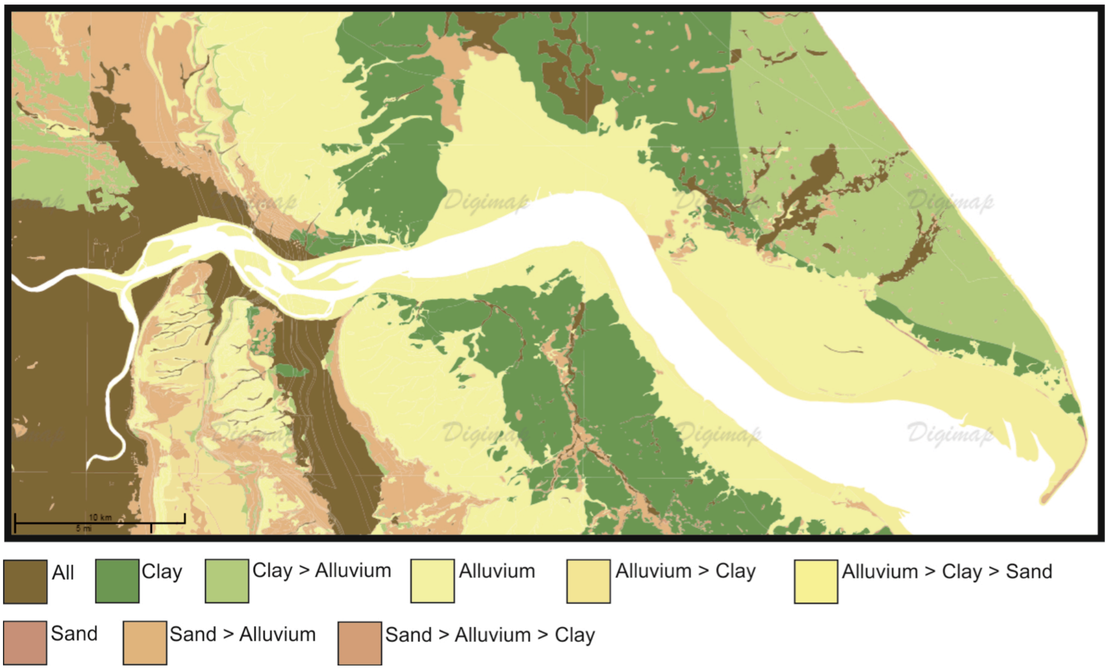

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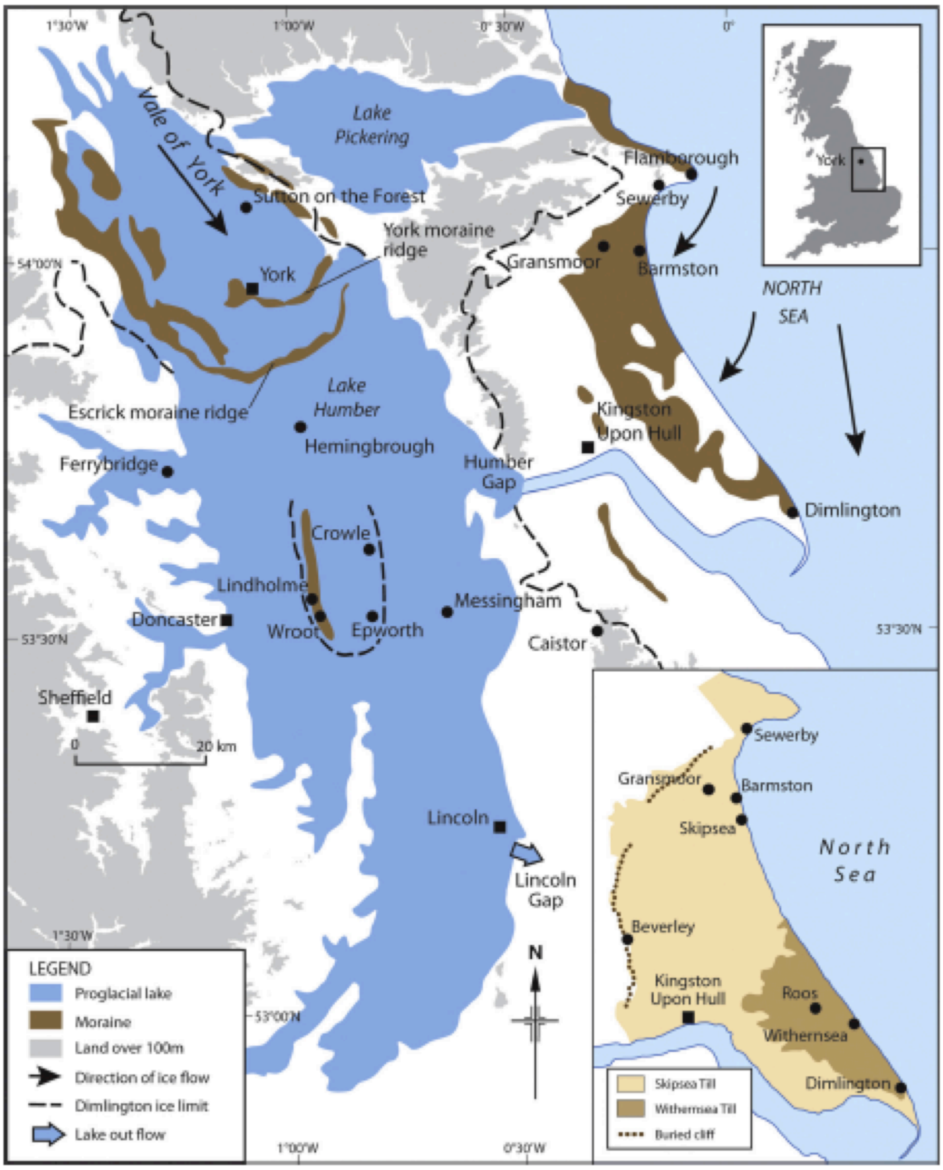

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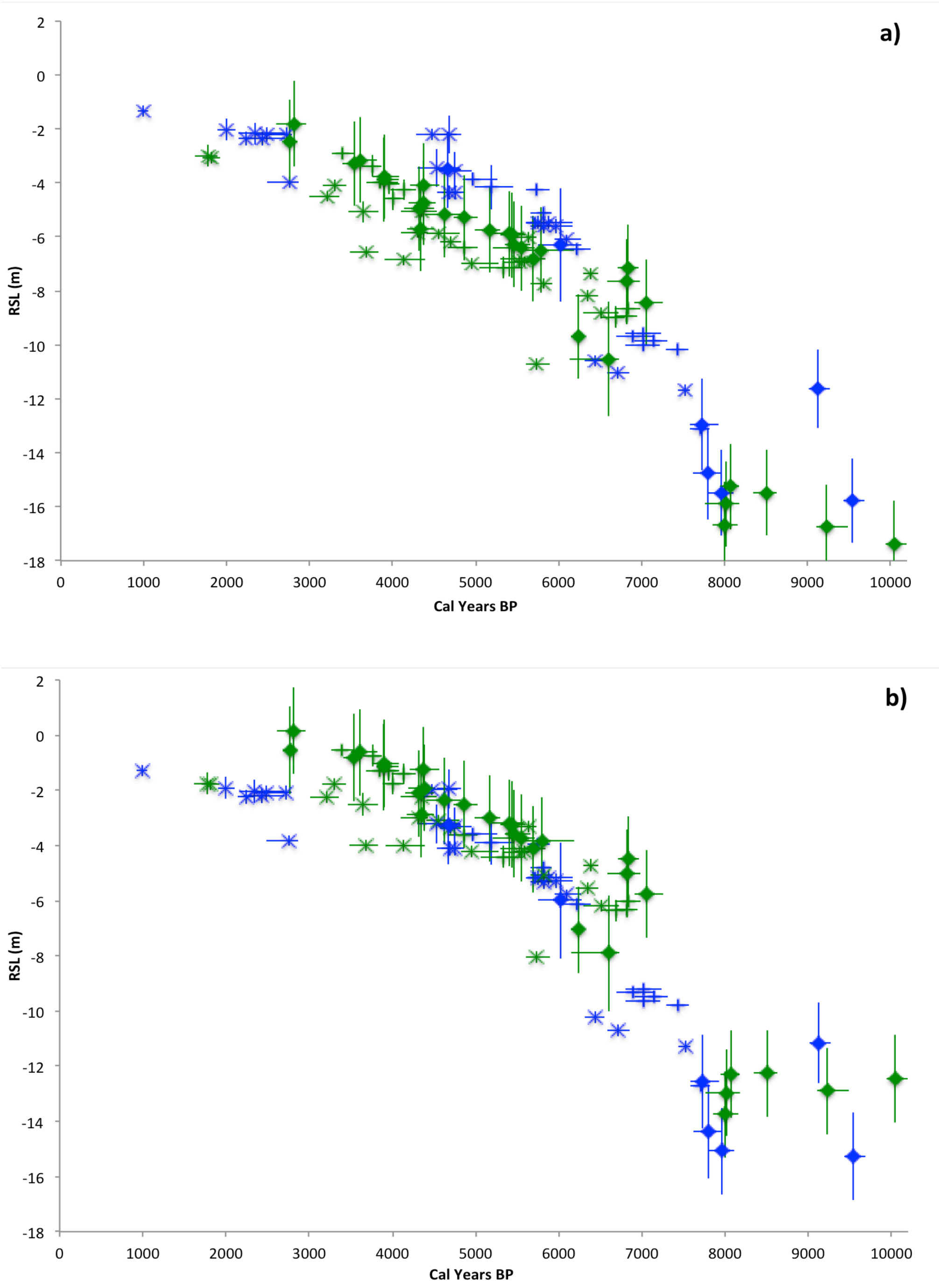

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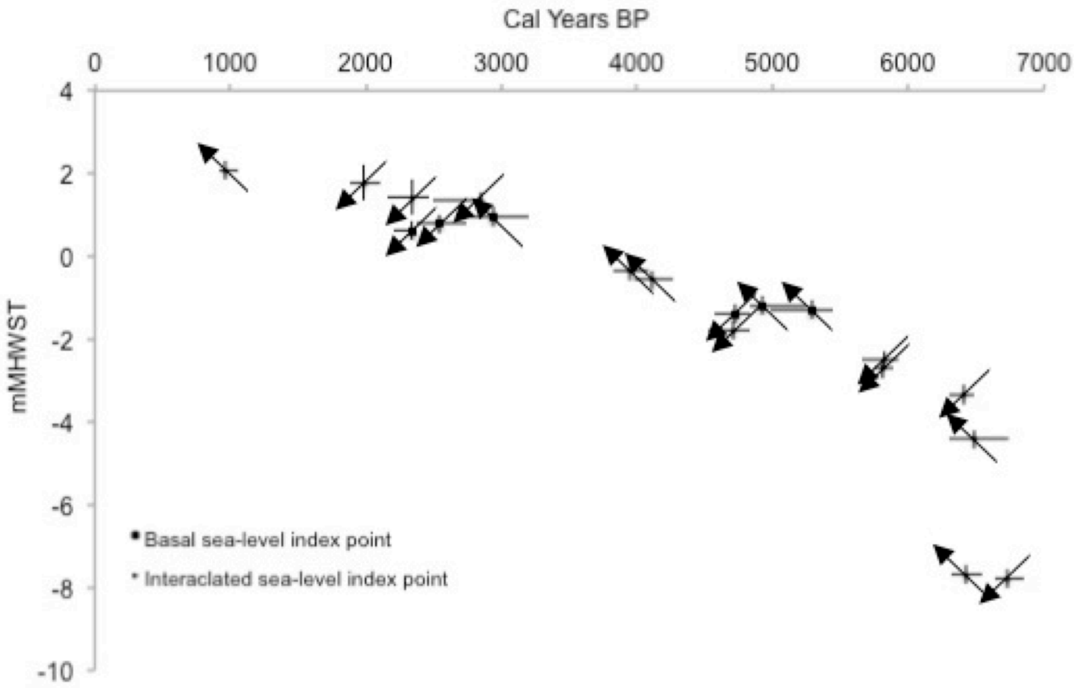

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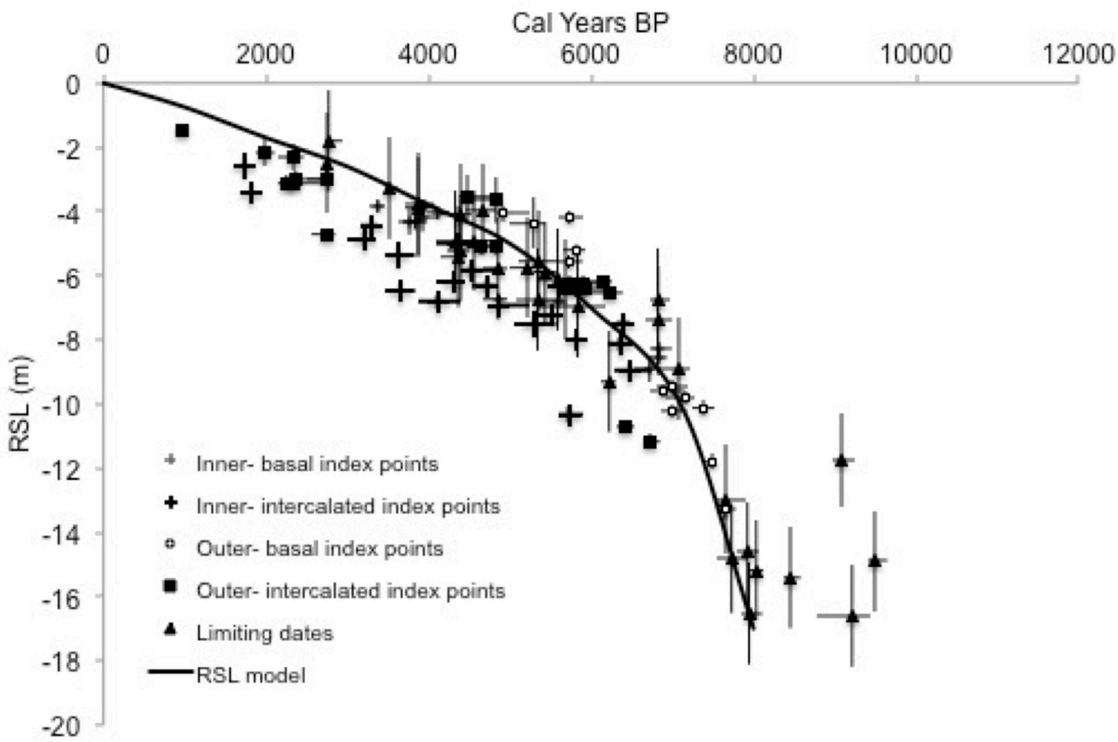

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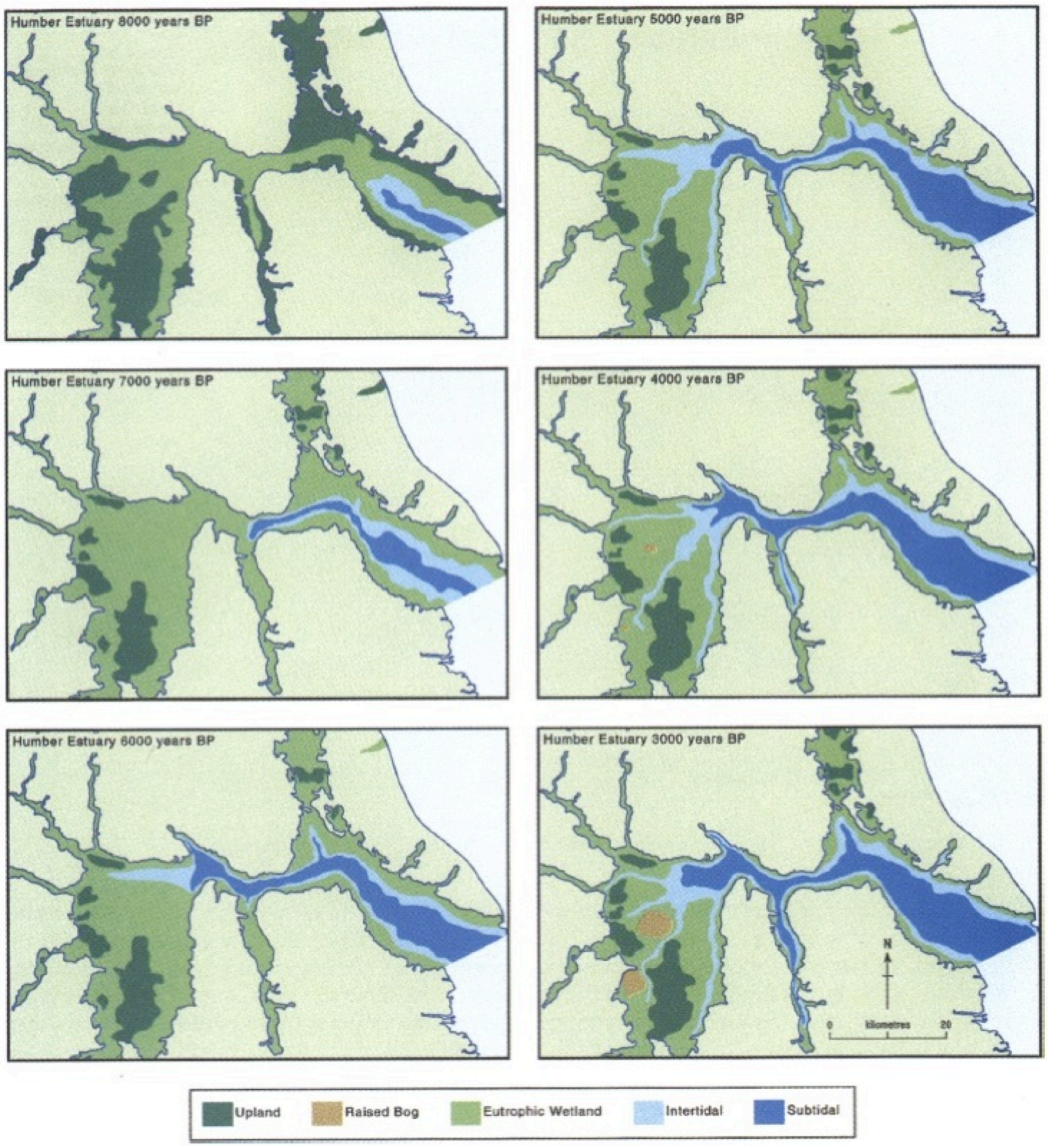

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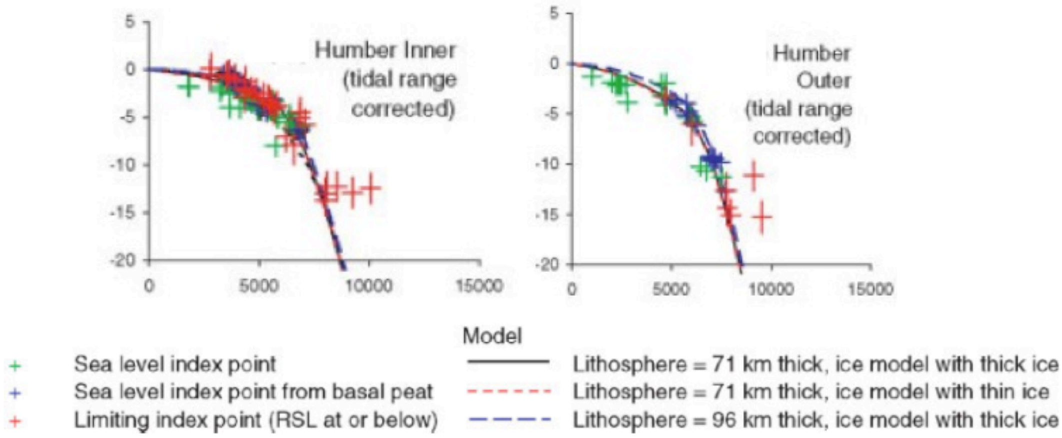

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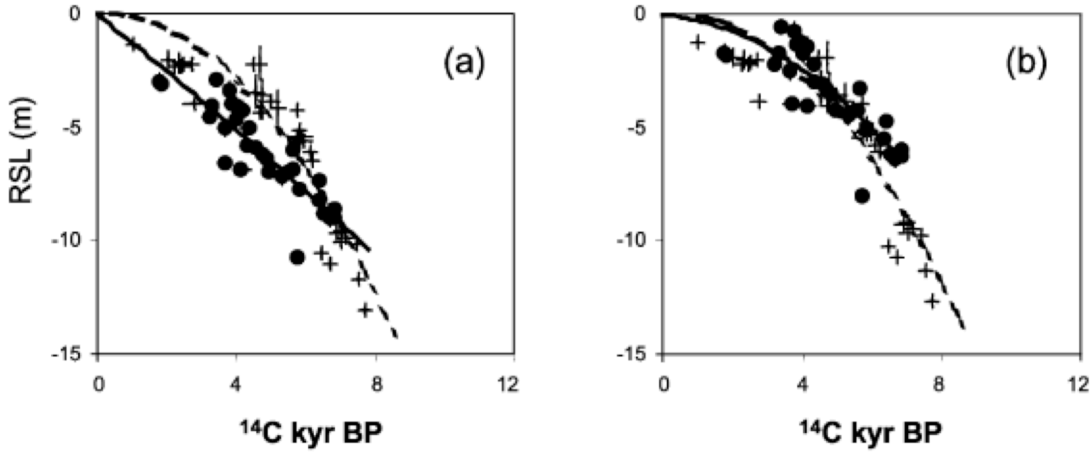

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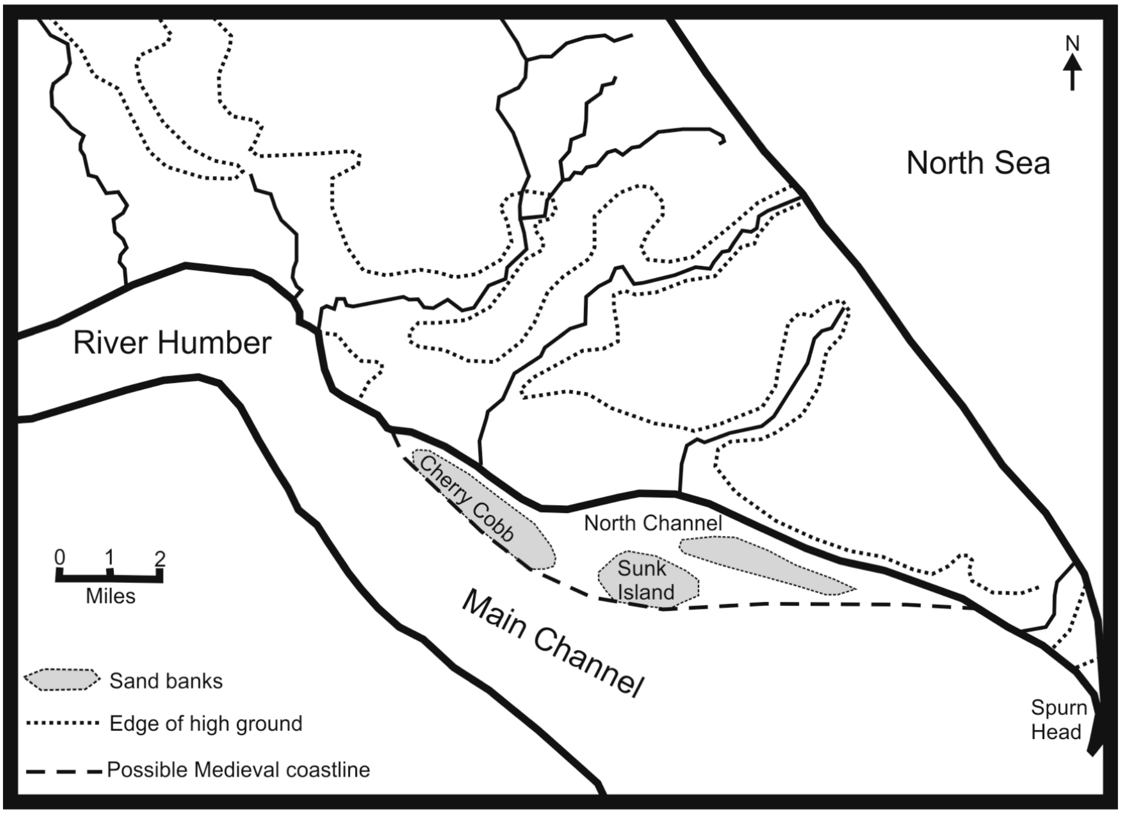

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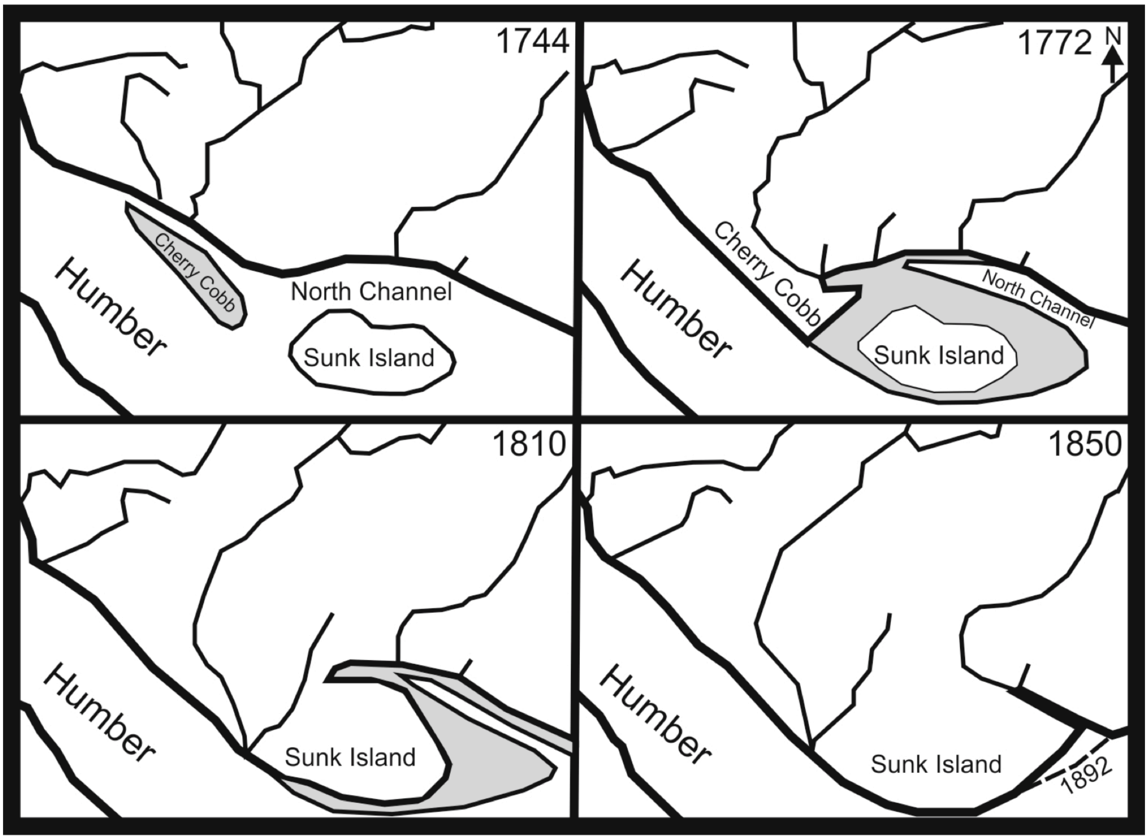

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5. Methodology

Table 5.1 Wentworth Scale of sediment size classification (1922), converted to millimetres.

Millimetres (mm)	Grade	Class
1-2	Very Coarse	Sand
0.5- 1	Coarse	
0.25- 0.5	Medium	
0.125- 0.25	Fine	
0.0625- 0.125	Very fine	
0.031- 0.0625	Coarse	Silt
0.0156- 0.031	Medium	
0.0078- 0.0156	Fine	
0.0039-0.0078	Very fine	
0- 0.00006	Clay	Clay

6. Contemporary Environment and Sea-Level Transfer Functions

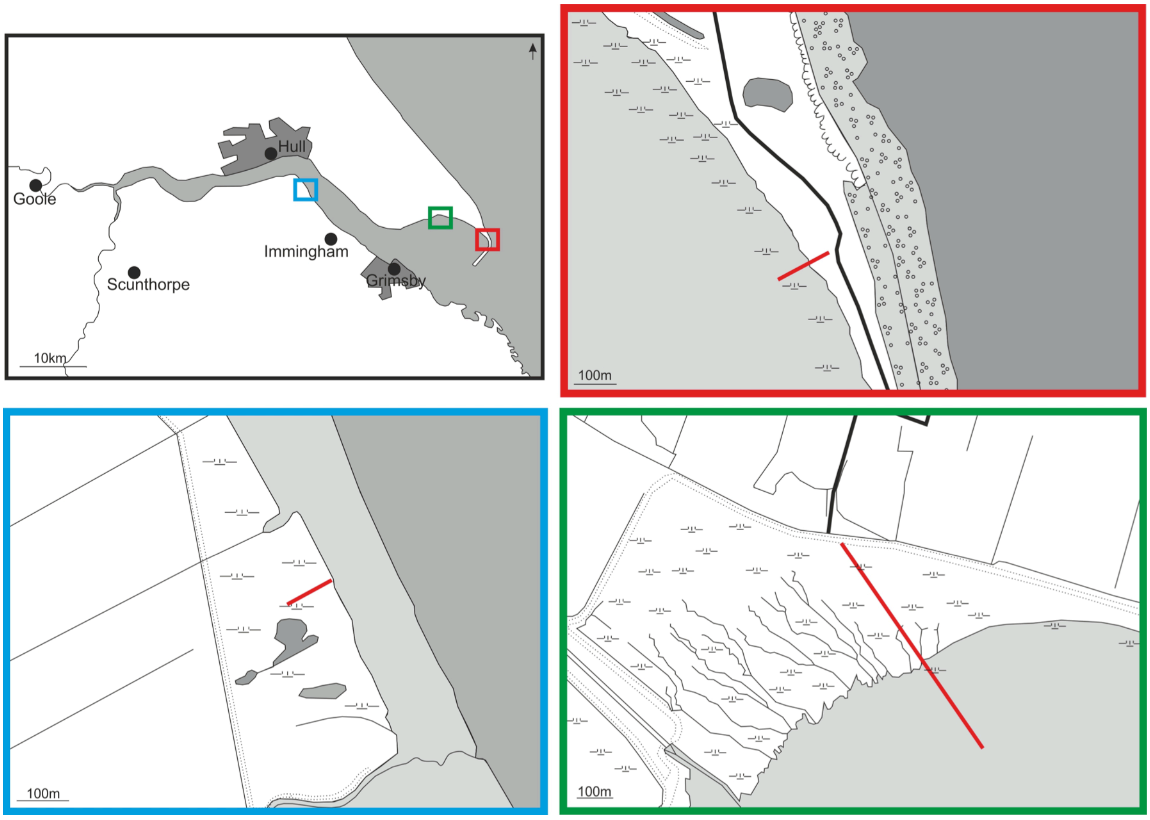


Figure 6.1 Location of the contemporary marsh study sites and modern surface sample transects. Blue= East Halton; green= Welwick; red= Spurn.

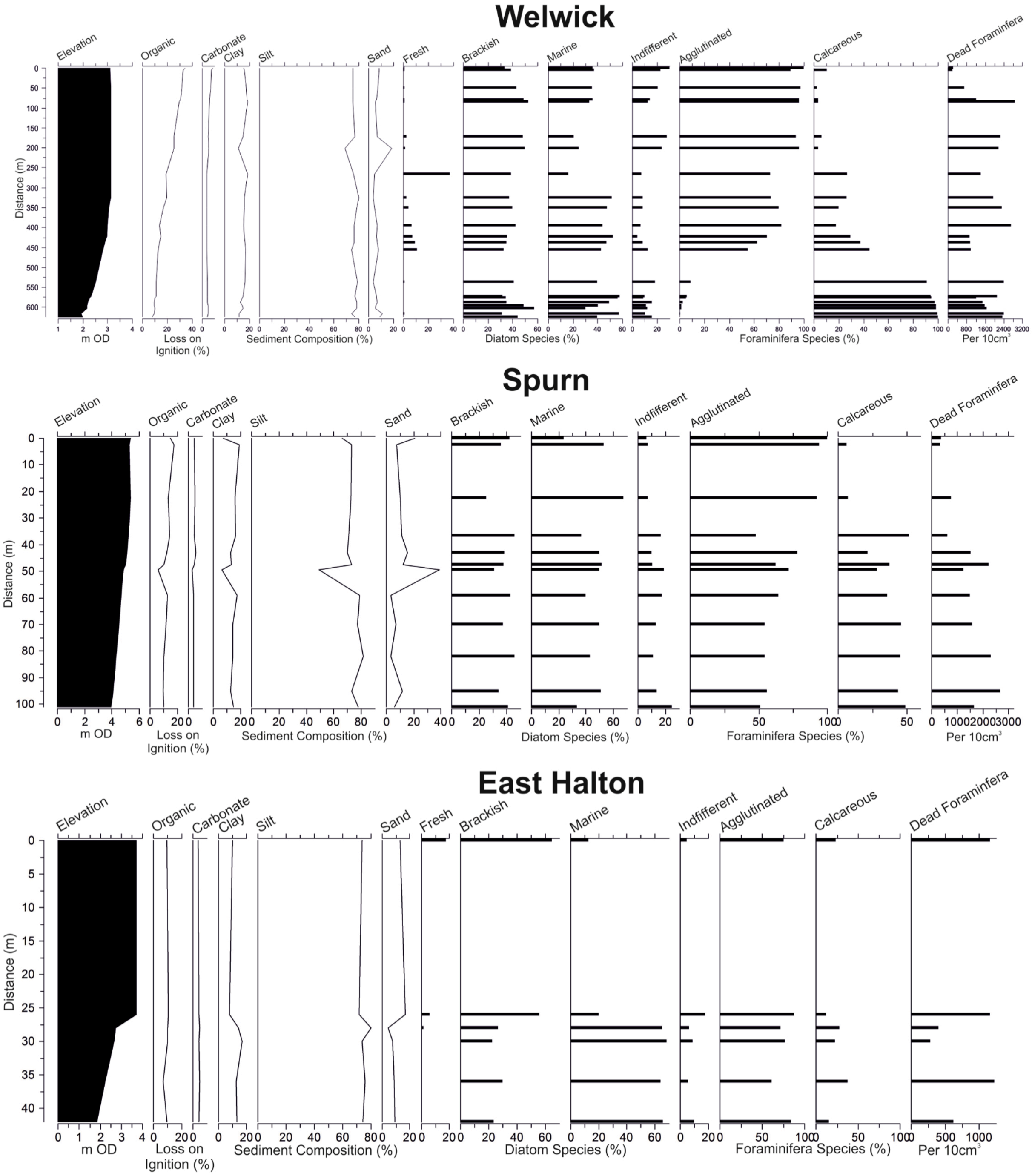


Figure 6.2 Summary diagrams of the laboratory analyses of contemporary surface samples from Welwick, Spurn and East Halton, including summary diatom and foraminifera assemblages, loss-on-ignition, particle size analysis and elevation.

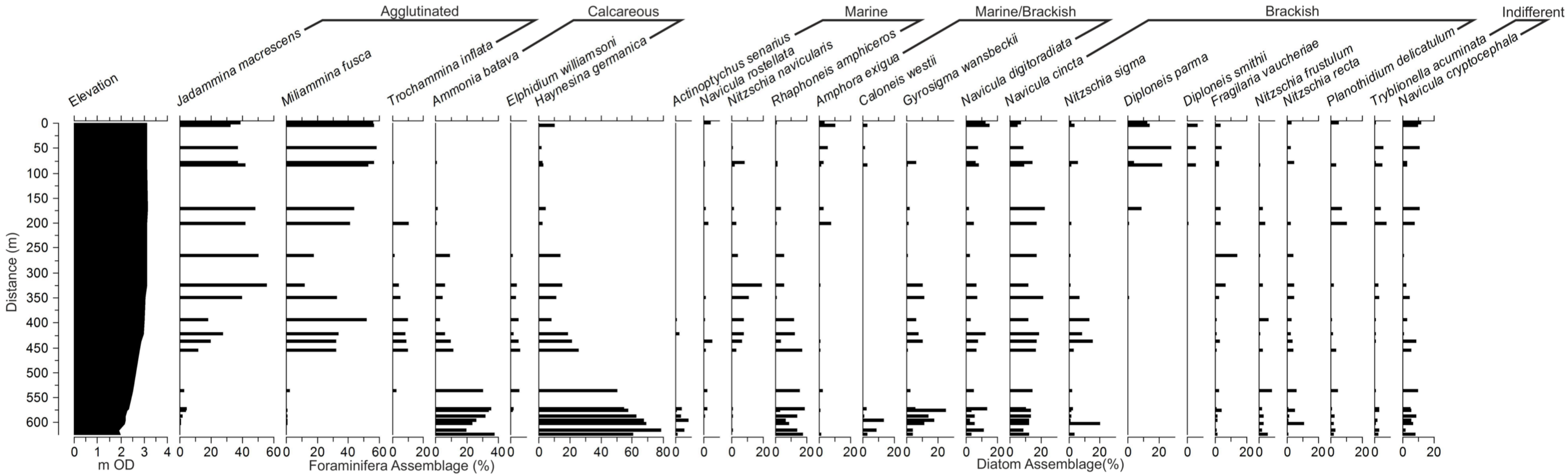


Figure 6.3 Summary percentage foraminifera and diatom assemblages of Welwick contemporary surface samples. Species >5% in two or more samples shown.

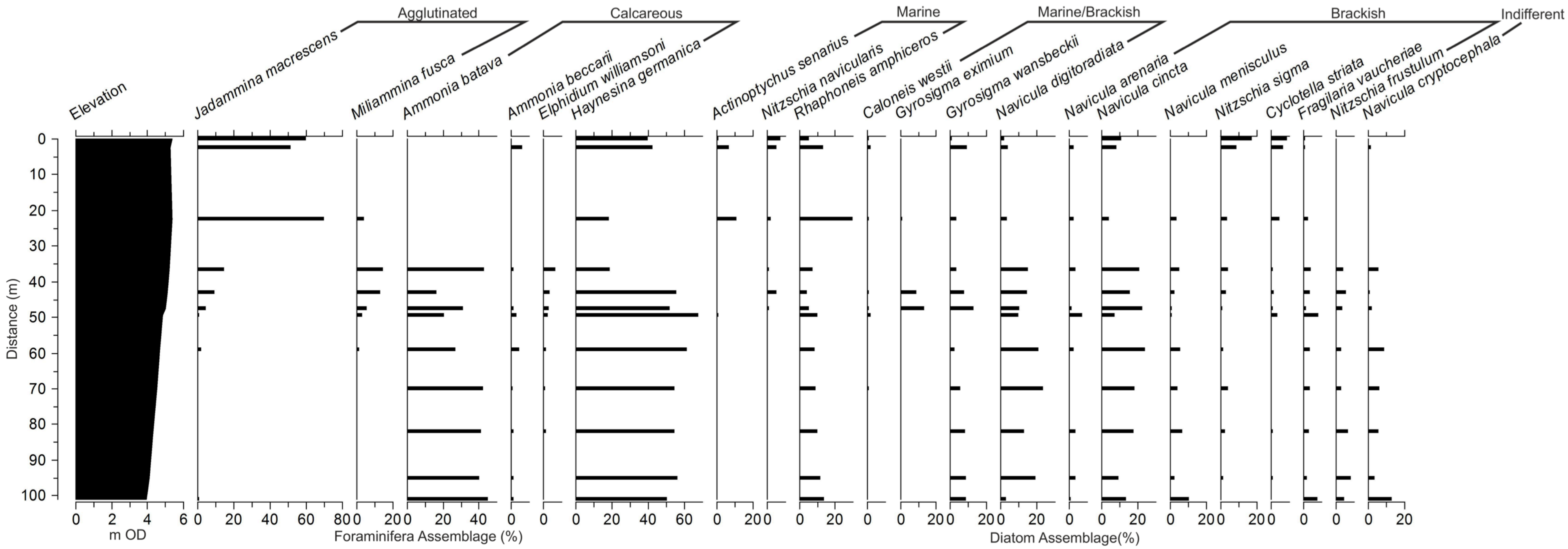


Figure 6.4 Summary percentage foraminifera and diatom assemblages of Spurn contemporary surface samples. Species >5% in two or more samples shown.

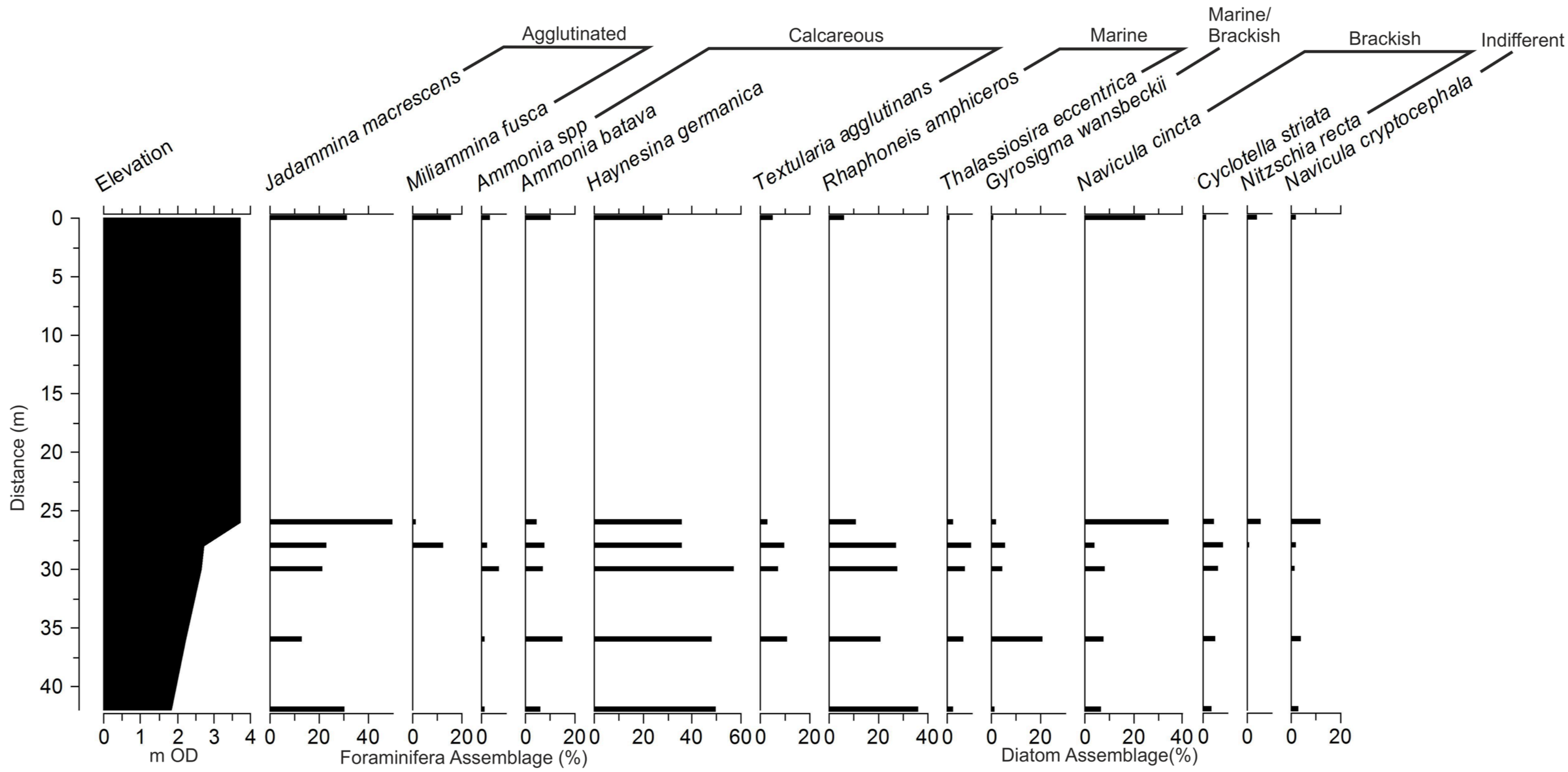


Figure 6.5 Summary percentage foraminifera and diatom assemblages of East Halton contemporary surface samples. Species >5% in two or more samples shown.

Table 6.1 Summary details of the 15 training sets formed, including the proxy type, size and source.

Name	Scale	Proxy	Sites	Samples	Source
D-1	Humber	Diatom	3	40	This study
D-2	UK	Diatom	6	88	Zong & Horton, 1999
D-3	UK-Humber	Diatom	9	128	This study; Zong & Horton, 1999
D-4	UK estuary	Diatom	3	51	Zong & Horton, 1999
D-5	UK estuary-Humber	Diatom	6	91	This study Zong & Horton, 1999
F-1	Humber	Foram	3	34	This study
F-2	UK	Foram	12	162	Horton & Edwards, 2006
F-3	UK-Humber	Foram	15	196	This study Horton & Edwards, 2006
F-4	UK estuary	Foram	4	64	Horton & Edwards, 2006
F-5	UK estuary-Humber	Foram	7	98	This study Horton & Edwards, 2006
M-1	Humber	Multi	3	40	This study
M-2	UK	Multi	18	250	Horton & Edwards, 2006 Zong & Horton, 1999
M-3	UK-Humber	Multi	21	290	This study Horton & Edwards, 2006 Zong & Horton, 1999
M-4	UK estuary	Multi	7	115	Horton & Edwards, 2006; Zong & Horton, 1999
M-5	UK estuary-Humber	Multi	10	155	This study Horton & Edwards, 2006 Zong & Horton, 1999

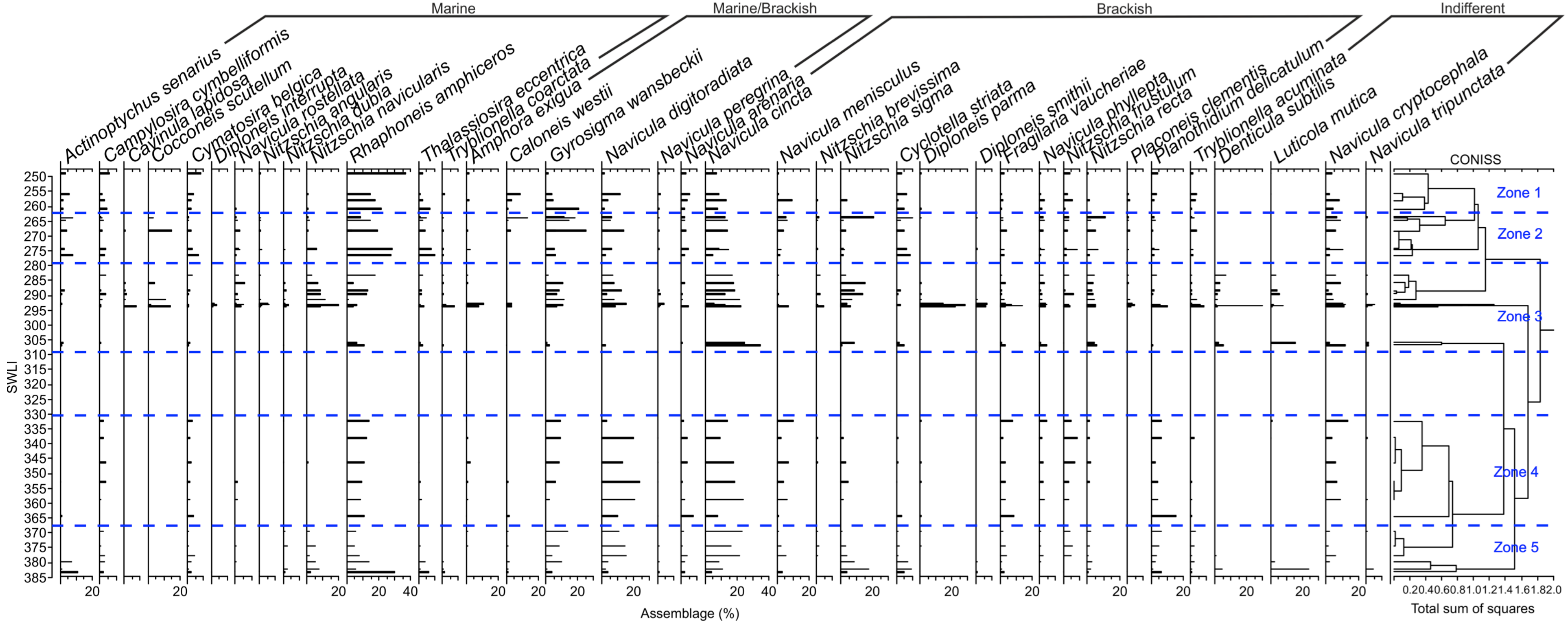


Figure 6.6 Results of cluster analysis on the diatom training set. Species with abundance >5% in at least three samples are shown.

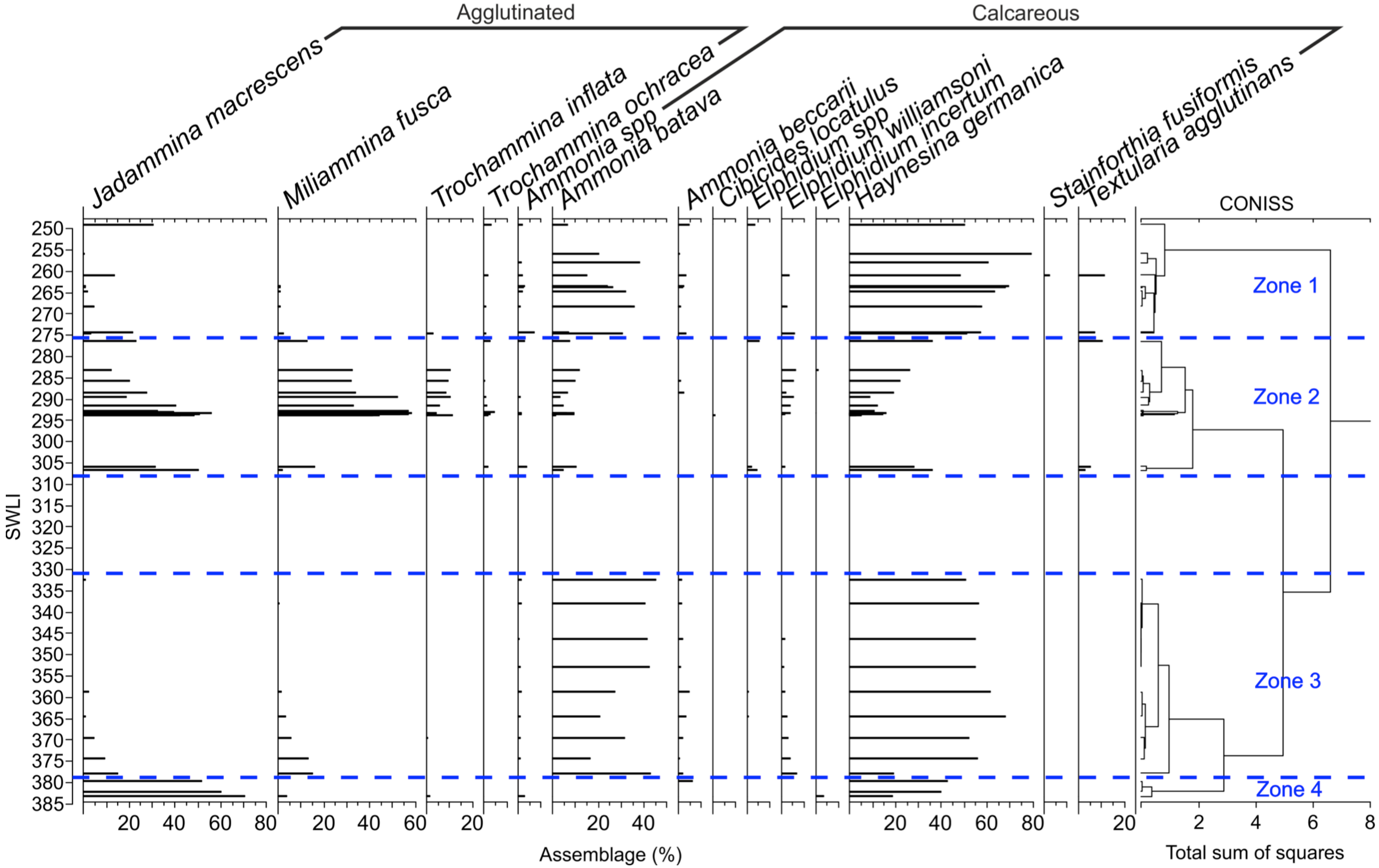


Figure 6.7 Results of cluster analysis on the foraminifera training set.

<table>
<tr><th>SWLI</th><th>Diatom Zones</th><th>Foraminifera Zones</th></tr>
<tr><td>310</td><td rowspan="2">Upper Saltmarsh</td><td rowspan="2">Upper Saltmarsh</td></tr>
<tr><td>305</td></tr>
<tr><td>MHWST 300</td><td colspan="2">No Samples</td></tr>
<tr><td>295</td><td rowspan="3">Upper Saltmarsh
D. interrupta, D. smithii, D. subtilis, N. cincta, N. digitoradiata, N. navicularis, N. sigma</td><td rowspan="4">Upper Saltmarsh
J. macrescens, M. fusca, T. inflata</td></tr>
<tr><td>290</td></tr>
<tr><td>285</td></tr>
<tr><td>280</td><td rowspan="4">Lower Saltmarsh
A. senarius, C. westii, G. wansbeckii, N. cincta, R. amphiceros,T. eccentrica</td></tr>
<tr><td>275</td><td rowspan="6">Lower Saltmarsh
A. batava, H. germanica, T. agglutinans</td></tr>
<tr><td>270</td></tr>
<tr><td>265</td></tr>
<tr><td>260</td><td rowspan="3">Tidal Flat
C. belgica, G. wansbeckii, R. amphiceros</td></tr>
<tr><td>255</td></tr>
<tr><td>250</td></tr>
</table>

Figure 6.8 Distribution of the diatom and foraminifera training sets in relation to SWLI as identified by cluster analysis, with named key species.

Table 6.2 Results of DCA analysis of the three Humber training sets.

Training Set	Axis 1 Length	Axis 1 Variation Explained (%)
Diatom	2.87	30.34
Foraminifera	2.32	53.52
Combined Multi-Proxy	2.42	38.02

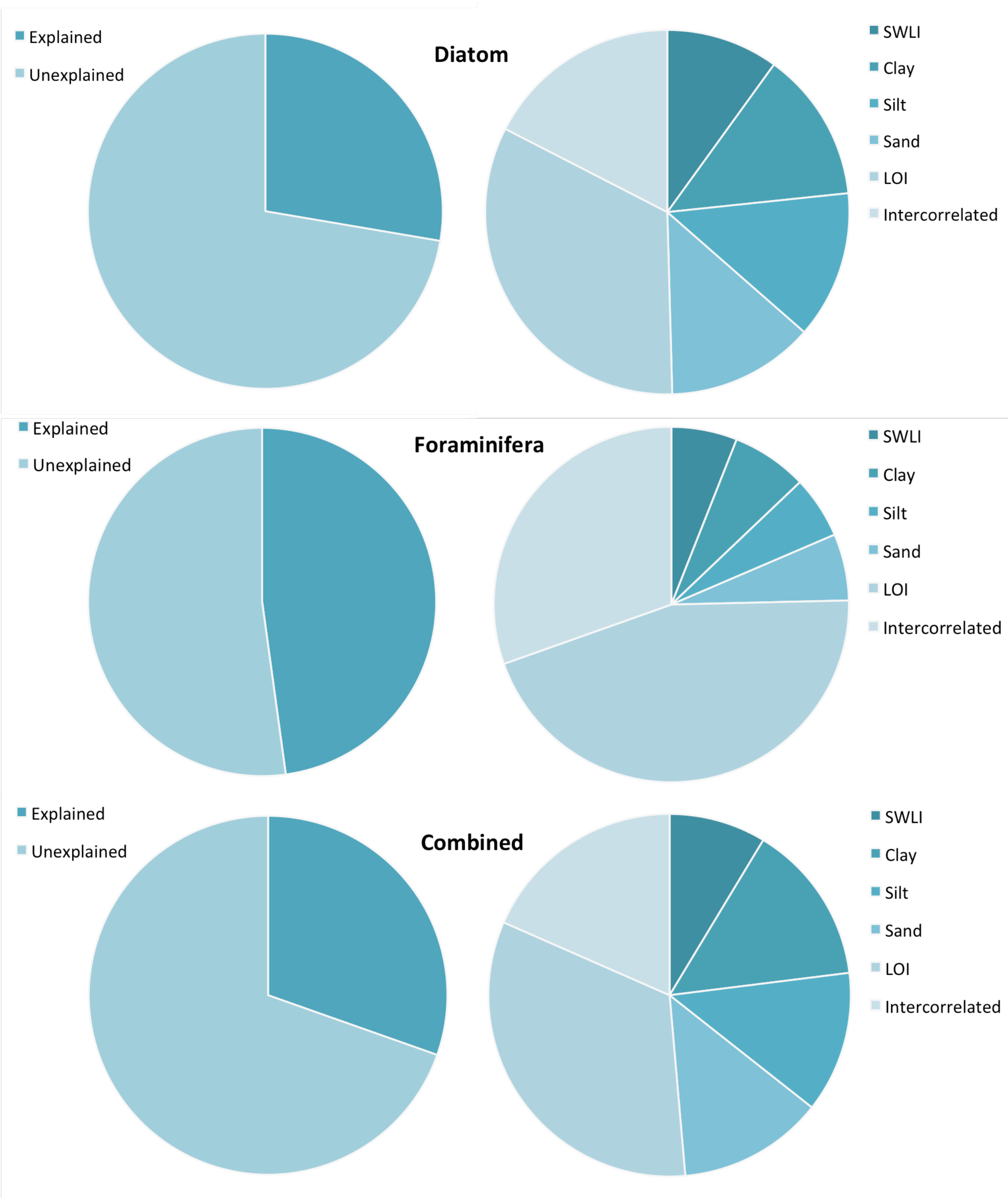


Figure 6.9 Results of CCA and partial CCA of the three Humber training sets.

Table 6.3 Summary of the performance of the 15 transfer functions developed from the training sets outlined in Table 6.1 (D= Diatom, F= Foraminifera, M= Multi-proxy).

Name	Component (% change)	RMSEP	Bootstrapped r^2
D-1	1	41.895	0.098
D-2	2 (6.15)	22.692	0.651
D-3	1	30.997	0.426
D-4	3 (7.51)	16.461	0.802
D-5	1	32.884	0.313
F-1	1	44.583	0.002
F-2	1	25.782	0.276
F-3	1	29.444	0.226
F-4	1	14.481	0.0917
F-5	1	28.325	0.026
M-1	2 (5.37)	42.790	0.142
M-2	2 (5.15)	24.196	0.484
M-3	1	28.474	0.363
M-4	3 (7.51)	15.707	0.659
M-5	1	26.973	0.297

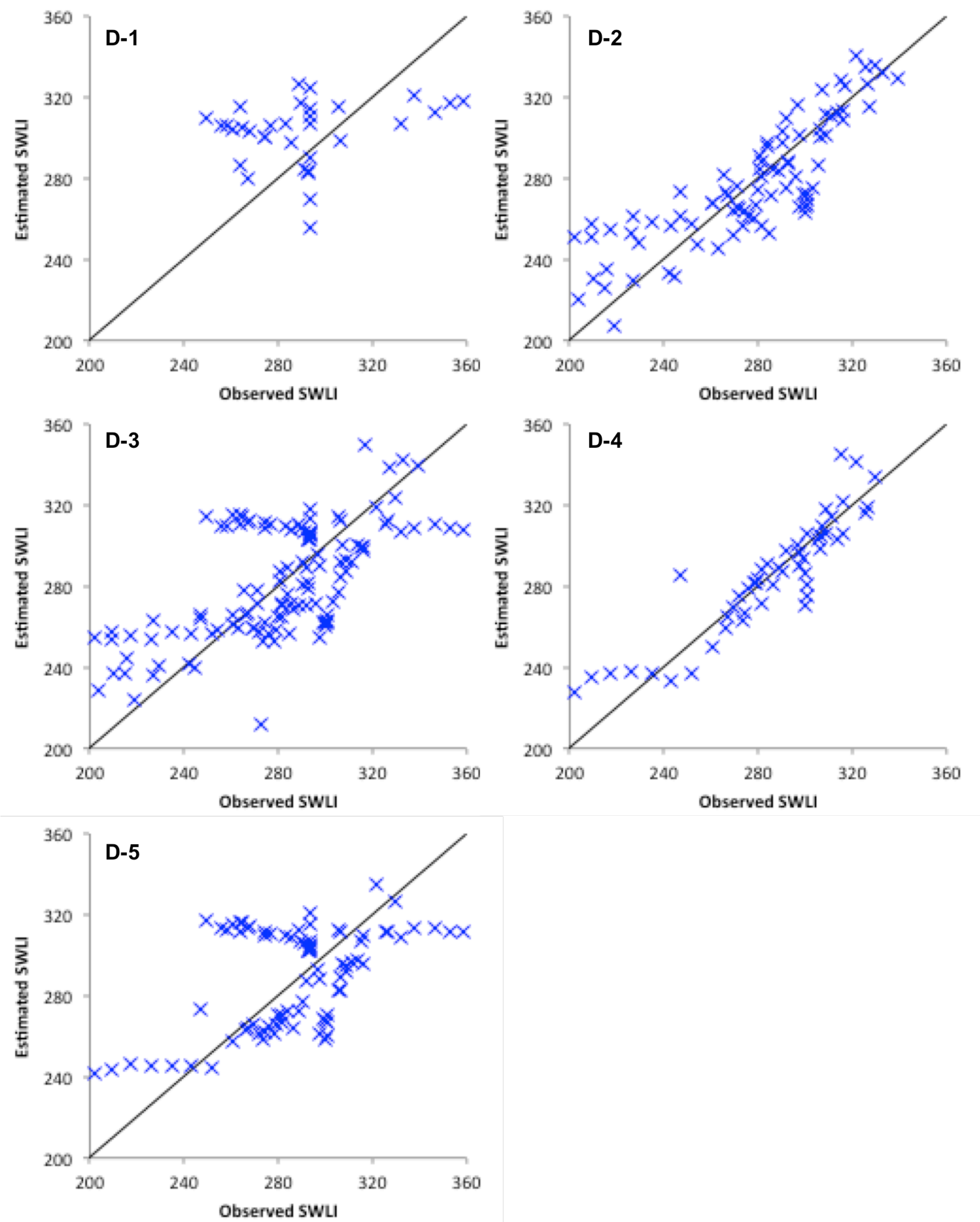


Figure 6.10 Observed SWLI and estimated SWLI predicted by the diatom transfer functions; components used are those outlined in Table 6.3.

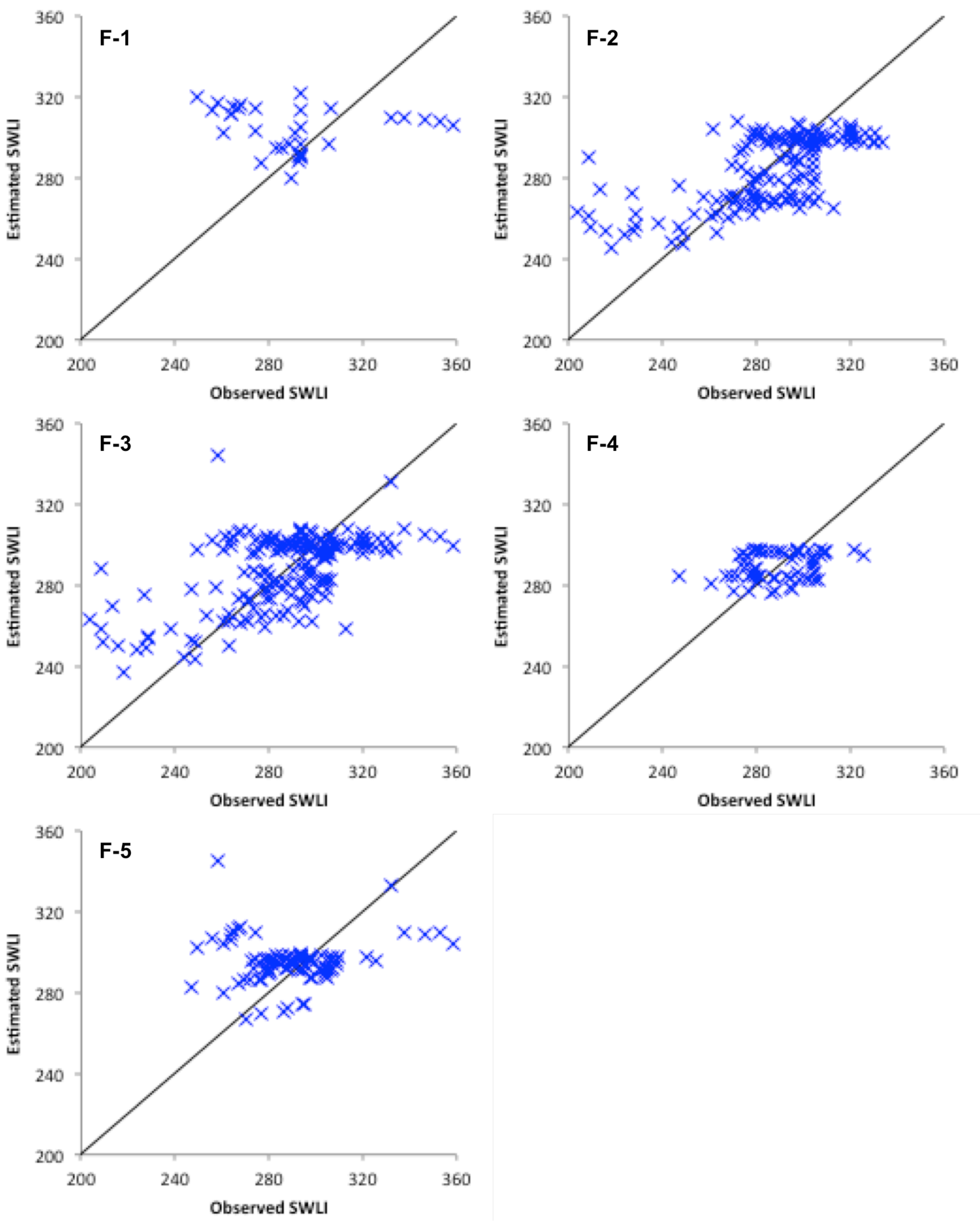


Figure 6.11 Observed SWLI and estimated SWLI predicted by the foraminifera transfer functions; components used are those outlined in Table 6.3.

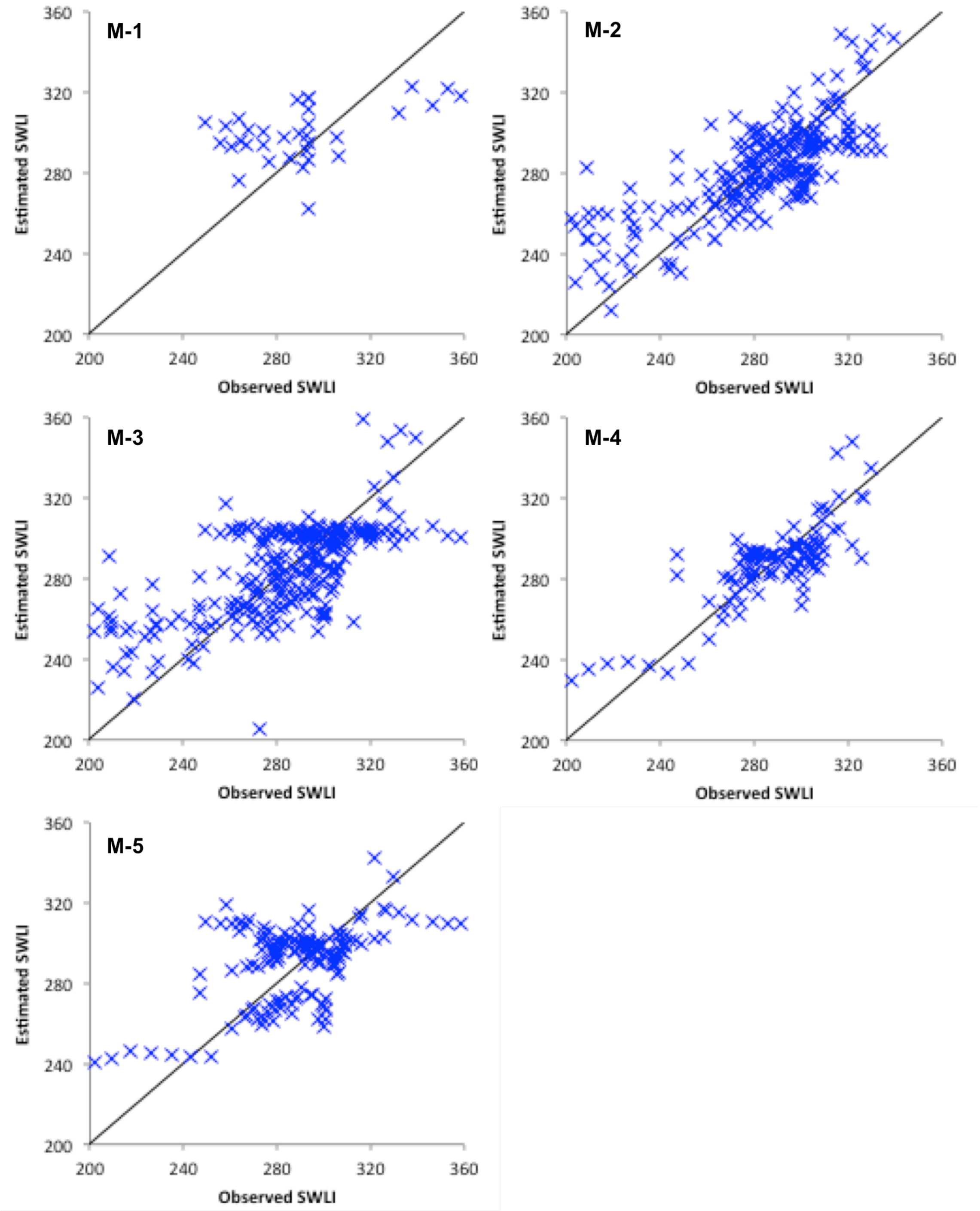


Figure 6.12 Observed SWLI and estimated SWLI predicted by the multi-proxy diatom and foraminifera transfer functions; components used are those outlined in Table 6.3.

7. Palaeoenvironment and Relative Sea-Level Reconstruction: East Halton

Figure 7.1 Location of the East Halton palaeo study site.

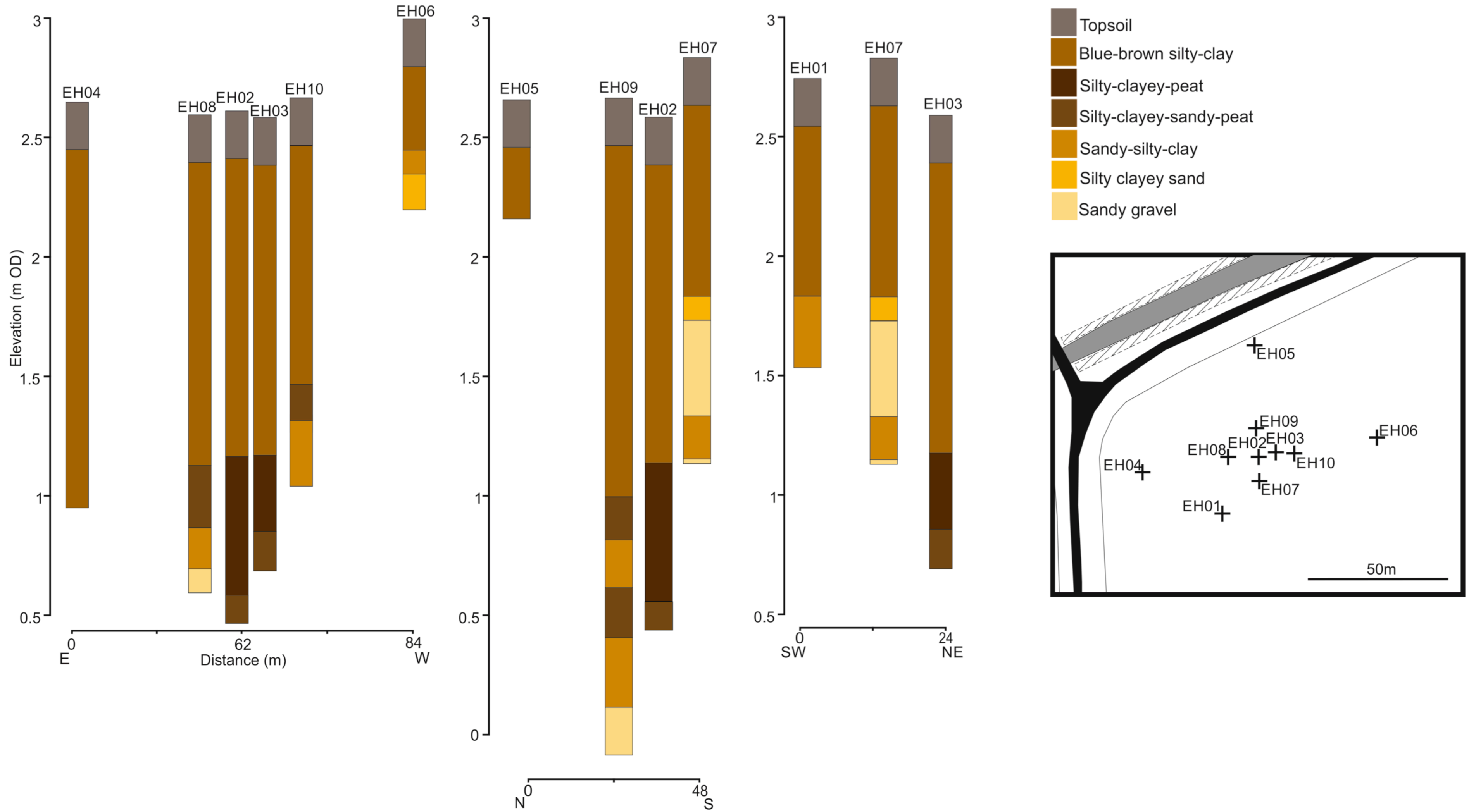


Figure 7.2 Location of cores taken during the survey and a simplified stratigraphic overview of the sediments.

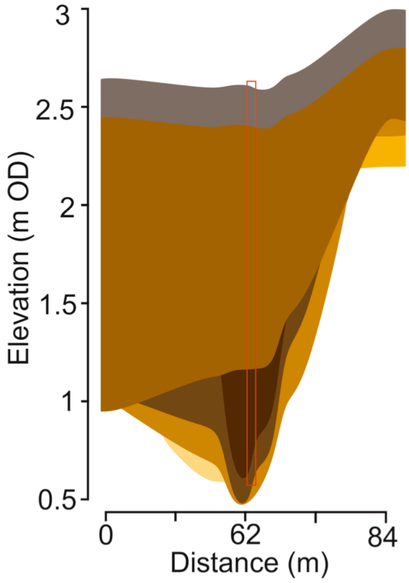


Figure 7.3 Stratigraphy of the east-west transect, with position of core EH03 highlighted. Stratigraphic key follows that in Figure 7.2.

Table 7.1 Sediment descriptions of core EH03.

Depth (m)	Elevation (m OD)	Description	Troels-Smith (1955) Description
0-0.3	+2.587 - +2.287	Brown stony topsoil	Nig 2; Strf. 0; Elas. 0; Sicc. 4; Lim. 0; Str. conf.; Ag2; As2
0.3-0.5	+2.287 - +2.087	Dense brown silt-clay	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2
0.5-1.33	+2.087 - +1.257	Dense brown-blue silt clay	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2
1.33-1.495	+1.257 - +1.092	Dense brown-grey-blue silt-clay	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2
1.495-1.54	+1.092 - +1.047	Gradational transition from brown-grey-blue silt-clay into dark brown silty-peat with visible sand and plant rootlets	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 1; Ag2; As1; Sh1; Ga+; Th+
1.54-1.85	+1.047 - +0.737	Dark brown silty-peat with sand and plant rootlets. Visible sand content decreases 1.75-1.54.	Nig 3; Strf. 0; Elas. 0; Sicc. 3; Lim. 1; Ag2; Sh2; As+; Ga+; Th+
1.85-1.9	+0.737 - +0.687	Dark brown sandy-silty-peat and basal stones	Nig 3; Strf. 0; Elas. 0; Sicc. 3; Lim. 1; Ag2; Sh2; As+; Ga+; Gs+; Gg(min)+; Gg(maj)+; Th+

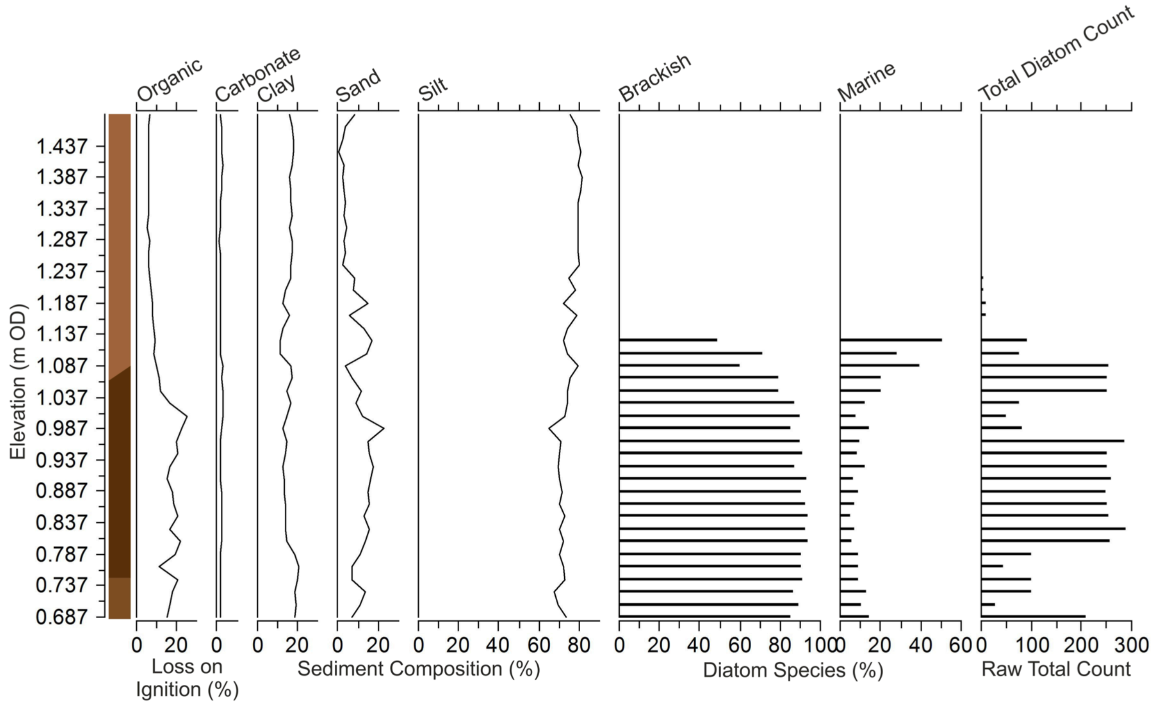


Figure 7.4 Summary diagram of laboratory analyses of core EH03, including summary diatom assemblage, loss-on-ignition and particle size results. Stratigraphic key follows that in Figure 7.2.

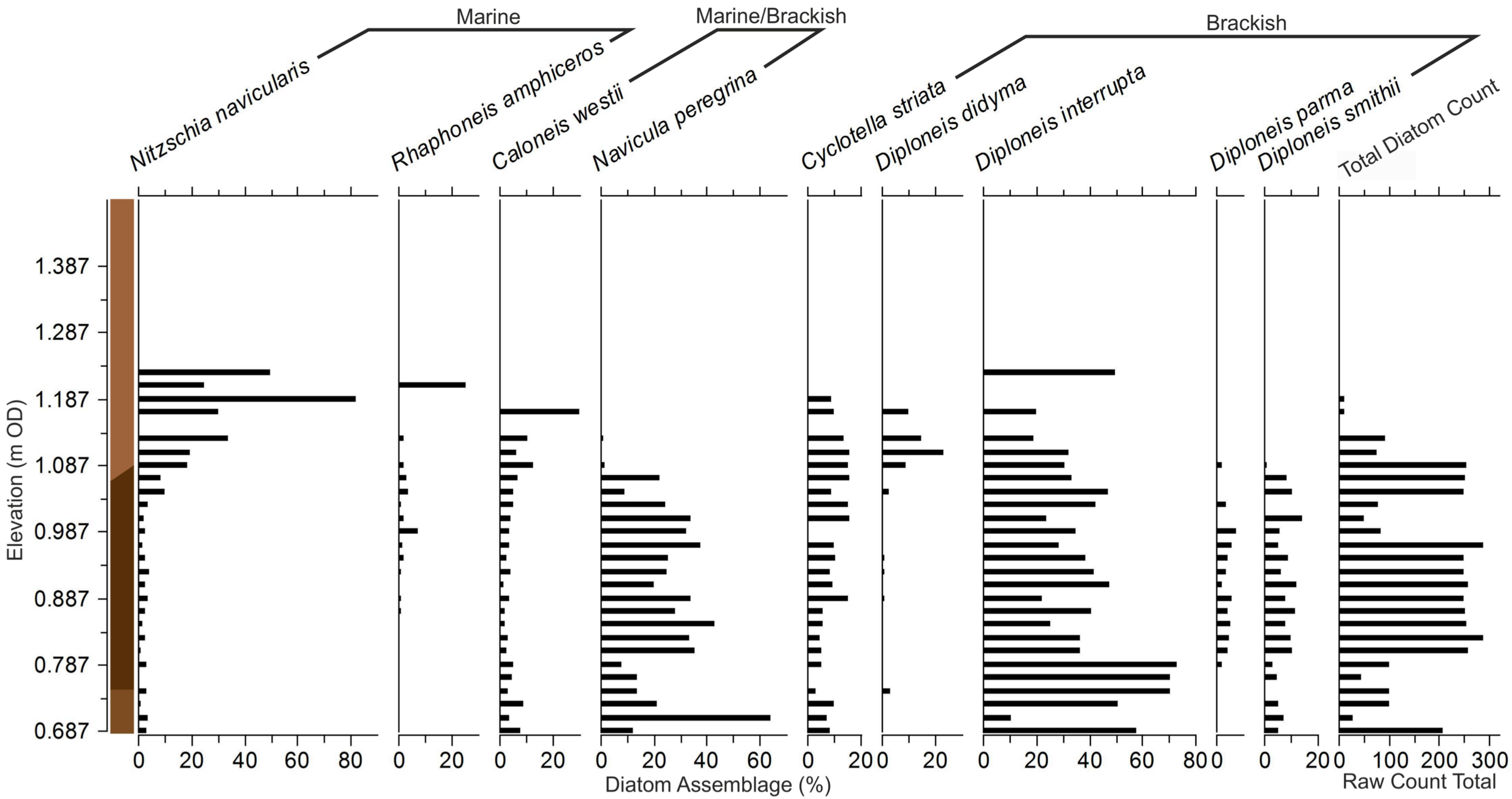


Figure 7.5 Summary percentage diatom assemblage of core EH03. Species >5% in two or more samples shown. Stratigraphy key follows that in Figure 7.2.

Table 7.2 Radiocarbon dates for core EH03 (analysis undertaken at [14]CHRONO Centre at Queens University Belfast.

Code	Identifier Core-Depth (cm)	Elevation (mOD)	Sample	Conventional Radiocarbon Age (years BP ±1σ)	Cal Years BP
UBA-27936	EH-155	+1.037	Bulk	3029±26	3227 (3158-3342)
UBA-27935	EH-190	+0.687	Bulk	3169±41	3395 (3257-3476)

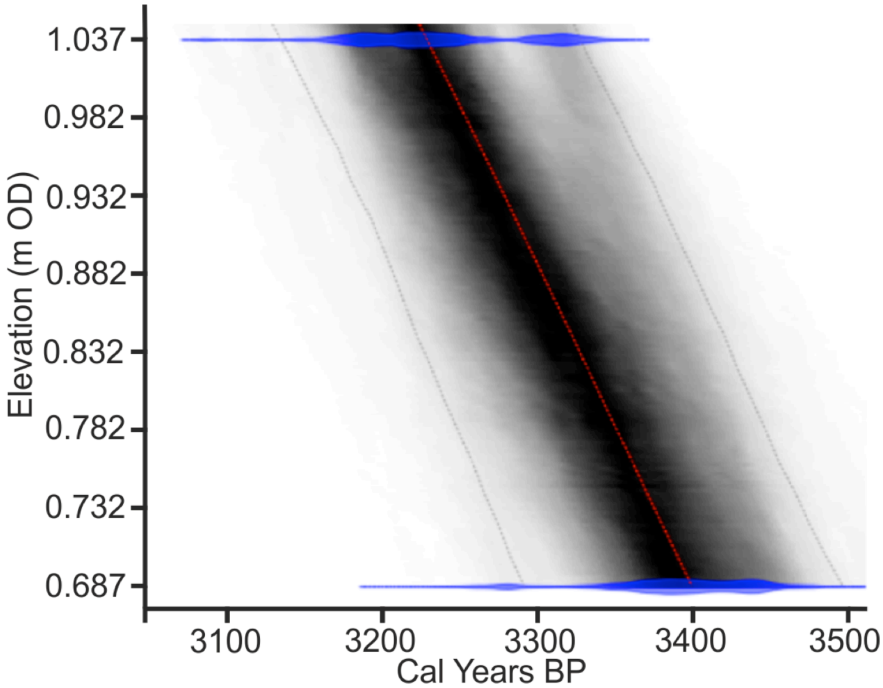


Figure 7.6 Chronology established using Bacon (Blaauw & Christen, 2011) for the lower 0.36m of core EH03, based on the two radiocarbon dates in Table 7.2.

Table 7.3 Summary performance of the diatom transfer functions (Table 6.1) and results of modern analogue analysis for core EH03.

Transfer Function	Component (% change)	RMSEP	Bootstrapped r^2	Modern Analogues		
				Poor	Close	Good
D-1	2 (5.08)	39.45	0.27	27	0	0
D-2	2 (6.65)	22.57	0.65	11	16	0
D-3	1	30.4	0.42	7	10	10
D-4	3 (7.92)	16.37	0.81	27	0	0
D-5	1	32.87	0.31	27	0	0

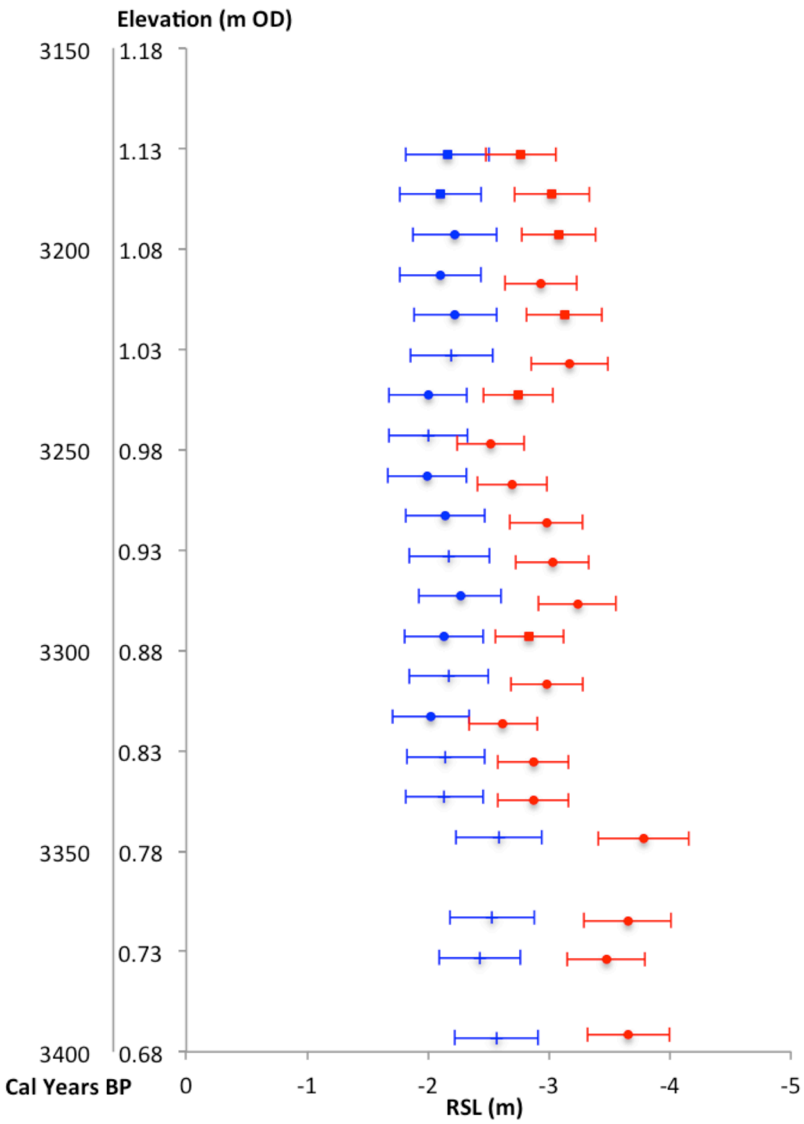


Figure 7.7 Sea-level reconstructions based on the UK *D-1* (red) and UK-Humber *D-3* (blue) transfer functions. Dash symbol represents estimate with good modern analogues, circle represents close, and square represents poor.

Table 7.4 Sea-level index points produced from core EH03.

Code	^{14}C Sample	^{14}C Age (Years BP +/-1σ)	Cal Years BP (+/- 2σ range)			Depth (m)	Elevation (m OD)	Indicative Meaning	Reference Water Level (m OD)	Correction (m)		Change in RSL (m)	Tendency
			Min	Median	Max					Tidal	Compaction		
EH-155	Bulk	3029+/-26	3158	3227	3342	1.55	1.037	(MHWST+HAT)/2	3.905 +/-0.395	-0.17	0.2847	-2.41 +/- 0.52	Positive
EH-190	Bulk	3169+/-41	3257	3395	3476	1.9	0.687	(MHWST+HAT)/2	3.905 +/-0.395	-0.18	N/A	-3.04 +/- 0.43	Positive

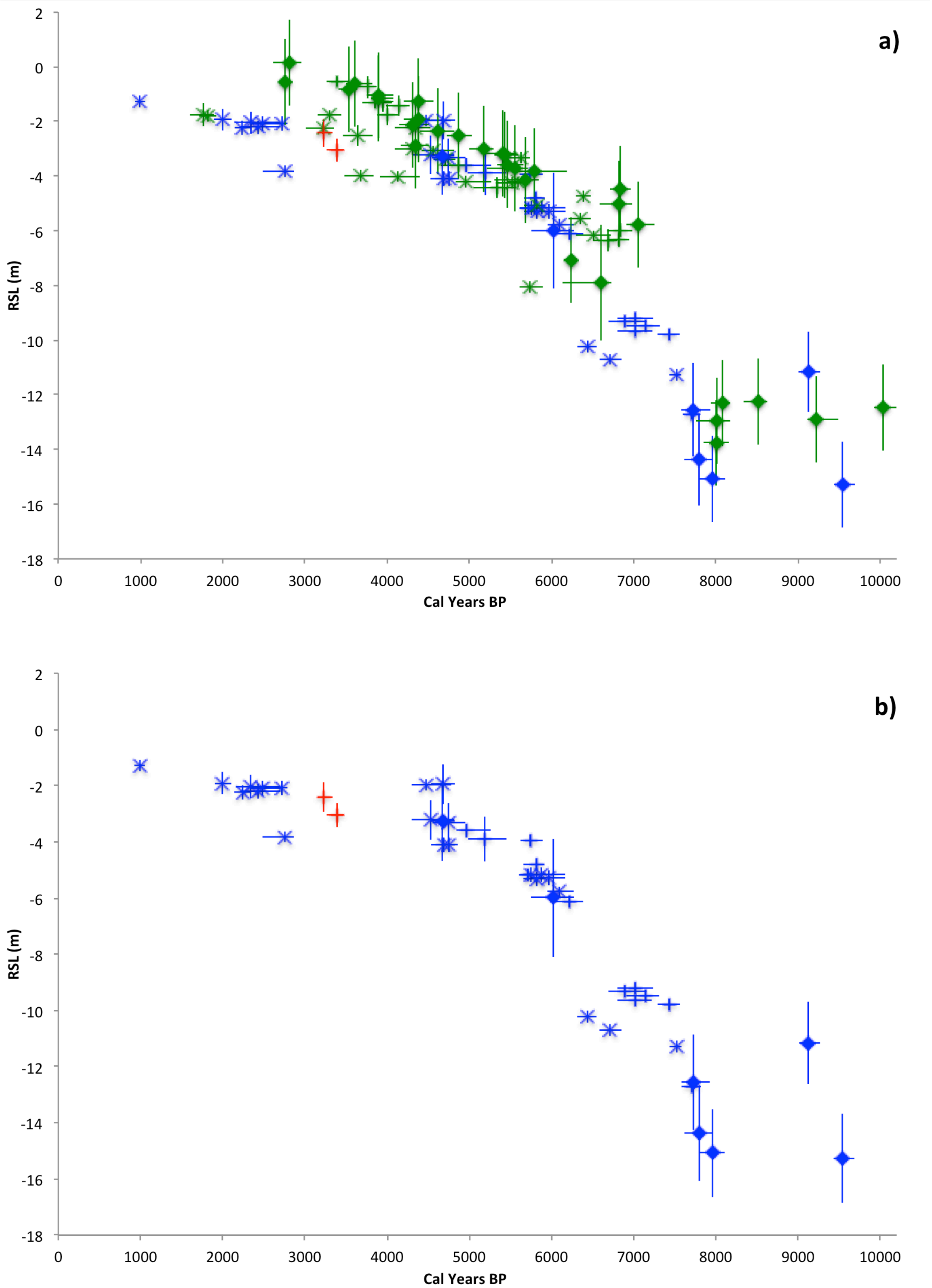


Figure 7.8 Two new sea-level index points (red plus symbol) with the existing tidal-corrected sea-level index points for the Humber Estuary: a) new sea-level index points with data from inner and outer estuary, and b) new sea-level index points with data from outer estuary only. Blue= outer estuary (east of Hull); green= inner estuary (west of Hull). Diamonds= limiting points; crosses intercalated points; plus= basal points; all include associated individual vertical and age error bars.

8. Palaeoenvironment and Relative Sea-Level Reconstruction: Brough

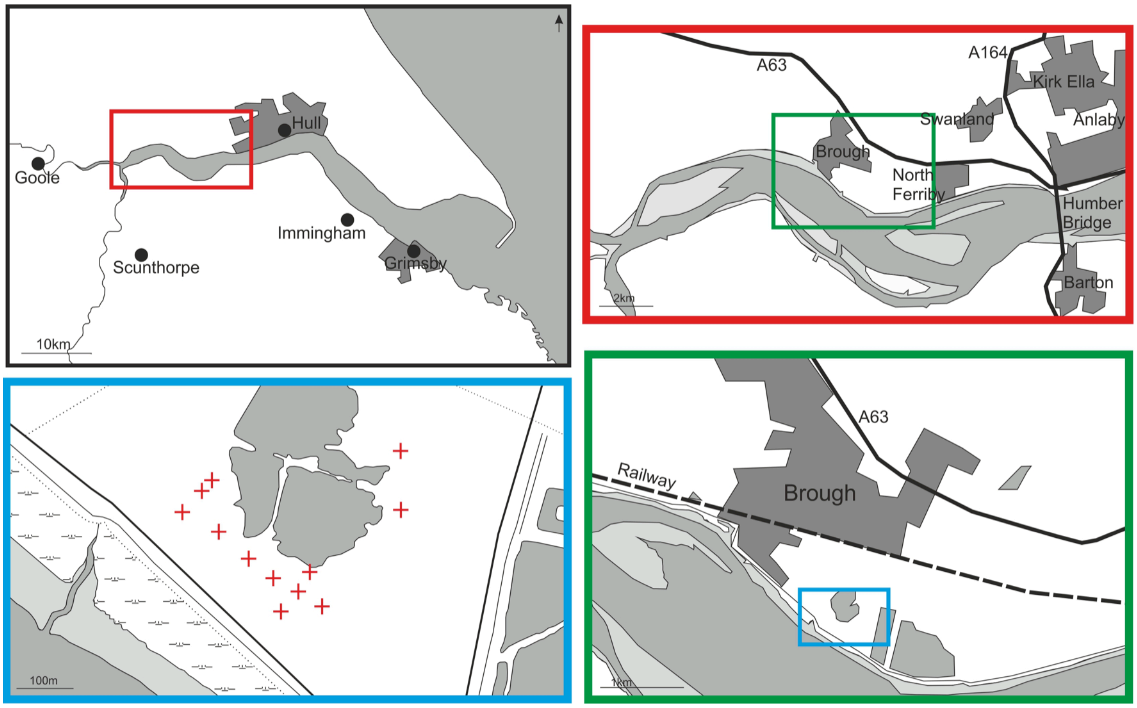


Figure 8.1 Location of Brough palaeo study site. Red crosses indicate location of stratigraphic cores from this study.

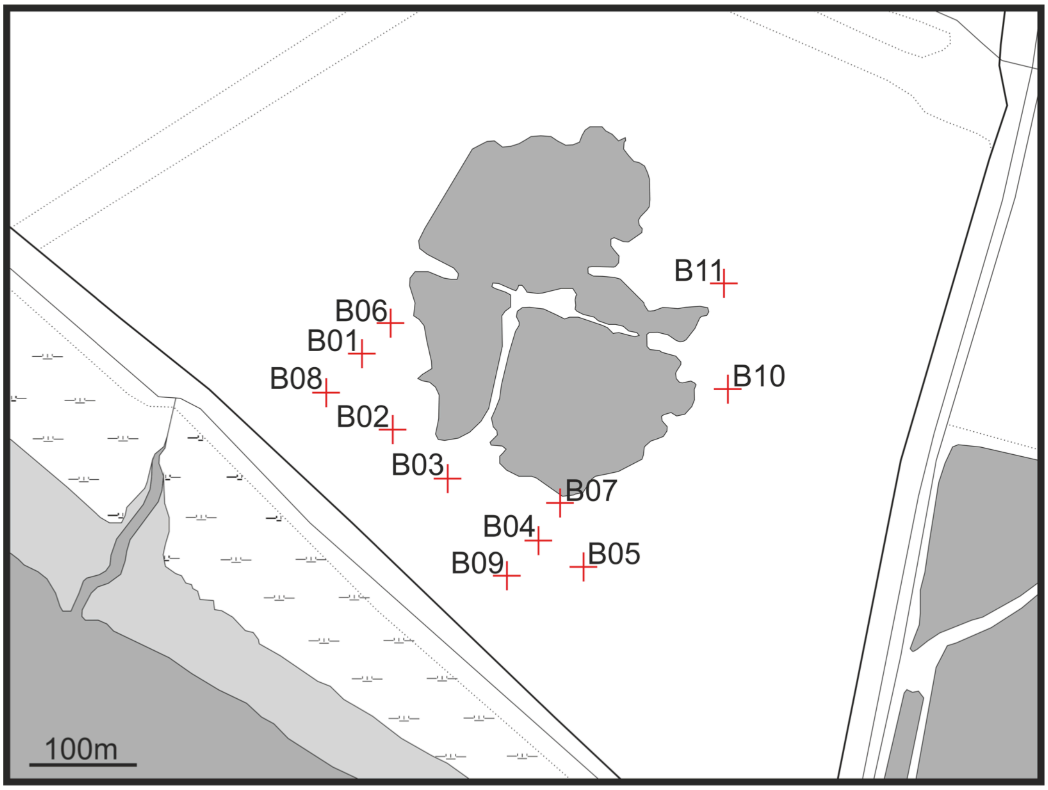


Figure 8.2 Location of boreholes taken for stratigraphic survey in this study.

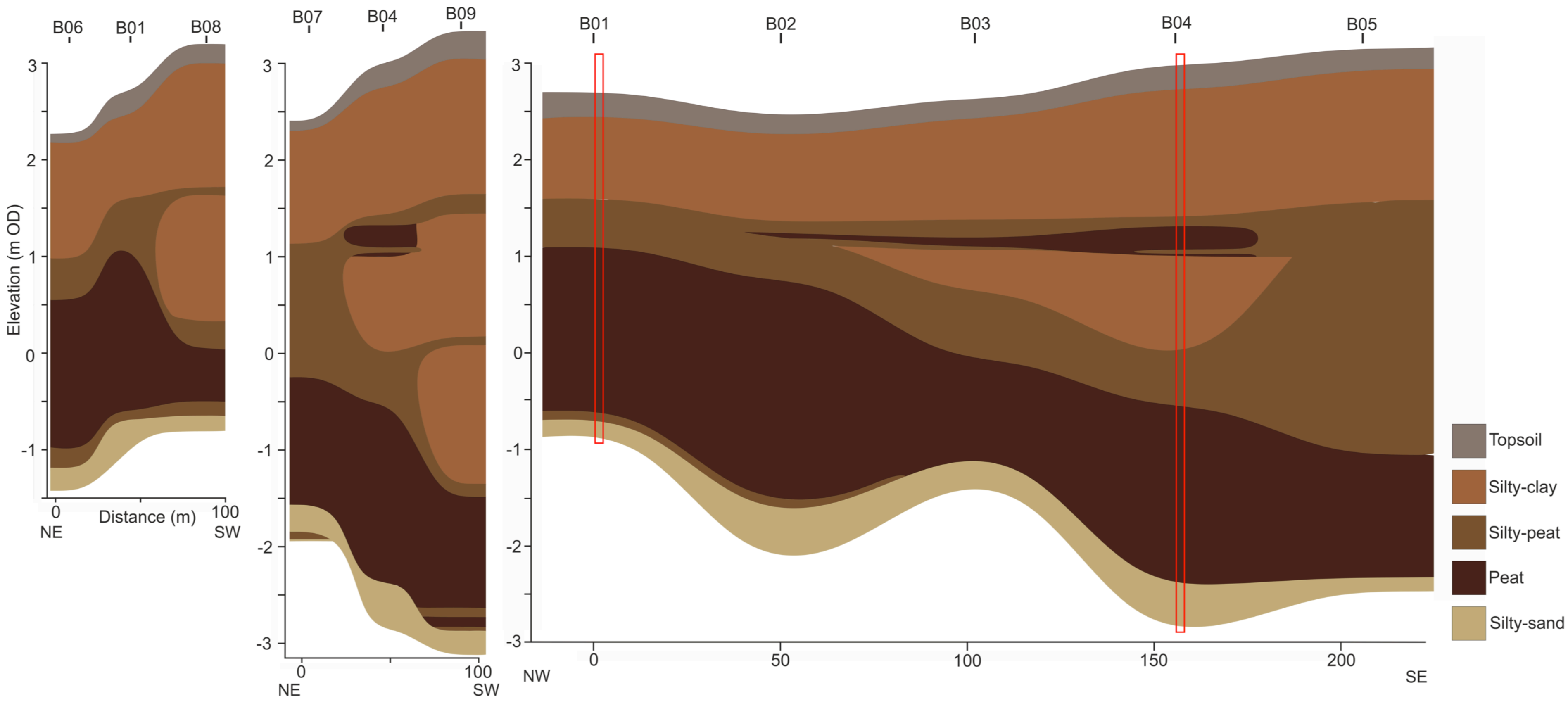


Figure 8.3 A simplified stratigraphic overview of the stratigraphy at Brough.

Table 8.1 Sediment descriptions of core BC01.

Depth (m)	Elevation (m OD)	Description	Troels-Smith (1955) Description
0-0.3	+2.702 - +2.402	Dense brown topsoil	Nig 2; Strf. 0; Elas. 0; Sicc. 4; Lim. 0; Strf. conf; Ag2; As2
0.3-0.88	+2.402-+1.822	Dense brown blue silty clay	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2
0.88-0.93	+1.822 - +1.772	Dense brown blue silty clay with plant fibres	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2; Th+
0.93-1.12	+1.722 - +1.582	Brown organic crumbly silty clay	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2; Sh+; Th+
1.12-1.19	+1.582 - +1.512	Brown silty peat	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; Sh2; Sh+; Th+
1.19-1.71	+1.512 - +1.002	Brown grey blue silty clay with organic patches; increasingly organic 1.48-1.71	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2; Sh+
1.71-2.0	+1.002 - +0.702	Dark brown silty peat	Nig 3; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; Sh2; Th+
2.0-2.18	+0.702 - +0.522	Dark brown peat	Nig 3; Strf. 2; Elas. 1; Sicc. 3; Lim. 0; Sh3; Th1
2.18-2.46	+0.522 - +0.242	Dark brown peat with occasional wood fragments	Nig 3; Strf. 2; Elas. 1; Sicc. 3; Lim. 0; Sh3; Th1; Tl+
2.46-3.26	+0.242 – -0.558	Dark red-brown woody peat	Nig 3; Strf. 2; Elas. 1; Sicc. 3; Lim. 0; Sh2; Tl1; Th1
3.26-3.32	-0.558 – -0.618	Dark brown silty peat	Nig 3; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; Sh2; Th+
3.32-3.38	-0.618 – -0.678	Dark brown silty peat with fine sand	Nig 3; Strf. 0; Elas. 0; Sicc. 3; Lim. 1; Ag2; Sh2; Th+; Ga+
3.38-3.49	-0.678 – -0.788	Yellow-grey silty coarse sand	Nig 1; Strf. 0; Elas. 0; Sicc. 3; Lim. 1; Ag2; Ga1; Gs1; Gg(min)+

Table 8.2 Sediment descriptions of core BC02.

Depth (m)	Elevation (m OD)	Description	Troels-Smith (1955) Description
0-0.47	+2.404 - +1.934	Dense brown topsoil	Nig 2; Strf. 0; Elas. 0; Sicc. 4; Lim. 0; Strf. conf; Ag2; As2
0.47-0.79	+1.934 - +1.614	Dense brown blue silt clay	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2
0.79-0.9	+1.614 - +1.504	Dense brown blue silt with organic patches	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2; Sh+
0.9-1.27	+1.504 - +1.134	Grey brown blue silty clay	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2
1.27-1.4	+1.134 - +1.004	Brown blue silty clay with organic patches; increasingly fibrous 1.32-1.4	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2; Sh+; Th+
1.4-1.67	+1.004 - +0.734	Dark brown silty peat	Nig 3; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; Sh2; Th+
1.67-2.14	+0.734 - +0.264	Grey blue silty clay with organic patches	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2; Sh+
2.14-2.44	+0.264 – -0.036	Dark brown silty peat	Nig 3; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; Sh2; Th+
2.44-2.6	-0.036 – -0.196	Blue brown silty clay with organic patches	Nig 2; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag2; As2; Sh+
2.6-3.6	-0.196 – -1.196	Dark brown peat	Nig 3; Strf. 2; Elas. 1; Sicc. 3; Lim. 0; Sh3; Th1
3.6-4.16	-1.196 – -1.756	Dark red brown woody peat	Nig 3; Strf. 2; Elas. 1; Sicc. 3; Lim. 0; Sh2; Tl1; Th1
4.16-4.29	-1.756 – -1.886	Brown black silty peat with shell fragments 4.18-4.29	Nig 4; Strf. 0; Elas. 0; Sicc. 3; Lim. 0; Ag3; Sh1; test (moll.); part.test.(moll.)
4.29-4.55	-1.886 – -2.146	Yellow-grey silty coarse sand	Nig 1; Strf. 0; Elas. 0; Sicc. 3; Lim. 1; Ag2; Ga1; Gs1; Gg(min)+

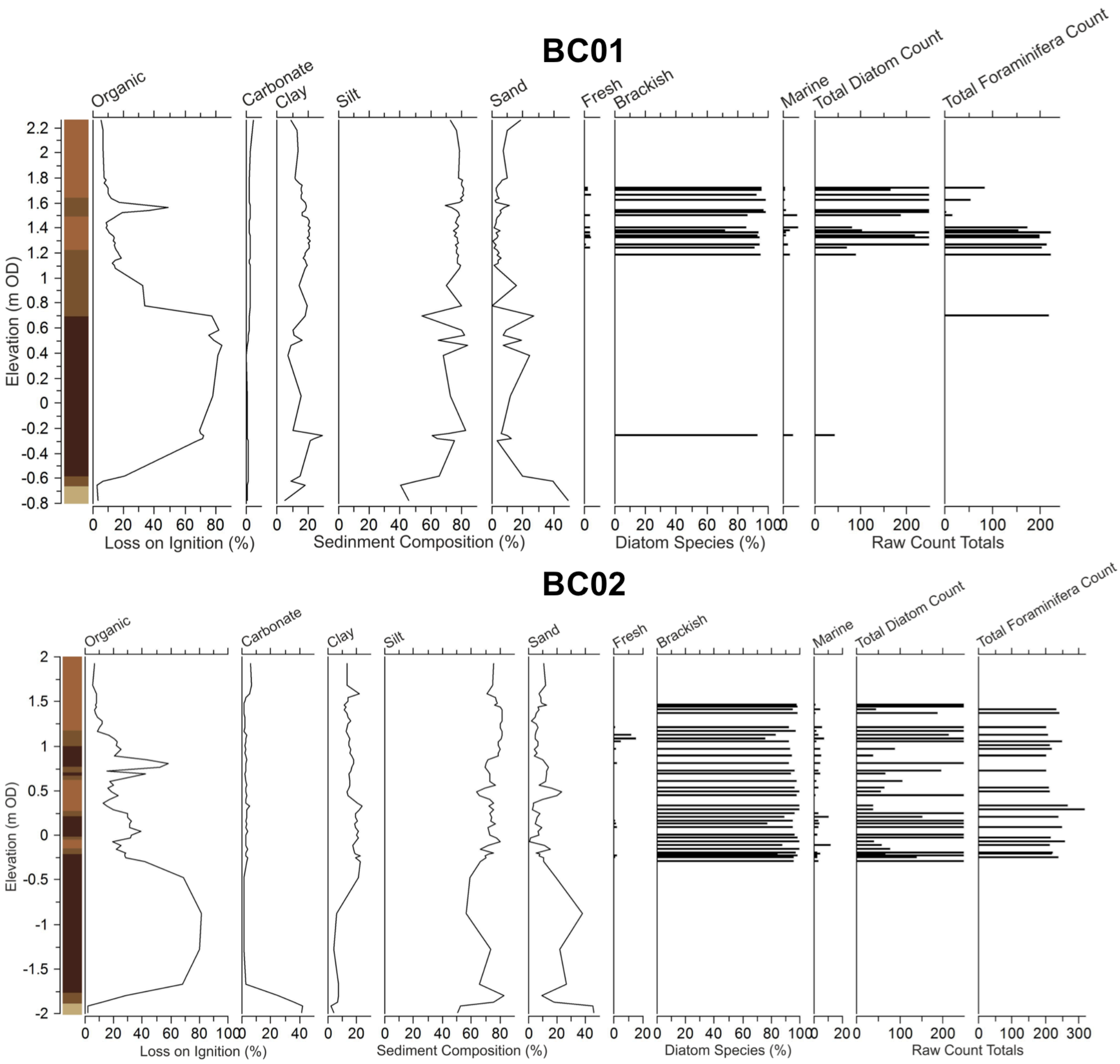


Figure 8.4 Summary diagrams of the laboratory analyses of cores BC01 and BC02, including summary diatom assemblages, foraminifera abundance, loss-on-ignition and particle size results. Foraminifera summaries are not included as all identified were agglutinated species. Stratigraphic key follows that in Figure 8.3.

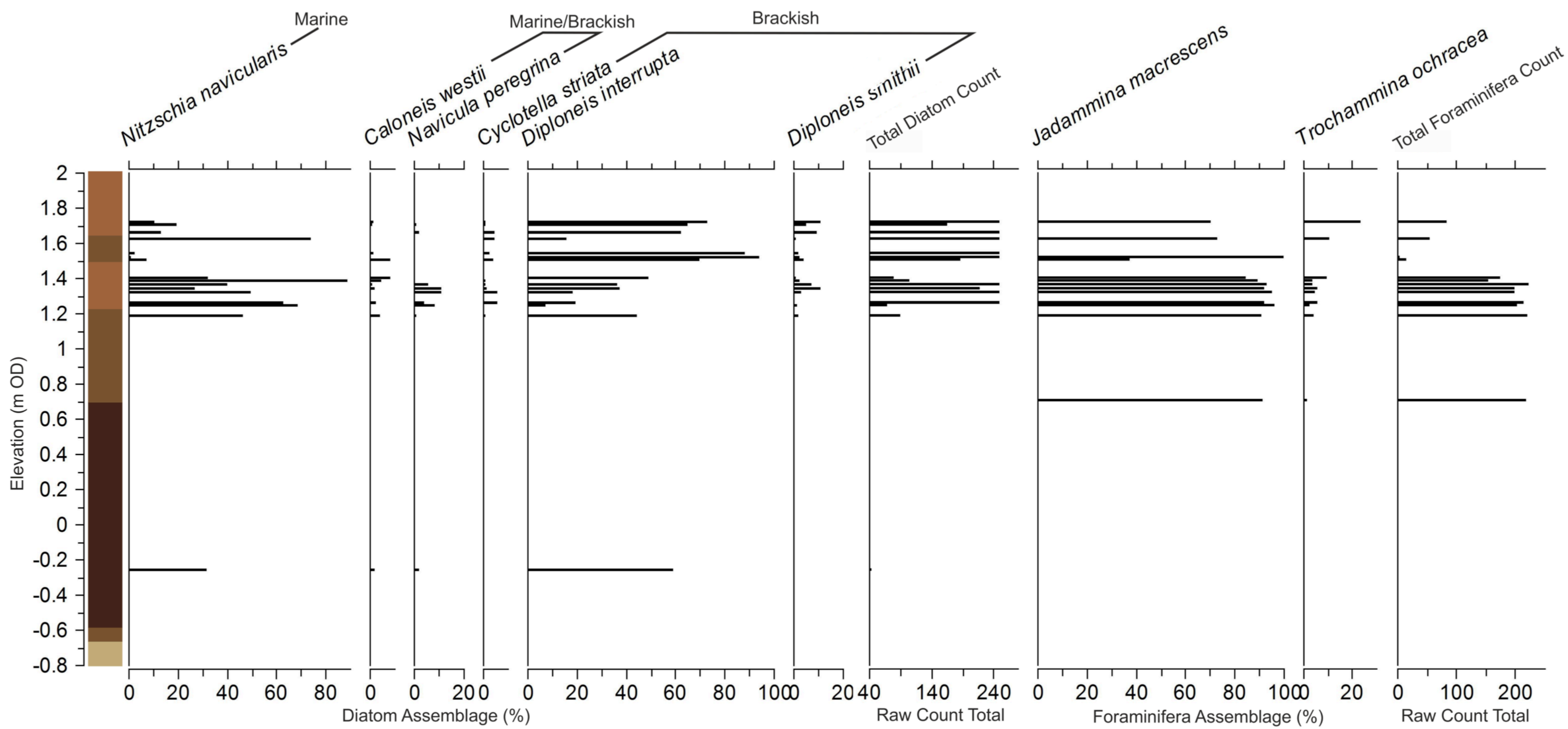


Figure 8.5 Summary percentage diatom and foraminifera assemblages of core BC01. Species >5% in two or more samples shown. Stratigraphic key follows that in Figure 8.3.

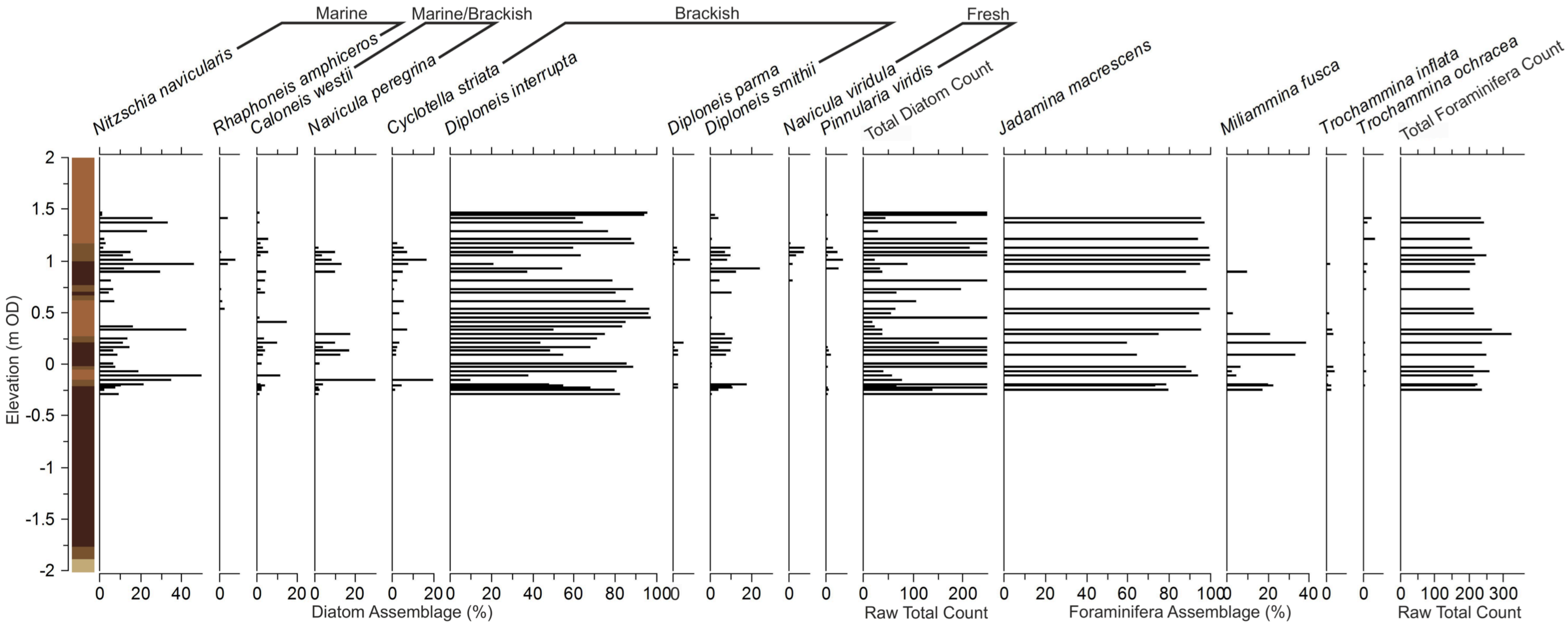


Figure 8.6 Summary percentage diatom and foraminifera assemblages of core BC02. Species >5% in two or more samples shown. Stratigraphic key follows that in Figure 8.3.

Table 8.3 Radiocarbon dates (analysis undertaken at NERC Radiocarbon Facility NRCF010001, allocation number 1932.1015).

Code	Identifier Core-Depth (cm)	Elevation (mOD)	Sample	Conventional Radiocarbon Age (years BP ± 1σ)	Cal Years BP
SUERC-65976	BC01-105	+1.652	Bulk	3624 ± 35	3935 (3841-4078)
SUERC-65980	BC01-119	+1.512	Bulk	2448 ± 37	2522 (2359-2705)
SUERC-65981	BC01-202	+0.682	Plant macrofossil	2606 ± 37	2745 (2540-2791)
SUERC-65982	BC02-93	+1.474	Bulk	7556 ± 39	8376 (8315-8425)
SUERC-65983	BC02-130	+1.104	Plant macrofossil	1583 ± 36	1470 (1396-1550)
SUERC-65984	BC02-159	+0.814	Plant macrofossil	1639 ± 37	1540 (1414-1616)
SUERC-65985	BC02-175	+0.654	Bulk	2343 ± 37	2356 (2209-2489)
SUERC-65986	BC02-259	-0.186	Bulk	3682 ± 38	4022 (3902-4145)

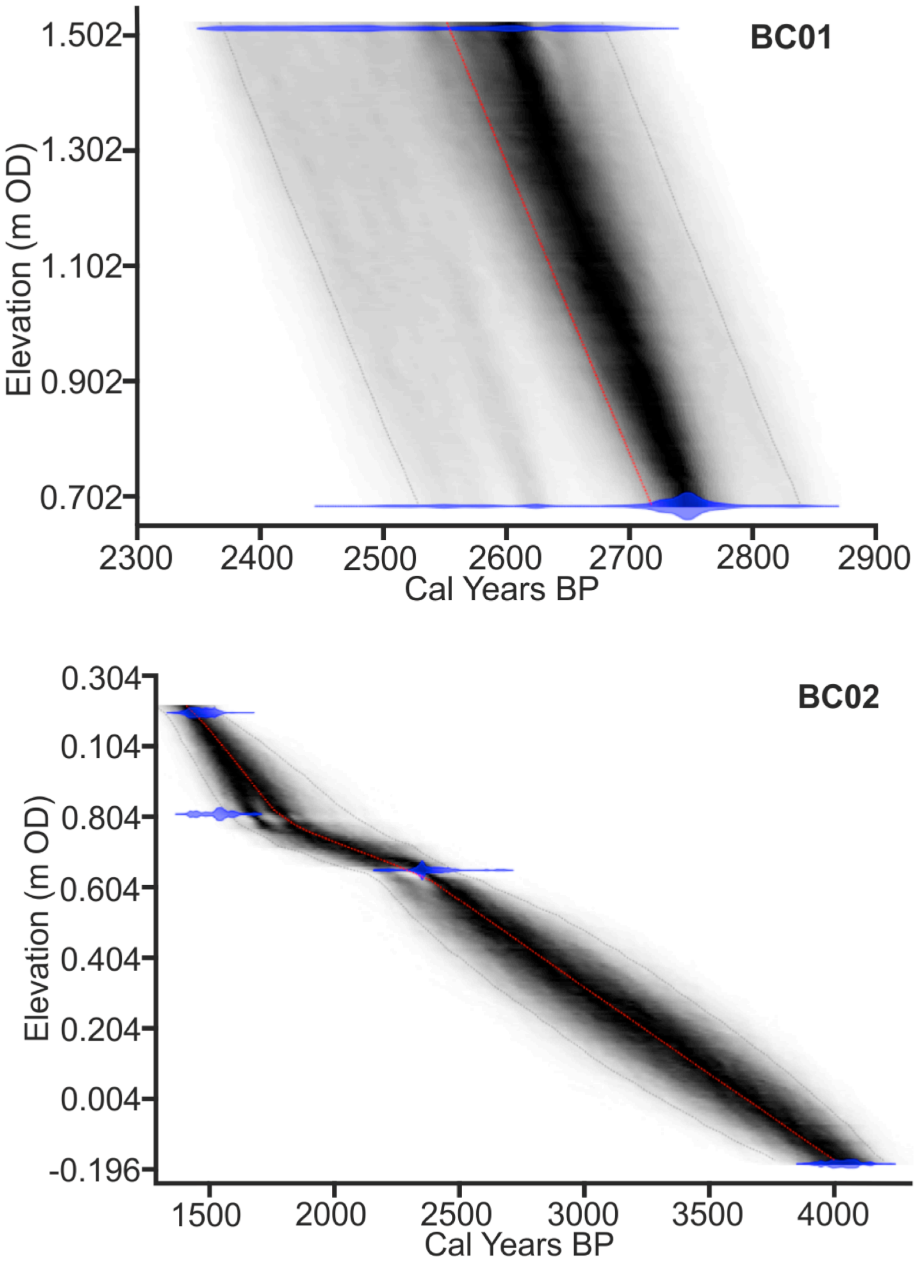


Figure 8.7 Chronology and age-depth model established using Bacon (Blaauw & Christen, 2011) for the dated sections of cores BC01 and BC02.

Table 8.4 Summary performance of the transfer functions (Table 6.1) and results of modern analogue analysis (P= poor; C= close; G= good) for cores BC01 and BC02.

Model	Component (% Change)	RMSEP	Boot-strapped r^2	Modern Analogues					
				BC01			BC02		
				P	C	G	P	C	G
D-1	1	41.90	0.10	16	0	0	35	0	0
D-2	2 (6.15)	22.69	0.65	16	0	0	15	10	0
D-3	1	31.00	0.43	7	9	0	6	20	9
D-4	3 (7.51)	16.46	0.80	16	0	0	35	0	0
D-5	1	32.88	0.31	16	0	0	35	0	0
F-1	1	44.58	0.00	9	0	0	16	4	1
F-2	1	25.78	0.28	0	0	9	0	0	21
F-3	1	29.44	0.23	0	0	9	0	0	21
F-4	1	14.48	0.09	0	0	9	0	0	21
F-5	1	28.33	0.03	0	0	9	0	0	21
M-1	2 (5.37)	42.79	0.14	16	0	0	36	0	0
M-2	2 (5.15)	24.20	0.48	7	6	3	15	10	11
M-3	1	28.47	0.36	1	10	5	3	20	13
M-4	3 (7.51)	15.71	0.66	7	6	3	18	6	12
M-5	1	26.97	0.30	7	4	5	16	4	16

Table 8.5 Sea-level index points produced from cores BC01 and BC02. Tidal corrections have not been incorporated in the change in relative sea-level erros.

Code	^{14}C Sample	^{14}C Age (Years BP +/- 1σ)	Cal Years BP (+/- 2σ range)			Depth (m)	Elevation (m OD)	Reference Water Level (m OD)	Correction (m)		Change in RSL (m)	Tendency
			Min	Median	Max				Tidal	Compaction		
BC01-119	Bulk	2448 +/- 37	2359	2522	2705	1.19	1.512	4.078 +/- 0.387	-1.759	0.014	-0.79 +/- 0.39	Negative
BC01-202	Plant	2606 +/- 37	2540	2745	2791	2.02	0.682	3.899 +/- 0.335	-1.915	0.126	-1.18 +/- 0.36	Positive
BC02-130	Plant	1583 +/- 36	1396	1470	1550	1.3	1.104	4.019 +/- 0.373	-1.025	0.171	-1.72 +/- 0.41	Positive
BC02-159	Plant	1639 +/- 37	1414	1540	1616	1.59	0.814	4.024 +/- 0.378	-1.074	0.236	-1.90 +/- 0.45	Negative
BC02-175	Bulk	2343 +/- 37	2209	2356	2489	1.75	0.654	3.952 +/- 0.377	-1.643	0.045	-1.61 +/- 0.38	Negative
BC02-259	Bulk	3682 +/- 38	3902	4022	4145	2.59	-0.186	3.982 +/- 0.369	-2.839	0.171	-1.16 +/- 0.41	Positive

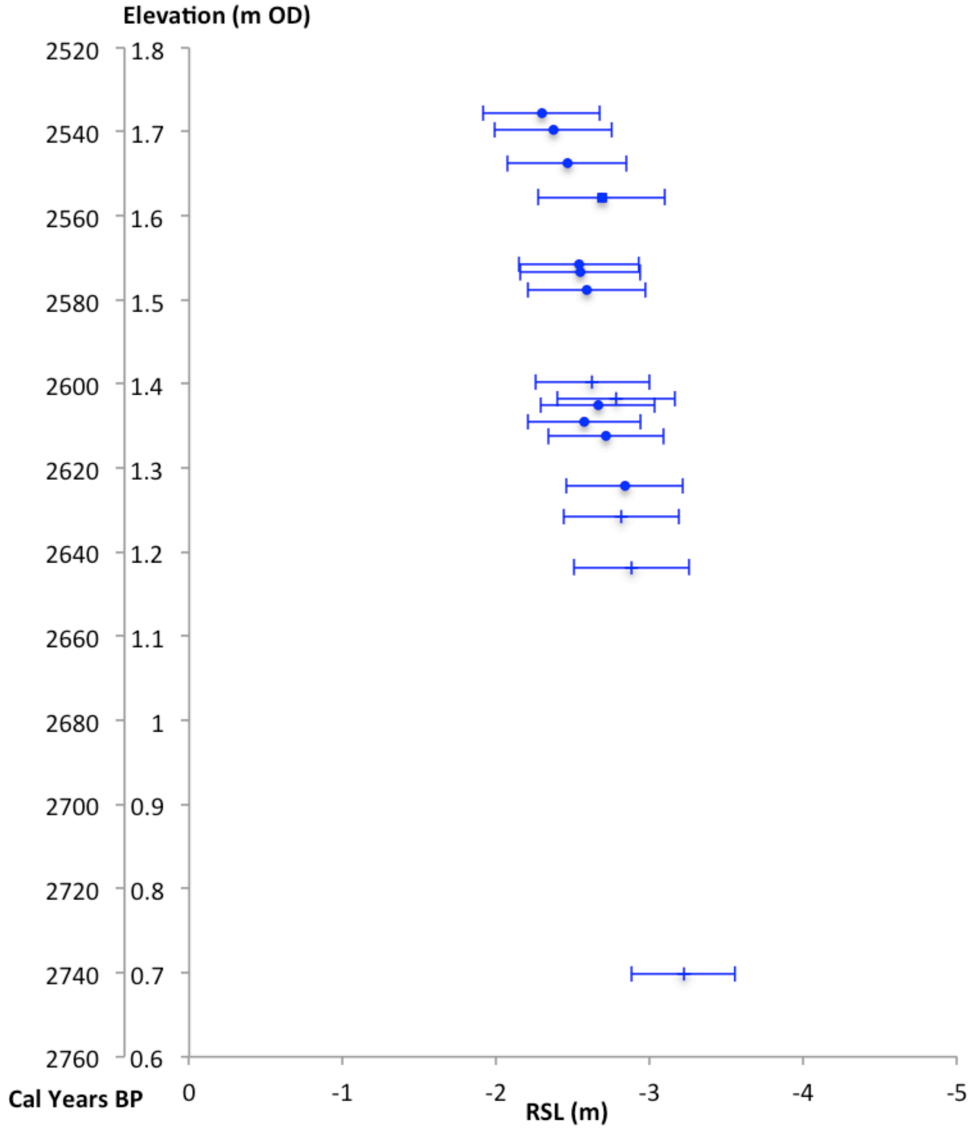


Figure 8.8 Transfer function reconstructions for core BC01 based on the multi-proxy UK-Humber model, *M-3*. Dash symbol indicates good modern analogues, circle represents close, and square represents poor. Ages are based on the chronology established between the two accepted radiocarbon dates at +1.512 and +0.682 m OD (Figure 8.7); the ages beyond this range are extrapolated from the model.

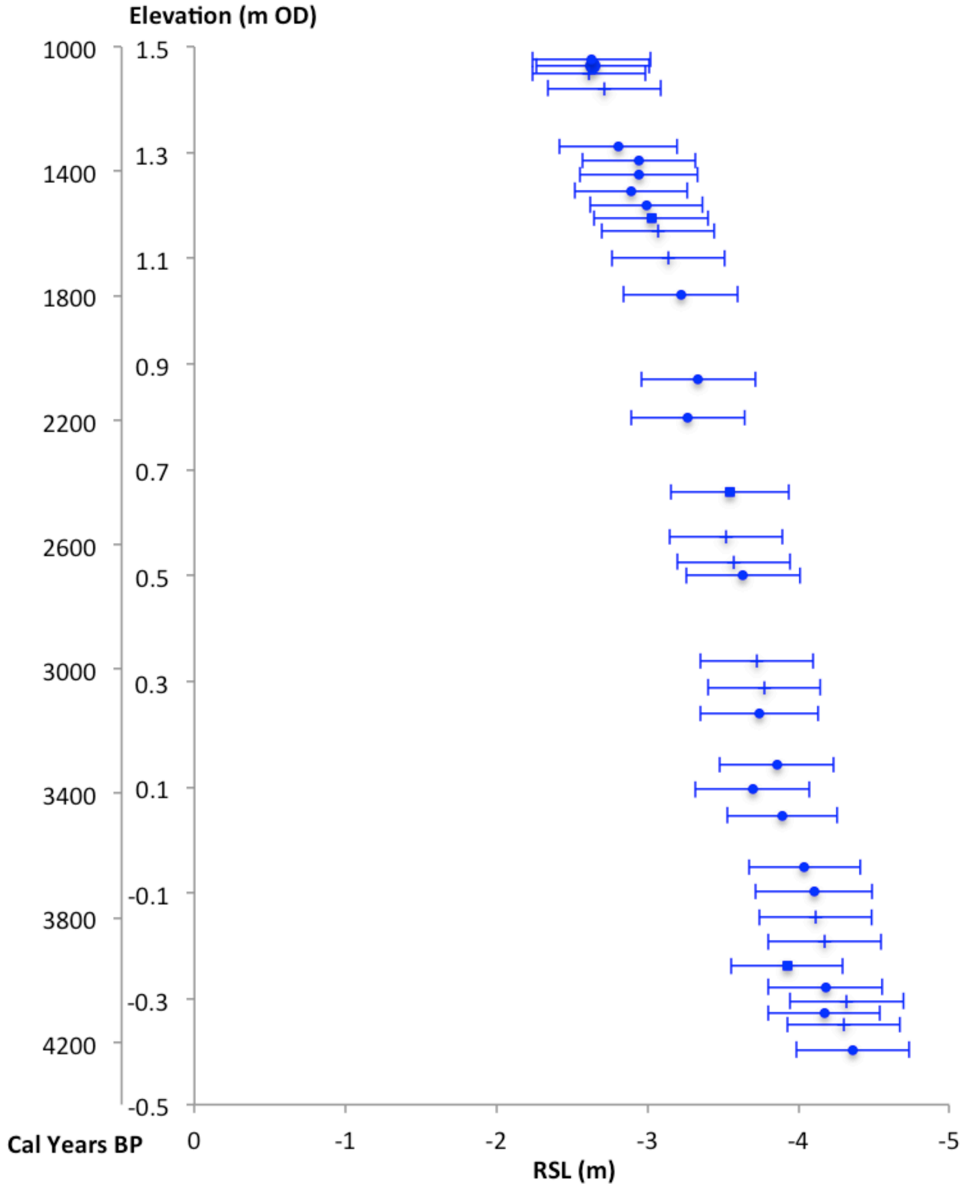
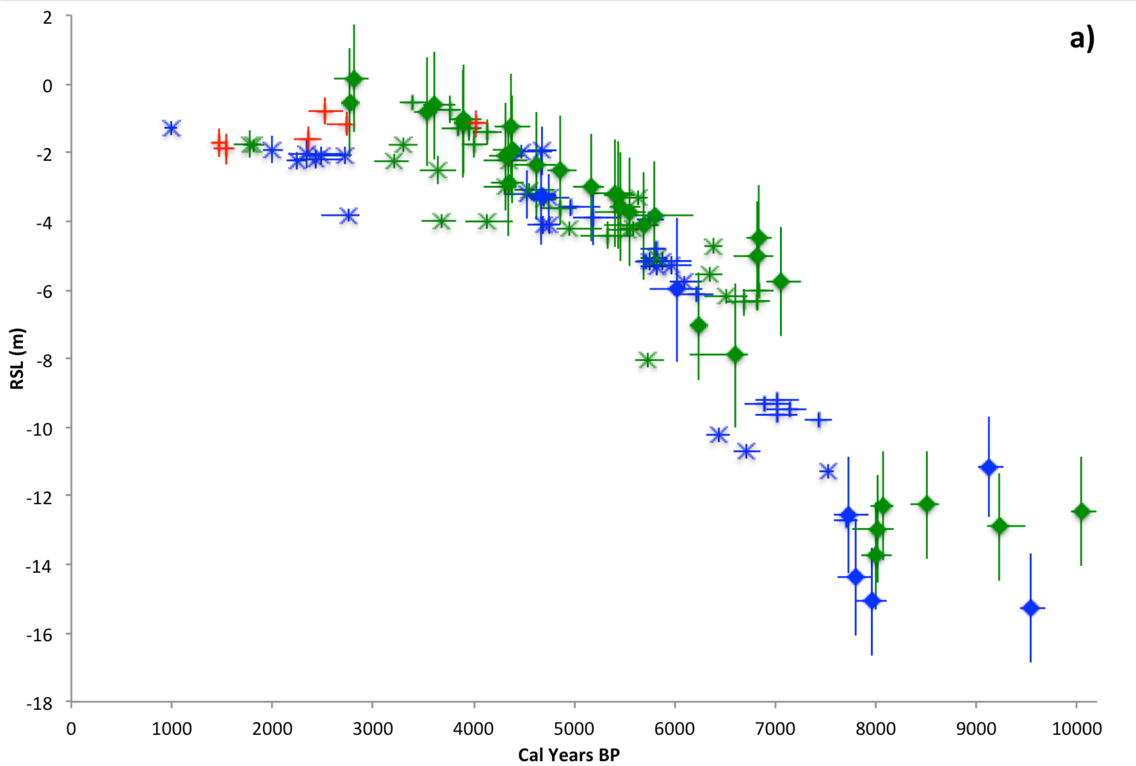


Figure 8.9 Transfer function reconstructions for core BC02 based on the multi-proxy UK-Humber model, *M-3*. Dash symbol indicates good modern analogues, circle represents close, and square represents poor. Ages are based on the age-depth model between the four accepted radiocarbon dates at +1.104, +0.814, +0.654 and and -0.186 m OD (Figure 8.7); the ages beyond this range are extrapolated from the model.



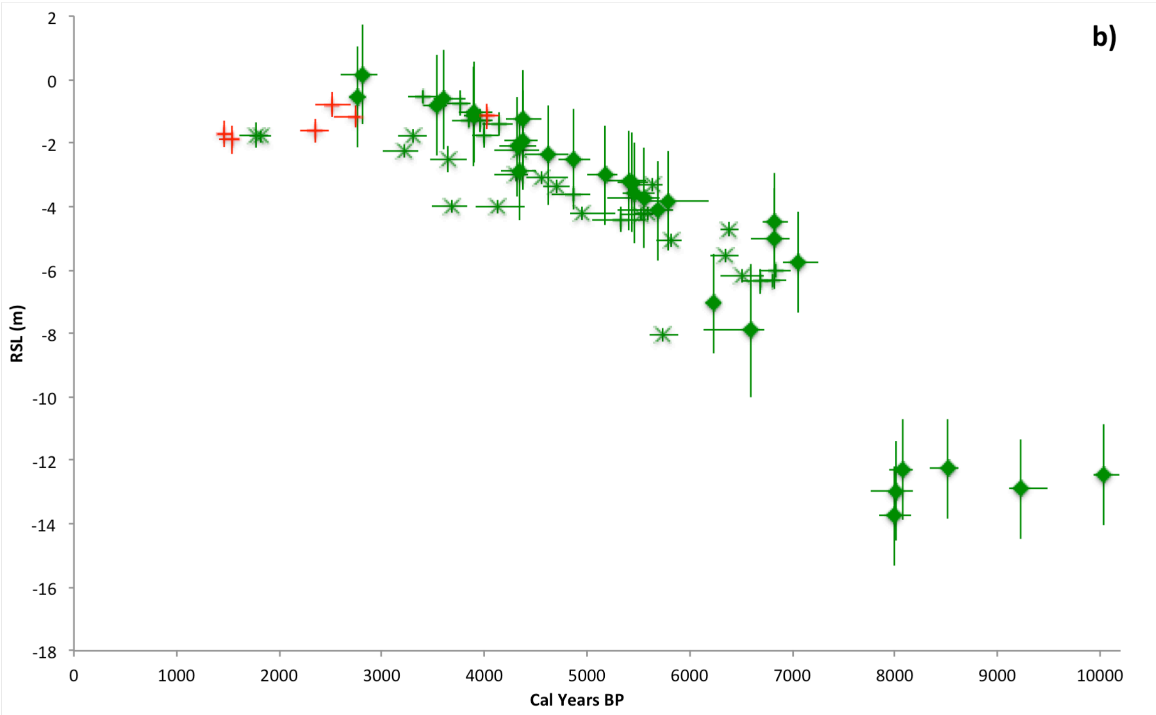


Figure 8.10 Six new sea-level index points (red plus symbol) with the existing tidal-corrected sea-level index points for the Humber Estuary: a) new sea-level index points with data from the inner and outer estuary, and b) new sea-level index points with data from the inner estuary only. Blue= outer estuary (east of Hull); green= inner estuary (west of Hull) Diamonds= limiting points; crosses= intercalated points; plus= basal points; all include associated individual vertical and age error bars.

9. Sea Level, Groundwater and Abstraction: Past, Present and Future

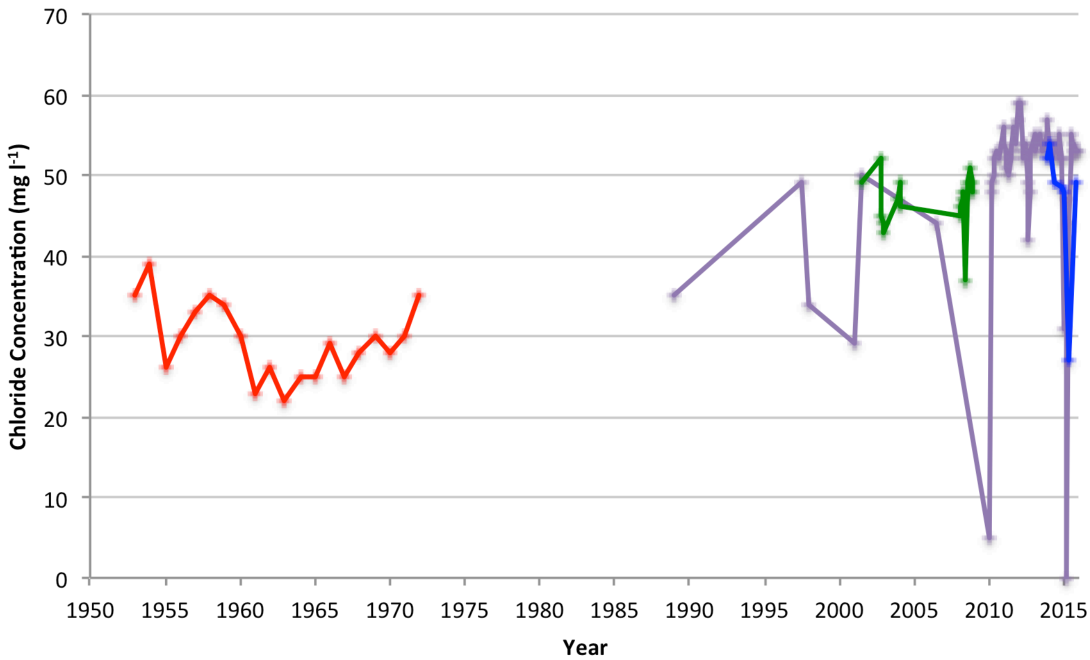


Figure 9.1 Chloride concentrations at Springhead. Red data is from Foster *et al.* (1976); purple, green and blue are data from Yorkshire Water (graph based on data presented in ARUP (2016)).

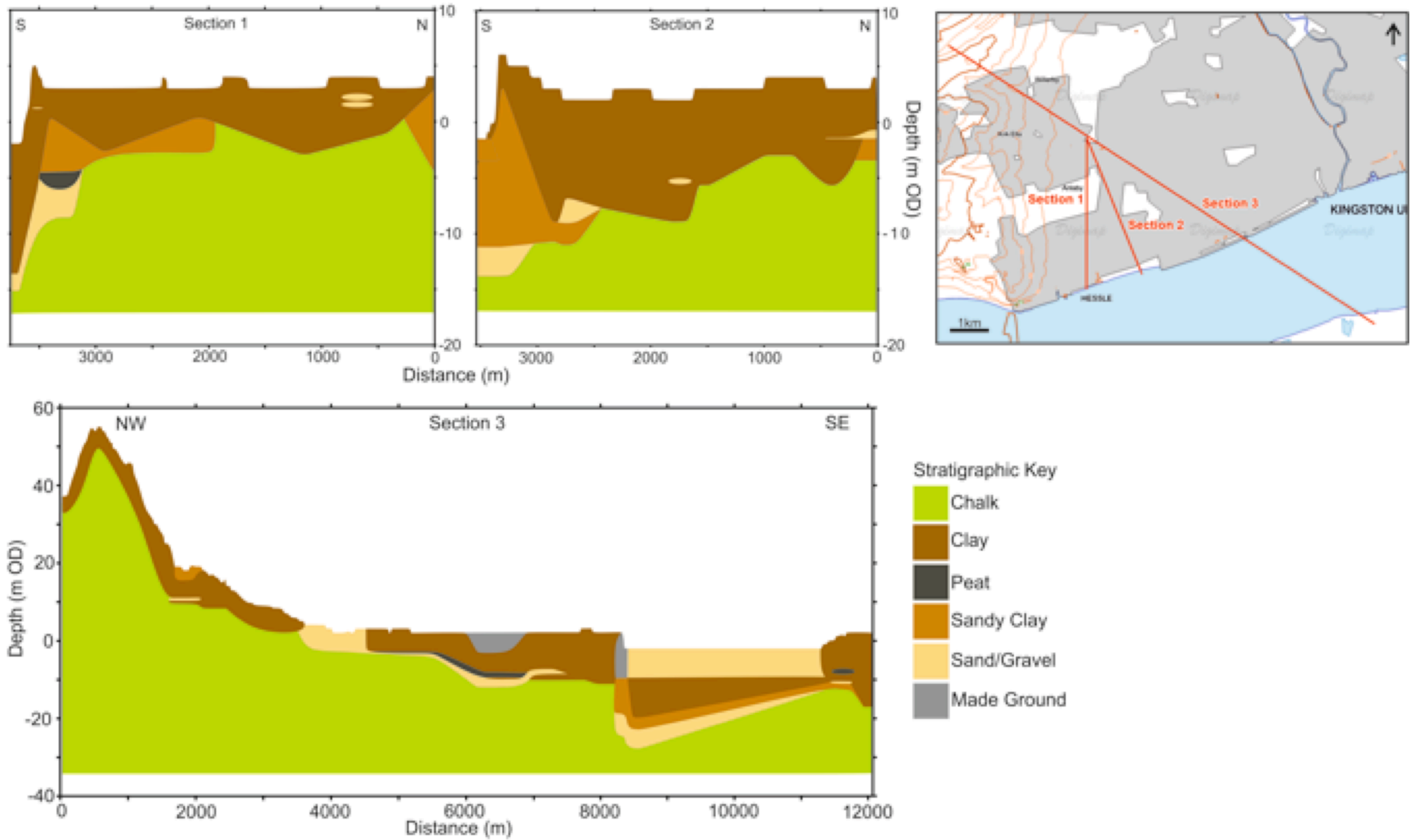


Figure 9.2 Simplified superficial geology transects around the Springhead- Humber Estuary area based upon published borehole records (British Geological Survey, 2015); map of transect locations from Digimap (2016) © Crown Copyright and Database Right (2016) OS (Digimap Licence).

Table 9.1 Outline of the nine scenarios simulated using the East Yorkshire Chalk numerical model. Naturalised, recent actual and fully licensed refers to the abstraction conditions (section 5.8.3). Head boundary represents sea level at the boundary of the model, the northern bank of the Humber Estuary (section 5.8.3).

Scenario	Period	Year	Abstraction	Sea-Level Change (m)	Head Boundary (m OD)
1	Palaeo	3000 BP	Naturalised	-1.2	-1
2	Palaeo	2000 BP	Naturalised	-0.4	-0.2
3	Palaeo	1000 BP	Naturalised	-0.2	0
4	Present	2016	Naturalised	0	0.2
5	Present	2016	Recent Actual	0	0,2
6	Present	2016	Fully Licensed	0	0.2
7	Future	2100	Naturalised	+0.73	+0.93
8	Future	2100	Recent Actual	+0.73	+0.93
9	Future	2100	Fully Licensed	+0.73	+0.93

Table 9.2 East Yorkshire Chalk model head and flow results at Springhead and Humber Estuary boundary cells (sections 5.8.3; 9.2.2) based on the nine scenarios (outlined in Table 9.1).

Scenario	Springhead		Estuary	
	Head (m OD)	Flows (m^3 d^{-1})	Head (m OD)	Flows (m^3 d^{-1})
1	5.307	733.564	-0.217	283.319
2	5.501	717.873	0.277	212.014
3	5.54	714.704	0.362	211.349
4	5.577	711.620	0.447	210.610
5	-0.108	1312.476	0.214	74.645
6	-2.835	1777.810	0.087	1.219
7	5.715	701.177	0.756	207.166
8	0.133	1319.266	0.536	79.019
9	-2.493	1786.314	0.419	14.741

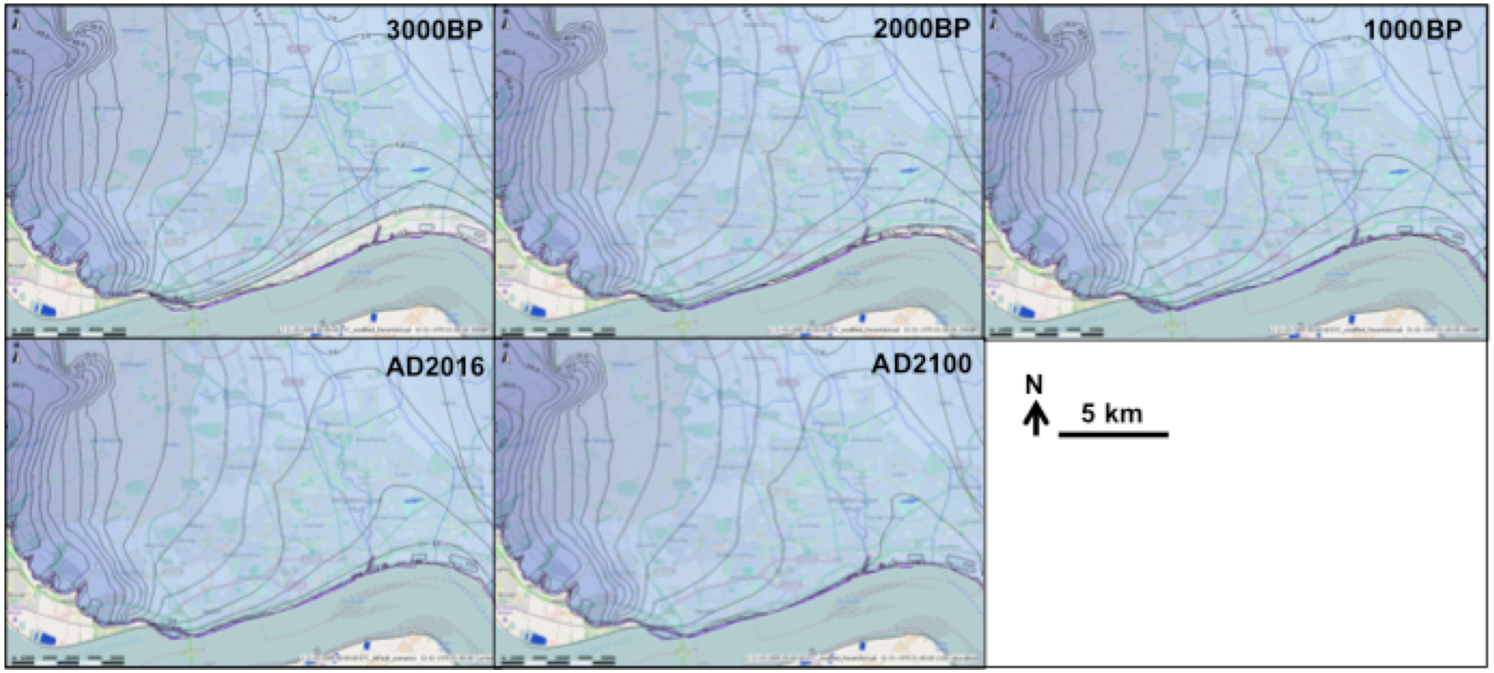


Figure 9.3 Chalk groundwater head contour maps of the Springhead area under naturalised scenarios (scenarios 1-4 and 7).

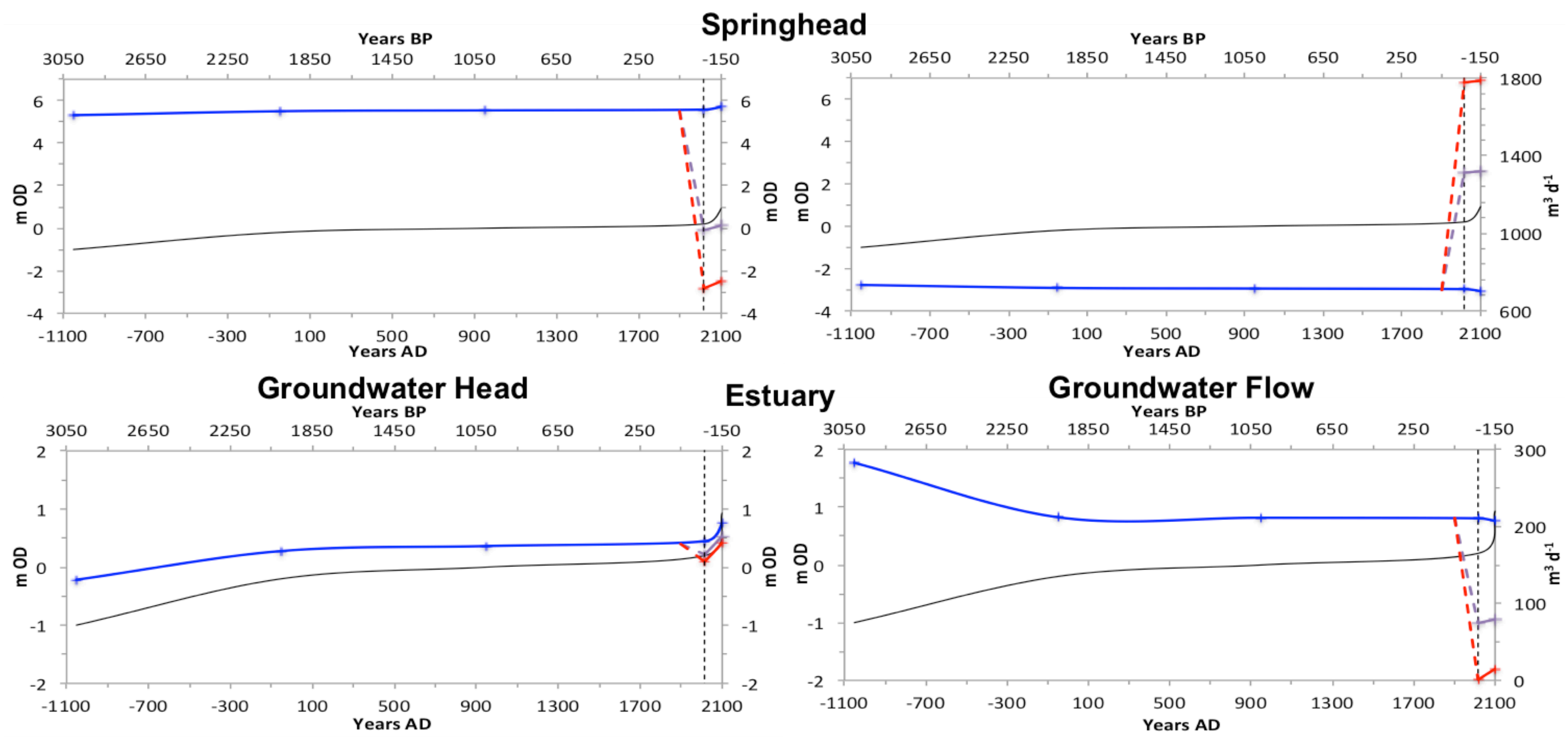


Figure 9.4 Groundwater head and flow results at Springhead and estuary boundary; blue = naturalised, purple = recent actual, red = fully licensed, black line = relative sea level, dashed black line = approximate start of abstraction at Springhead.

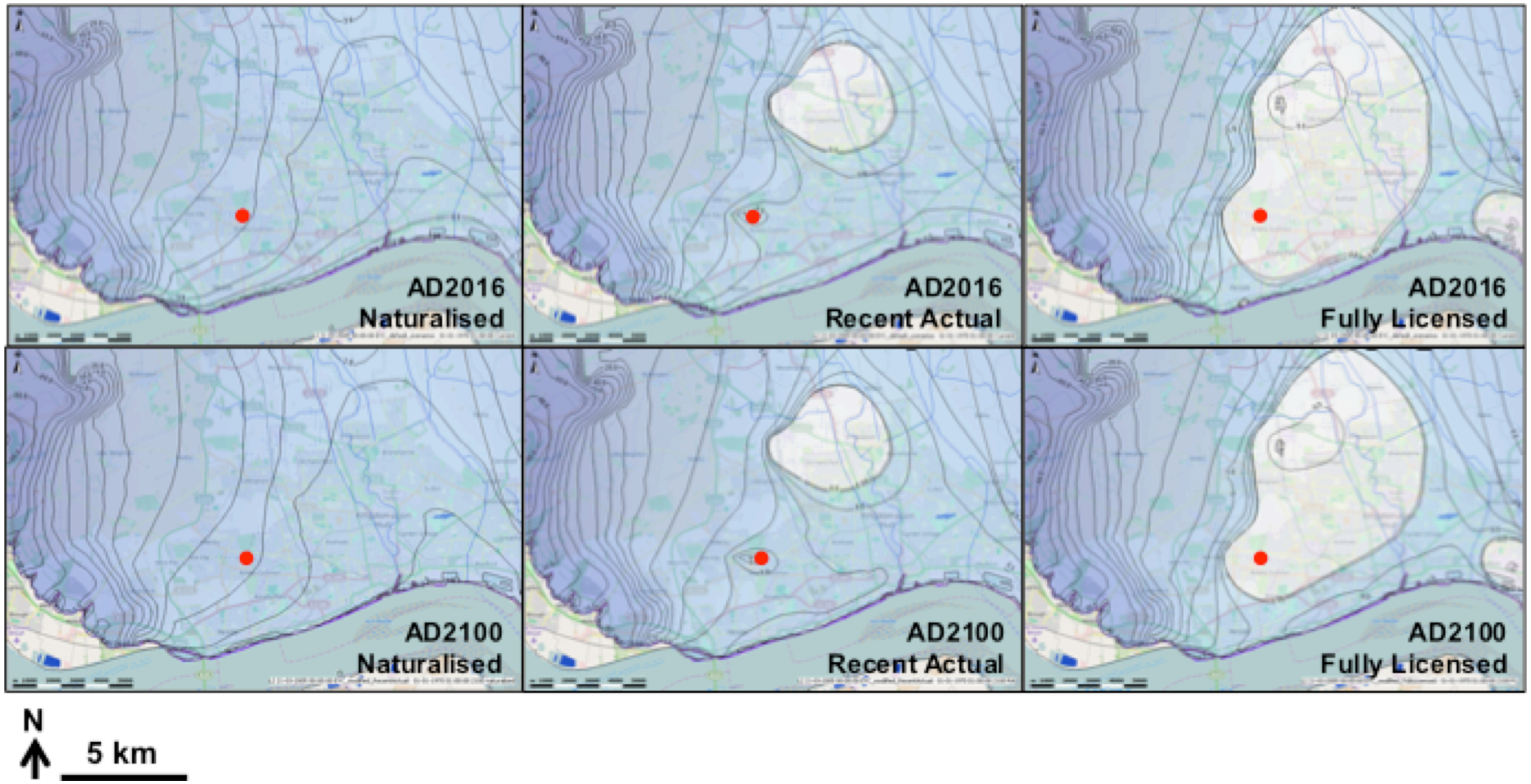


Figure 9.5 Chalk groundwater head contour maps of the Springhead area in the present and future scenarios (scenarios 4-9). Red dot denotes Springhead location.

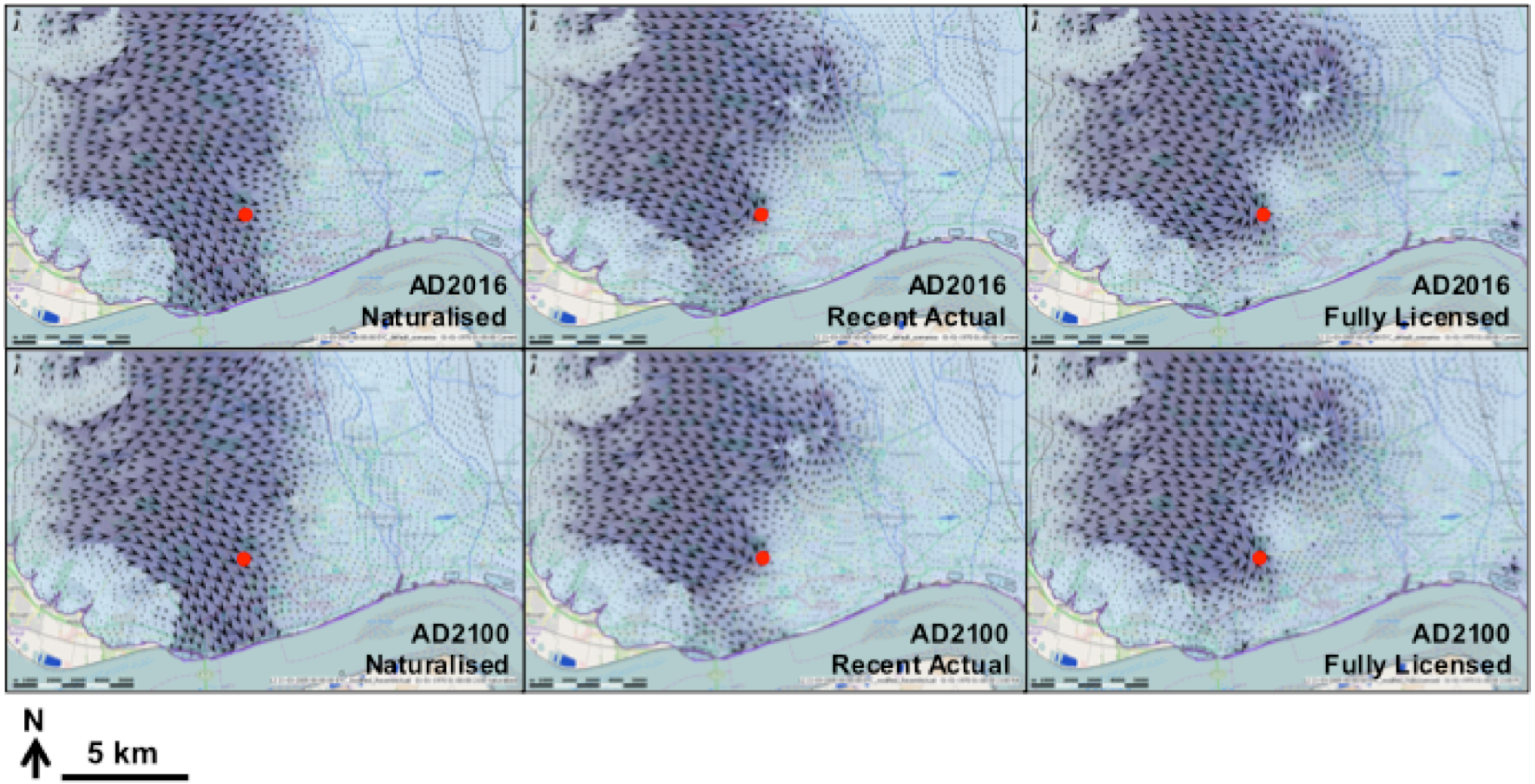


Figure 9.6 Chalk flow vector maps of the Springhead area in the present and future scenarios (scenarios 4-9). Red dot denotes Springhead location.

Table 9.3 Ghyben-Herzberg relationship results at Springhead and the estuary boundary for each of the scenarios outlined in Tables 9.1 & 9.2. *h*= height of fresh groundwater above sea level, *z*= depth of freshwater below sea level assuming *z*=40*h*.

Scenario	Sea Level (m OD)	Groundwater Head (m OD)	*h* (m)	*z* (m)	Saline Water Depth (m OD)
Springhead					
1	-1	5.307	6.307	252.28	-253.28
2	-0.2	5.501	5.701	228.04	-228.24
3	0	5.54	5.54	221.6	-221.6
4	0.2	5.577	5.377	215.08	-214.88
5	0.2	-0.108	-0.308	-12.32	N/A
6	0.2	-2.835	-3.035	-121.4	N/A
7	0.93	5.715	4.785	191.4	-190.47
8	0.93	0.133	-0.797	-31.88	N/A
9	0.93	-2.493	-3.423	-136.92	N/A
Estuary					
1	-1	-0.217	0.783	31.32	-32.32
2	-0.2	0.277	0.477	19.08	-19.28
3	0	0.362	0.362	14.48	-14.48
4	0.2	0.447	0.247	9.88	-9.68
5	0.2	0.214	0.014	0.56	-0.36
6	0.2	0.087	-0.113	-4.52	N/A
7	0.93	0.756	-0.174	-6.96	N/A
8	0.93	0.536	-0.394	-15.76	N/A
9	0.93	0.419	-0.511	-20.44	N/A

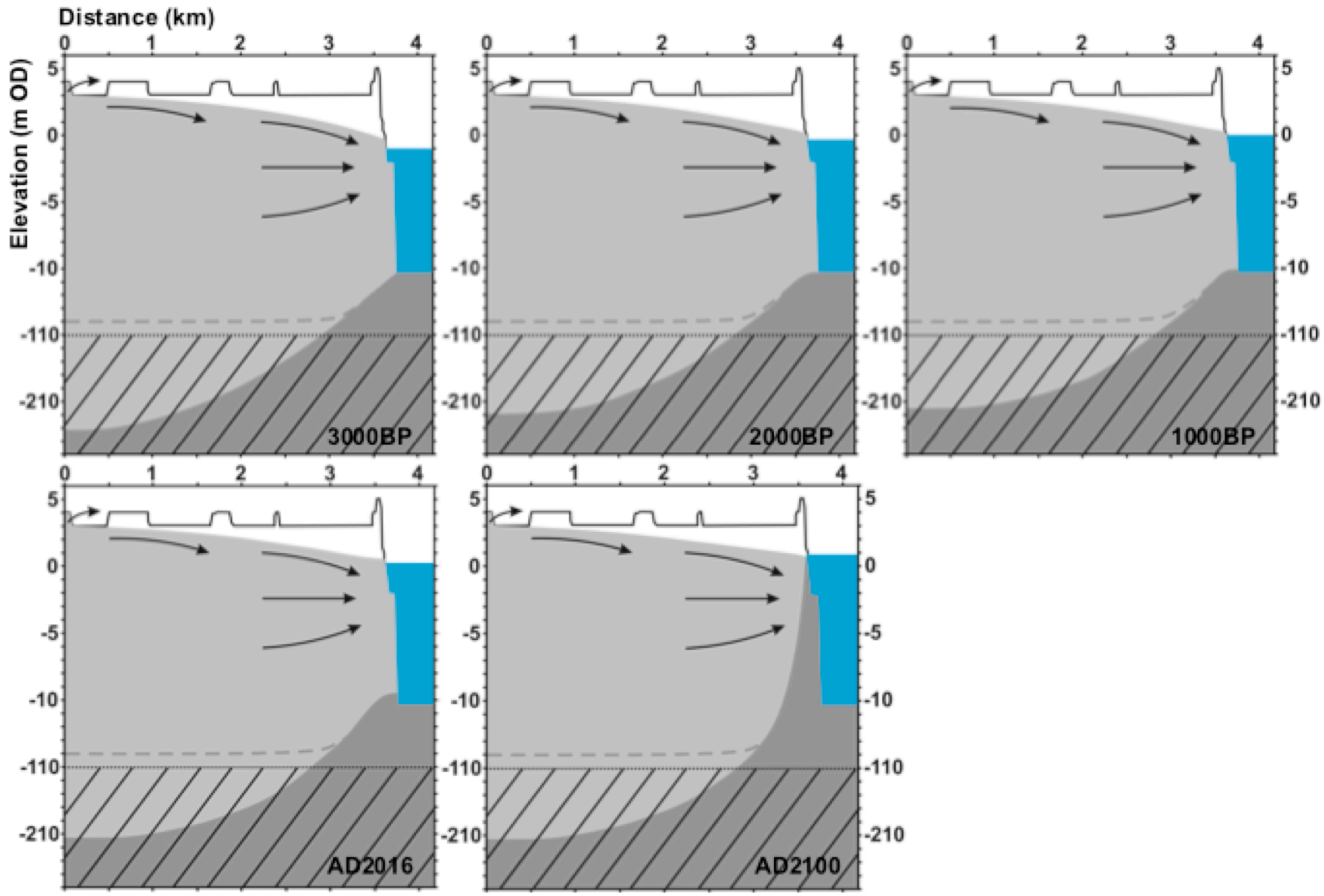


Figure 9.7 Cross-sections representing the results of the naturalised scenarios (scenarios 1-4 and 7) between Springhead and the Humber Estuary. Light grey= freshwater, dark grey= saline water. Arrows= direction of groundwater flow. Hatched area= below approximate base of Chalk aquifer; dashed line= potential pathway and layer of saline water at base of chalk.

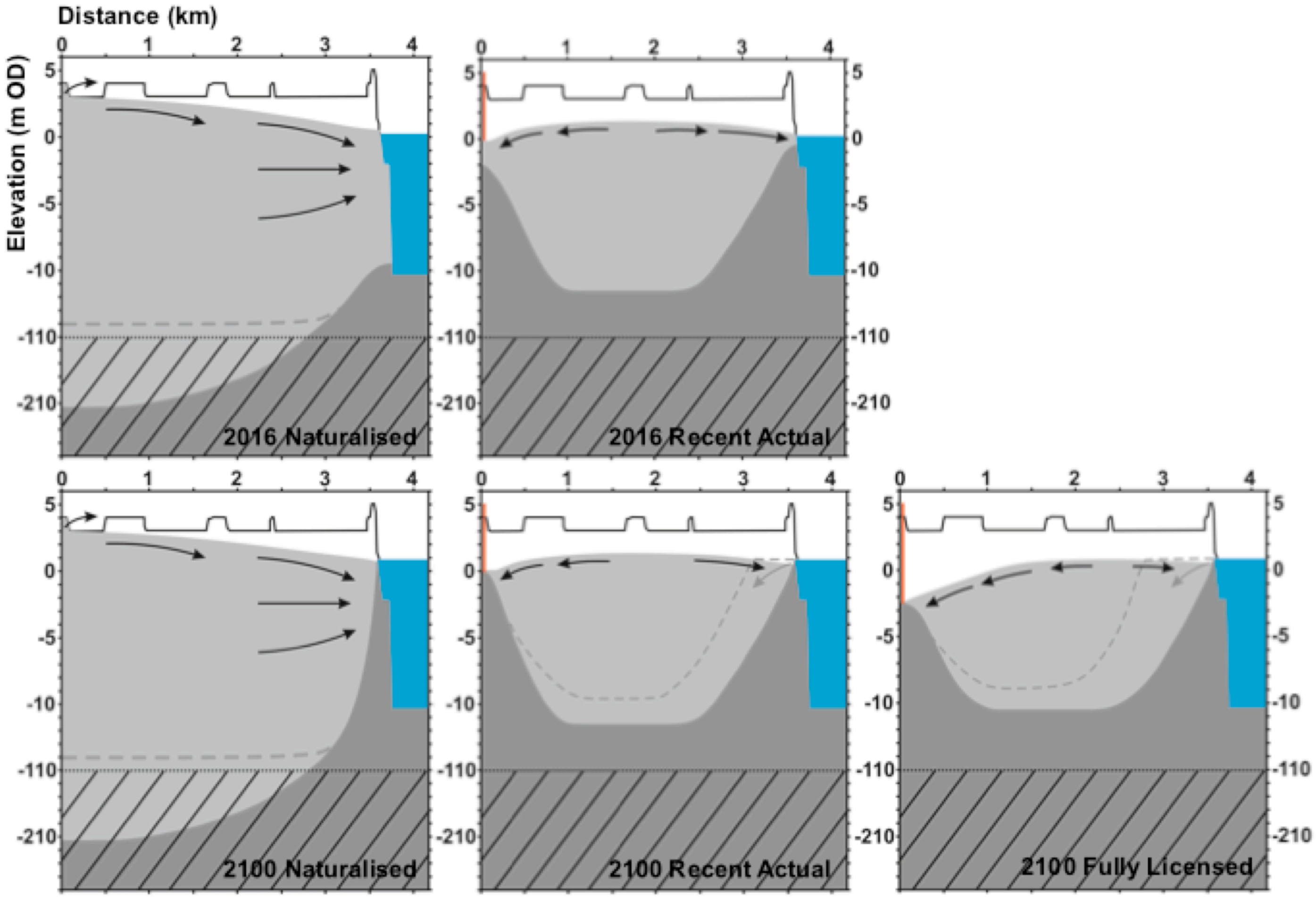
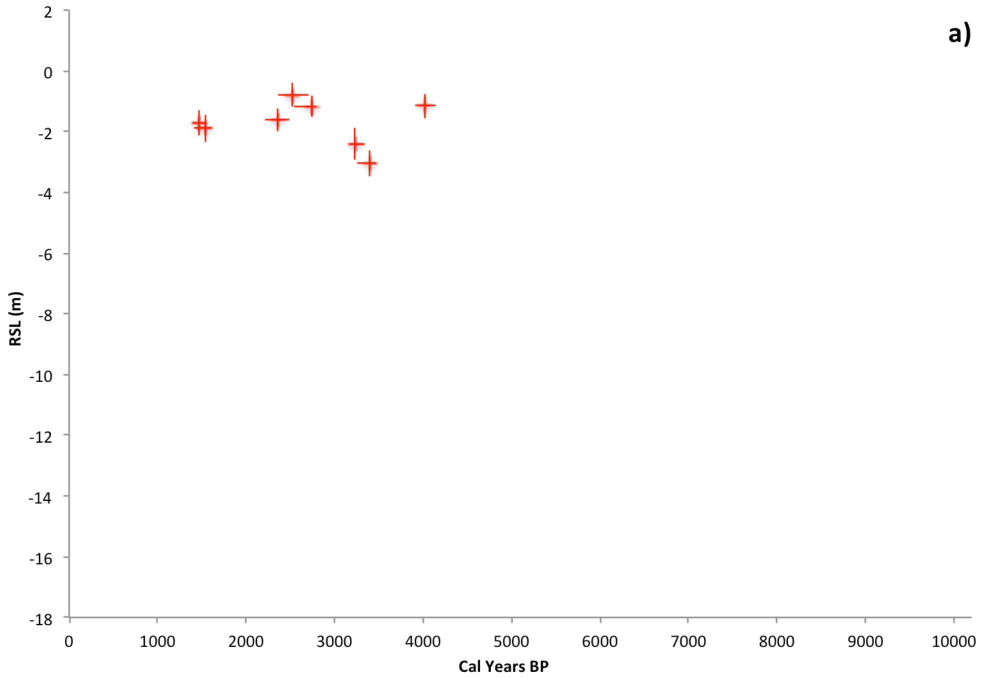


Figure 9.8 Cross-sections representing the results of some of the present and future scenarios (scenarios 3-4 and 7-9) between Springhead and the Humber Estuary. Light grey= freshwater, dark grey= saline water. Arrows= direction of groundwater flow. Hatched area= below approximate base of Chalk aquifer; dashed line= potential pathway and layer of saline water at base of chalk. Red line= Springhead location.

10. Discussion



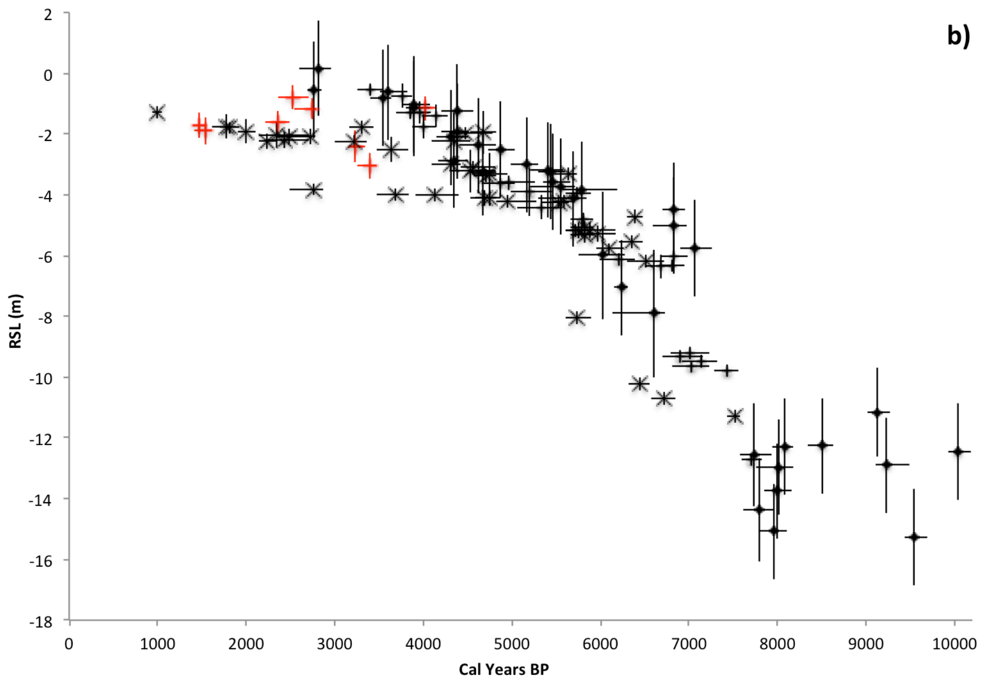


Figure 10.1 New and existing sea-level index points for the Humber Estuary: a) eight new sea-level index points produced in this thesis (Chapters 7 and 8), and b) new sea-level index points with the existing data from estuary. Red= this study; black= existing data (diamonds= limiting points; crosses= intercalated points; plus= basal points).