Holocene sea-level history and coastal evolution of the north-western Fenland, eastern England

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Key words: Sea-level change, coastline changes, foraminifera, sediment supply, Late Quaternary.

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Abstract

Holocene relative sea-level reconstructions reveal spatial and temporal patterns, indicating the importance of regional- to local-scale processes for understanding coastal evolution. We reconstruct the Holocene sea-level history and coastal evolution of the north-western Fenland using detailed analyses of lithostratigraphy, microfossil (foraminifera and pollen) assemblages and a suite of 18 radiocarbon dates. We illustrate the balance between sea-level change, sedimentary palaeoenvironment and coastline movements. An initial transgression occurred *c*. 7700 cal. BP as sea level rose around 8 mm/yr, reaching its maximum inland extent *c*. 4150 cal. BP. As the rate of sea-level rise reduced to less than 2 mm/yr, a series of local regressive and transgressive phases followed. A regional transgressive event inundated much of the area after *c*. 2600 cal. BP. Salt marsh peat and intertidal mud dominate inland sequences whereas further seawards, intertidal and subtidal nearshore sand occur, comparable with modern sediments of the adjacent Wash embayment. The north-western Fenland sequence shows similarities with sequences in southern Fenland and The Wash, indicating some regional sea-level control.

Key words: Sea-level change, coastline changes, foraminifera, sediment supply, Late Quaternary.

1. Introduction

The reconstruction of relative sea level (RSL) during the Holocene provides an understanding of the forcing mechanisms of sea-level change (e.g. Mitrovia and Milne, 2002) and a context within which to frame the recent sea-level acceleration (e.g. Shennan *et al*., 2009). Holocene RSL data can identify regional variations (e.g. Engelhart *et al*., 2009) and constrain geophysical models of glacial isostatic adjustment (GIA) (Peltier, 2002; Mitrovica, 2003; Milne and Peros, 2013; Lambeck *et al*., 2014). GIA from the British Isles ice sheet produced contrasting patterns in RSL across the United Kingdom during the Holocene (Shennan and Horton, 2002; Bradley *et al*., 2011). RSL records from locations situated closer to the centre of the ice sheet in Scotland display a mid-Holocene highstand associated with isostatic rebound (Smith *et al*., 2012), while records in southern and eastern England show Holocene RSL rise associated with subsidence of the proglacial forebulge (Shennan *et al*., 2009).

The Fenland of eastern England is an extensive area of Holocene sediments (Smith *et al*., 2010). It is a low coastal plain underlain by a sequence of marine-brackish sediments and peat which have accumulated during the post-glacial transgression (Skertchly, 1877; Godwin, 1940; Horton, 1989; Brew *et al*., 2000; Smith *et al*., 2010). The north-western Fenland, which forms the subject of this paper, extends along the Lincolnshire coast adjacent to The Wash (Figure 1). Except for the work of Waller *et al*. (1994), the Holocene sedimentary history of this region is unknown, which limits the interpretation of the driving mechanisms of Holocene RSL dynamics in the Fenland. Previous studies of RSL changes in the Fenland (e.g. Shennan, 1986a, b; Waller, 1994; Shennan and Horton, 2002) and comparisons with GIA models (e.g. Lambeck, 1995; Shennan *et al*., 2000a, b; Shennan *et al*., 2006, 2012) showed that the area experienced a general trend of rising RSL throughout the Holocene. Deviations from this general trend may explain some of the major horizontal shifts in coastal palaeoenvironments, but differences in the configuration of the underlying pre-Holocene surface, sedimentary processes and geomorphology are also important. The combination of all these factors resulted in variations in the Holocene evolution of various parts, usually because of the presence of different topographic depressions or basins open to the sea, in the pre-Holocene surface (Shennan, 1986b; Waller, 1994). Although it is a large area, there is no unequivocal evidence for differential isostatic rebound within the Fenland (French and Pryor, 1993). This conclusion is qualified by the resolution of the RSL data compared to the likely effects of differential rebound (Shennan *et al*., 2000a, b). Thick sequences of Holocene sediments result in sediment consolidation, the effects of which, help to explain some of the aberrant points in the full dataset of Fenland sea-level index points.

This paper presents new Holocene RSL data obtained from changes in lithology between terrestrial and marine sediments (transgressive and regressive contacts) from a series of cores located between the Rivers Witham and Steeping, north-western Fenland (Figure 1). These lithostratigraphic changes are supported by microfossils (foraminifera and pollen), which are used to delineate the initiation or removal of brackish and marine conditions and, verify that the contacts are conformable (Tooley, 1985; Shennan, 1986a). We produce 18 new sea-level index points that show rates of RSL change were highest during the early Holocene and have decreased over time, due to the continued response of the Earth to GIA and the reduction of ice equivalent meltwater input. We compare our results from north-western Fenland with analysis of sea-level data and palaeoenvironmental studies from the east coast of England to identify regional scale variability.

2. Setting

The Fenland covers areas of Lincolnshire, Cambridgeshire, north Norfolk and parts of Suffolk in the United Kingdom. The area is low-lying (generally less than +3 m OD) and is bounded to the north-west by uplands composed of Cretaceous rocks, flanked by Pleistocene sediments (Waller, 1994; British Geological Survey, 1995, 1996, 1997) and to the west by a ridge of morainic sediments known as the Stickney Moraine (Straw and Clayton, 1979) (Figure 1). The pre-Holocene surface is irregular and comprised mostly of Jurassic clays, overlain by Pleistocene tills, sands and gravels (Wyatt, 1984) and the heterogeneous sandy clays of the Crowland Beds (Brew *et al*., 2000; Smith *et al*., 2010). The local Pleistocene basement is an undulating surface of till which has a series of depressions or basins which open seawards. The overlying Holocene sediments cover approximately 4,000 km^2 and are up to 30 m thick (Smith *et al*., 2010). However, in places, particularly near Wrangle and Fishtoft, the till outcrops at the surface without any overlying Holocene sediments (Lane, 1993). Where present, the Holocene sediment comprises freshwater peat, silici-clastic salt marsh, intertidal mudflat and sandflat deposits and subtidal nearshore sands, showing evidence of a complex palaeoenvironmental history (Skertchly, 1877; Godwin, 1940; Horton, 1989; Waller, 1994; Simmons, 2013).

Robson (1985) divided the area of the north-western Fenland inland of the present artificial coastline (an embankment for sea defence), into four provinces. From seaward to landward, these are the Marshes, Tofts, Low Grounds and East Fen (Figure 1). The Tofts is a low but distinct ridge (the origin of which is debated), 12 km long and 1 km wide, which is elevated up to 4 m above the surrounding Fenland. The Marshes which lie to seaward of the Tofts were formed by a series of seaward-progressing land claims that began in Roman times and became extensive in the 17th century (Darby, 1940; Robson, 1985). Seaward of the reclaimed Marshes are the modern salt marshes and intertidal flats (Figure 1).

3. Methods

Cores used to obtain reliable sea-level index points are located in the Marshes, Low Grounds and East Fen, and these data and associated palaeoenvironmental information are the focus of this paper. The new data, additional to those described by Waller (1994), comprise five cores (F1, F2, F3A, F4 and F5) taken as part of the NERC Land-Ocean Interaction Study (LOIS), and various sections exposed during land drainage work (Baker's Bridge and Butterwick Ings, C1 and D5) (Figure 1). The drilling technique was based upon a typical shell and auger rig, but utilising a marine vibrocore barrel. Core recovery was very good, in most cases being virtually 100%. Most holes were cased with steel tubing after removal of the core barrel and the hole then cleaned to the depth of penetration ready for the next 1 m core barrel. Additional borehole records, archived at the National Geoscience Records Centre, British Geological Survey (BGS), were also used to expand the general stratigraphy away from the LOIS cores.

Cores were logged according to a protocol (Ridgway *et al*., 1998, 2000) to ensure a degree of consistency between logs recorded by different workers. To provide an initial assessment and suggest whether the influence of sediment consolidation is significant we have separated basal peats from other index points (Shennan *et al*., 2000a, b; Horton and Shennan, 2009). Basal peats are thought to be compaction-free, because the underlying substrates (e.g. Pleistocene sediment) are typically assumed to be unaffected by compaction. The tops of all cores were levelled to Ordnance Datum (OD) to provide standard elevations against which stratigraphic horizons and sea-level index points could be referenced. The elevation of the ground level at core sites was determined using a total station levelling system.

Holocene palaeoenvironments were reconstructed using microfossil (foraminifera and pollen) assemblages. We sampled for foraminifera and pollen at regular intervals with more frequent sampling at stratigraphical contacts. The use of foraminifera has become increasingly important in sea-level studies, because the well-defined foraminiferal zones that subdivide the intertidal zone enhance the identification of fossil marsh deposits, providing accurate indicators of former sea level during the Holocene (e.g. Horton and Edwards, 2006). Scott and Medioli (1978) stated that assemblages of salt marsh foraminifera are the most accurate sea-level indicators on temperate coastlines and that such assemblages exhibit a strong correlation with elevation with respect to the tidal frame. Furthermore, the assemblages are well preserved, easily detectable in fossil deposits and occur in high numbers (100 to 200 per cm^3), thereby providing a good statistical base for palaeoenvironmental interpretations. The foraminiferal assemblages were subdivided into two groups: firstly, an agglutinated assemblage that is restricted to the vegetated marsh; secondly, a calcareous assemblage that dominates the mudflats and sandflats of the intertidal zone (Horton and Edwards, 2006). Sample preparation, identification and classification of foraminifera followed Horton and Edwards (2006). Wet counts were completed under a binocular microscope. A minimum of 200 foraminifera were counted per sample where possible and they are expressed as relative abundances.

The analysis of fossil pollen and spore assemblages is a sensitive technique for the reconstruction of past plant communities (Moore *et al*., 1991), sea-level history and coastal zone palaeogeography (e.g. Waller, 1998; Long *et al*., 1998). The primary use of pollen analysis within this study has been to assign the organic units within sediment cores to depositional wetland environments in order to reconstruct the palaeogeography of the coastal zone. Pollen preparation and identification in this study followed the standard procedures outlined in Moore *et al*. (1991). Pollen was grouped into five broad physiognomic categories: trees, shrubs, herbs, aquatics and pteridophytes. Calculation of individual taxa is expressed as a percentage of the total sum of land pollen.

Radiocarbon dating of 18 samples provides an independent chronological framework (Table 1). Most samples comprised bulk organic material and were selected to date key stratigraphic changes in sediment columns, following the validation of the sample's importance by biostratigraphic analyses. Organic/clastic contacts validated as sea-level index points were a priority. Calibration of radiocarbon dates followed Stuiver and Reimer (1993).

4. Results

A systematic description of the Holocene stratigraphy of each of Robson's (1985) provinces is presented, followed by a synthesis of the evolution of the north-western Fenland and the establishment of regional correlations for the east coast of England. A series of cores along the modern coast, behind the sea embankment between Wrangle Lowgate and Gibraltar Point recovered Holocene deposits underlying the seaward part of the Marshes (Figure 1). The stratigraphy of East Fen, which lies between the Low Grounds and the Pleistocene deposits of the Fenland edge, between Midville, Eastville and Lade Bank was investigated by Waller *et al*. (1994). Additional data for East Fen have been derived for this study from core F3A (Figure 1).

4.1 Wrangle Lowgate, Marshes

Core F5 describes the Holocene sequence at Wrangle Lowgate. The Holocene sediments rest on a weathered till surface at -9.86 m OD and comprise a basal peat overlain by less than a metre of laminated clay (with numerous *Hydrobia* spp.), followed, with a sharp contact, by 13 m of fine to very fine sand (Figure 2). Foraminifera from the basal peat are dominated by *Jadammina macrescens* with subordinate *Trochammina inflata*, indicating deposition in a salt marsh environment (Figure 2). The base of the peat between -9.84 m and -9.85 m OD has a date of 7540-7791 cal. BP (AA-22366) and towards the top of the peat at its transition with the overlying clay, between -9.70 m and -9.71 m OD, has a date of 7558-7898 cal. BP (AA-22365) (Figure 2 and Table 1).

Foraminifera from the overlying laminated clay indicate alternating intertidal mudflat and salt marsh conditions prevailed during deposition (Figure 2). Inspection of the contact between the laminated clay and the overlying sand (at -9.25 m OD in core F5) suggests that it is erosional. Foraminiferal assemblages from the sands are diverse and consist of mainly *Haynesina germanica*, *Ammonia beccarii*, *Buccella frigida*, *Cibicides lobatulus*, *Elphidium excavatum*, *Haynesina depressula* and planktonic forms (Figure 2). The foraminiferal data suggest that the sand unit was deposited in either subtidal nearshore or open intertidal sandflat settings. This sand unit is capped by silts of the now reclaimed marsh and mudflat deposits.

4.2 Friskney to Gibraltar Point, Marshes

The sand unit with the erosive base at Wrangle Lowgate is laterally continuous beneath the Marshes north-eastwards towards Gibraltar Point, but with some variations. Near the coast south-east of Wainfleet (e.g. core F2, Figure 1), the basal Holocene unit comprises less than a metre of shelly, gravelly fine to medium sand resting on a till or bedrock surface at about -12.5 m OD. This unit is overlain by 14 m of very fine sand. In boreholes near the mouth of the River Steeping at Gibraltar Point (Figure 1), the sand unit is about 6 m thick and overlain by up to 5 m of sand and gravel (interpreted as channel deposits of an ancient River Steeping or older open coastal ridges of a similar composition, as seen today at Gibraltar Point).

The sand body beneath the Marshes (and Tofts, Brew and Evans, unpublished data) was probably deposited in intertidal and subtidal nearshore areas adjacent to The Wash. The westward or north-westward extension of these environments as the Holocene transgression proceeded caused erosion of the older salt marsh and mudflat deposits beneath the Marshes and subsequent burial by these sands. The latest phase appears from borehole evidence to have been progradation to seaward, as the sand is overlain by upper intertidal mudflat and salt marsh deposits. Indeed, the modern salt marshes on the western side of The Wash are still extending south-eastwards (Pye, 1995).

4.3 Wainfleet, Low Grounds

The Holocene sequence of the Low Grounds is recorded in a transect adjacent to the modern River Steeping, north-west of Wainfleet (Figure 1). The sequence rests on a surface of till or sand and gravel deepening from -2.5 m OD in the north-west to more than -6 m OD in the south-east (Figure 3). It generally comprises a basal peat (absent in most holes) overlain, in turn, by silty clay and clayey silt, intercalated peat (just below OD), and is capped by silty clay.

Stratigraphic details of the sequence are described using core F1 (Figure 4). Between the basal peat (which was not recovered *in situ*) and the intercalated peat are 2.9 m of silty clay overlain by 1.6 m of clayey silt. Foraminifera from the silty clay record three transgressive phases interspersed with two regressive phases. The base of the silty clay is dominated by a *Trochammina inflata*, *Jadammina macrescens*, *Arenoparrella mexicana* assemblage, indicating a salt marsh depositional environment, followed by assemblages dominated by *Haynesina* *germanica* with subordinate *Ammonia beccarii*, *Elphidium excavatum* and *Elphidium williamsoni* suggesting an intertidal mudflat. These assemblages record the initial transgressive phase on top of the basal peat. The upper foraminiferal assemblages indicate a reversion to salt marsh conditions and the initial regressive phase, followed by a return to intertidal mudflat conditions representing the second transgressive phase. A phase of salt marsh deposition marks the second regressive phase followed by the third transgressive phase, and development of a low energy intertidal mudflat environment (Figure 4).

The overlying unit of clayey silt is barren of foraminifera (and diatoms) and, without adequate microfaunal control, it is difficult to interpret the environment of deposition. However, pollen assemblages from the base of the overlying intercalated peat indicate a salt marsh environment, with *Artemisia* and high frequencies of Chenopodiaceae (Figure 5). Very high alder values suggest eutrophic alder carr and freshwater environments nearby. The upper part of the peat contains pollen which indicates acid, probably bog, environments, with *Calluna* frequencies reaching almost 50% of total land pollen, low percentages of *Sphagnum* moss and some open grassland and disturbed habitat taxa including *Plantago lanceolata*, *Rumex* and *Pteridium*. A further silty clay overlies the peat with an erosional contact. The regressive contact at the base of the peat (between –0.10 m and –0.11m OD) has a date of 2870-3248 cal. BP (AA-26355) (Figure 4 and Table 1). The basal regressive contact of a peat in a similar stratigraphic position, near Wainfleet, was dated at 3473-3839 cal. BP (Q-2807). The upper transgressive contact of the peat was dated at 2334-2751 cal. BP (Q-2805) (Waller *et al*., 1994).

4.4 Friskney, Low Grounds

The evolution of the Low Grounds landward of the Tofts at Friskney was investigated using core F4 (Figure 1). The Holocene sequence rests on till (at -2.71 m OD) and comprises thin basal units of clayey silt overlain by silty clay and laminated peat, followed in turn by 1.75 m of silty clay, 0.2 m of interlaminated silt and very fine sand and a further 1.2 m of silty clay (Figure 6). The base of the laminated peat (between -2.58 m and -2.59 m OD) has a date of 5311-5596 cal. BP (AA-26374) and the top (between -2.50 m and -2.51 m OD) has a date of 4864-5445 cal. BP (AA-26373) (Table 1).

The lowermost Holocene units (including the peat) contain foraminifera characteristic of salt marsh environments (mainly *Jadammina macrescens* and *Trochammina inflata*) (Figure 6) indicating the onset of an initial transgressive phase. Higher in the sequence, salt marsh foraminifera give way to *Ammonia beccarii*, *Haynesina germanica* and *Elphidium williamsoni* indicating an open intertidal mudflat environment and continuation of the transgressive phase. This transgressive phase was followed by a regressive phase with a return to salt marsh conditions (Figure 6).

The unit of interlaminated silt and very fine sand is barren of foraminifera but contains a diatom assemblage indicating marine conditions (unpublished data). This unit is interpreted as the infill of a small tidal creek. The topmost silty clay is also barren of foraminifera but diatoms indicate brackish conditions (unpublished data). The absence of foraminifera may be due to decalcification.

Waller *et al*. (1994) found a Holocene sequence at Small End, Friskney (Figure 1) similar to that in F4, apart from the presence of a split intercalated peat at about OD. The intercalated peat is split by marine-brackish clay indicating that two regressive phases separated by a transgressive phase occurred, which are not recorded in F4. A split intercalated peat may have been present formerly in F4 but was cut out by erosion, followed by deposition of the tidal creek silts. Waller *et al*. (1994) dated the intercalated peat boundaries (Table 1): the regressive contact of the lower intercalated peat was dated at 3367-3621 cal. BP (Q-2828); the transgressive contact at 3214-3462 cal. BP (Q-2827); the regressive contact of the upper intercalated peat at 2750-2952 cal. BP (Q-2826); and the transgressive contact at 2320-2713 cal. BP (Q-2825).

4.5 Butterwick Ings to Baker's Bridge, Low Grounds

Between Butterwick Ings and Baker's Bridge (Figure 1), the till surface is overlain by a basal peat that grades upwards into slightly laminated clay and silt. Three cores record the diachronous development of the basal peat from around –4.5 m OD to above –1.7 m OD. At Butterwick Ings core C1 the radiocarbon dates and pollen assemblages (Figure 7), with Chenopodiaceae, Gramineae, *Spergularia* and *Artemisia,* indicate the destruction of mixed woodland by salt marsh peat developing on the till 6284-6416 cal. BP (SRR-4638) and overlain at 5993-6283 cal. BP (SRR-4637) by clay and silt. The transition from peat into clay and silt is interpreted as a transgressive contact between salt marsh and intertidal mudflat. Comparable pollen assemblages from Baker's Bridge (Figure 1) and the radiocarbon date, 5597-5842 cal. BP (SRR-4634) at the peat/mud boundary, show the diachroneity of this transgressive contact, here at –2.9 m OD (Table 1). This trend continues to at least –1.7 m OD at Butterwick Ings core D5 (Figure 1) where the change from salt marsh peat to intertidal mudflat is dated at 4873-5291 cal. BP (SRR-4635).

4.6 Midville to Lade Bank, East Fen

Between Midville and Lade Bank, the pre-Holocene surface (maximum elevation -1.3 m OD) is overlain by a basal peat grading upwards into marine-brackish silty clay and sandy silt with areas of laminated tidal creek sands (Waller *et al*., 1994). The transgressive contact of the basal peat at -2.19 m OD was dated at 4567-4973 cal. BP (Q-2543) (Table 1). The silici-clastic sediment is overlain by an intercalated peat overlain with a sharp contact, by silty clay and then a thin organic layer which is probably a buried soil. The regressive contact of the intercalated peat was dated at 3465-3829 cal. BP (Q-2564) and 3378-3690 cal. BP (Q-2562). The transgressive contact (possibly erosional and therefore not a sea-level index point) was dated at 3480-3180 cal. BP (Q-2563).

Core F3A recovered 5.8 m of interlaminated very fine sand, silty clay and clayey silt, interpreted as infill of a tidal creek, overlain by a thin clay and, in turn, with a sharp contact, by an intercalated peat and 0.8 m of silty clay. The intercalated peat (at –0.06 m to –0.07 m OD) is dated to 3219-3549 cal. BP (AA-26356) (Table 1). Pollen from the peat suggests a salt marsh environment, with high frequencies of Chenopodiaceae and lower percentages of *Artemisia, Spergularia*, *Plantago maritima* and *Aster*-type (Figure 8). High frequencies of *Typha angustifolia* and grass pollen occur, which are probably derived from local freshwater to brackish reed swamp habitats.

4.7 Midville, East Fen

Waller *et al*. (1994) described a Holocene section at Midville comprising a basal peat overlain by clay then a local upper (surface) peat, all resting on a pre-Holocene surface between -1.25 m and -0.25 m OD. The transgressive contact of the basal peat was dated at 3986-4415 cal. BP (Q-2525) and the regressive contact of the upper peat at 3214-3549 cal. BP (Q-2526) (Table 1).

5. Discussion

5.1 Relative sea-level changes

We used stratigraphical information supported by the microfossil indicators to produce 18 sea-level index points for north-western Fenland. The sea-level index points show the position of RSL in time and space. The age of an index point is obtained from radiocarbon dating of the sample (Table 1) and its associated calibrated age range. The elevation of an index point is estimated using the indicative meaning of a sample. The indicative meaning describes the vertical relationship between the local environment in which a sea-level indicator accumulated and a contemporaneous reference tide level (Shennan, 1986a; van de Plassche, 1986; Horton *et al*., 2000). It is defined in terms of the modern vertical range occupied by the sea-level indicator (the indicative range) measured relative to a given tide level (the reference water level) such as mean high water spring tide (MHWST). Shennan (1986a), Horton *et al*. (2000) and Shennan and Horton (2002) established the indicative meaning for litho- and biostratigraphical sequences commonly used to produce sea-level index points. However, if tidal range was greater in the past, the reference water level values would be greater and consequently RSL would be lower (Horton *et al*., 2013). Palaeotidal modelling, which applies former bathymetries and coastline configurations to give estimations of tide levels during the Holocene (e.g. Hinton, 1995; Shennan *et al*., 2000a, b, 2003), suggests changes in tidal range at the open coast of eastern England are relatively small. In contrast, within the large estuaries of the Humber and the Fenland, modelled tidal ranges are 20% to 40% smaller 3000 to 6000 cal. BP (Shennan and Horton, 2002), but these models do not include changes in sediment deposition or erosion (Shennan *et al*., 2003) and, thus we do not use such models in this paper.

The 18 sea-level index points (Table 1) show a general trend of rising sea level (Figure 9) comparable with those from the much larger dataset for the whole Fenland (Shennan and Horton, 2002). RSL reconstructions from regions in the UK peripheral to the British ice sheet exhibited variable rates of sea-level rise due to the balance between eustatic processes and the total isostatic effect of glacial rebound process including ice (glacio-isostatic) and water (hydro-isostatic) load contributions (e.g. Engelhart *et al*., 2011). The eustatic function is controlled by melting (or growth) of land-based ice (mass contribution) and ocean water density changes from temperature and salinity variations (steric contribution). Isostasy is the process whereby Earth's shape is modified in response to large-scale changes in surface mass load. Rates of RSL change were highest during the early Holocene and have decreased over time, due to the diminishing response of the Earth's mantle GIA, because the process takes the form of an exponential relaxation with a timescale on the order of several thousand years, and reduction of meltwater input that corresponds to the end of significant Laurentide Ice Sheet melting (Carlson *et al*., 2008).

The index point from core F5 in the Marshes forms part of a small dataset that records the earliest part of the transgression inland of the present coast between 8000 and 7500 cal. BP that indicate a rate of sea-level rise up to 8mm/yr. The later index points suggest that from 7500 to 4500 cal. BP the general trend averaged about 2.7mm/yr falling to around 1mm/yr over the last 4000 cal. years (Figure 9).

In the absence of the detailed lithological data needed for quantitative assessment of sediment compaction (e.g. Allen, 2000; Brain *et al*., 2014), subdivision of the index points into basal and intercalated peats provides an initial assessment of the influence of compaction (e.g. Shennan *et al*., 2000a, b; Horton and Shennan, 2009).The index points from the north-western Fenland generally lie in the upper section of the scatter of the whole dataset (Figure 9). Quantitative analysis of these data shows no statistically significant relationship that could indicate differential isostatic rebound, such as less subsidence for these northern sites (Shennan *et al*., 2000a, b). However, their analysis shows a statistically significant effect for sediment consolidation. Prior to 4000 cal. BP the index points from the north-western Fenland are mainly from thin basal peats that are likely to undergo lesser consolidation than from peat intercalated within thick sequences of silici-clastic sediments. Hence, they lie at the top of the scatter in this period. After 4000 cal. BP the index points from the north-western Fenland sites are also from intercalated peats and they now lie within the overall scatter.

5.2 Palaeoenvironmental history

The palaeoenvironmental history of the different provinces of the north-western Fenland allow further analysis of the relative importance of the different regional and local factors.

Prior to 7000 cal. BP

As relative sea level rose rapidly (up to 8mm/yr), the impaired drainage of Fenland rivers and a rising ground water table led to waterlogging of the land surface and resulted in the formation of a transgressive basal peat (Figures 10A and 11A) with the earliest date from core F5 (*c*. 7650 cal. BP). The deposition of intertidal muds below the present-day Marshes, at Wrangle Lowgate (Figures 2 and 10A) marked the onset of marine conditions. Offshore, in the area of the subtidal Wash, Brew (1997a) identified a marine flooding surface between 14 m and 19 m below mean present sea level. The surface was estimated to be pre-7000 ^{14}C BP in age, above which estuarine sediments were postulated to have been deposited. The area of the Tofts, Low Grounds and East Fen would have been above sea level during the early Holocene flooding of the Marshes (Figures 10A and 11A). Pollen from the basal peats (Waller *et al*., 1994) suggests that, prior to flooding, a wooded landscape with much lime was common in the area. This is also illustrated by the Butterwick Ings and Baker's Bridge sites as the transgression extended later on to higher ground (Figure 7).

7000-3800 cal. BP

Progressive waterlogging of the Tofts, Low Grounds and East Fen ground surface initiated a change from fen-woodland to reed swamp, then salt marsh conditions. Six dates from the transgressive contacts of the basal peat mark the inland progression of the marine incursion, at Butterwick Ings (*c*. 6200 and 5100 cal. BP), Baker's Bridge (*c*. 5650 cal. BP), Wrangle Bank, Friskney (*c*. 5200 cal. BP), Lade Bank (*c*. 4850 cal. BP, Waller *et al*., 1994) and Midville (*c*. 4200 cal. BP, Waller *et al*., 1994) (Figure 10). Apart from isolated till 'highs', most of the north-western Fenland would have been flooded by the latter date (Figures 10B and 11B). This marine episode deposited a silty clay-dominated wedge of intertidal mudflat and salt marsh sediments, cut by a series of tidal creeks (Lane, 1993). Further seawards, intertidal and subtidal nearshore sands migrated westwards (i.e. landward) in response to the extension of marine environments (with rising sea level) which caused erosion of the older salt marsh and intertidal mudflat sediments beneath the Marshes (as in F5) (Figure 10B).

Marine silt-clay deposition was replaced by peat accumulation around 3800 cal. BP, signalling the start of a freshwater phase (Figures 10C and 11C). Foraminiferal data from the silty clay units between the basal peat and intercalated peat suggest that different areas developed independently during the initial marine incursion and subsequent marine withdrawal. The different stratigraphic developments shown by the cores at Friskney and Wainfleet (Figures 4 and 6) suggest separate areas of deposition which may coincide with the two south-east-opening basins discussed by Waller (1988) and Waller *et al*. (1994); a southern basin centred around Wrangle-Friskney and a northern basin centred around Wainfleet. The presence of irregularities in the till surface (*cf*. the Lincolnshire Marsh, Brew, 1997b) or buried moraines would make such areas of separate development likely during the early phases of the Holocene transgression.

In the Wrangle-Friskney basin, salt marsh deposits which rest on the till surface are overlain by intertidal mudflat deposits (Figure 6), the latter formed probably at the same time as marine conditions reached their maximum inland extent (a little after *c*. 4200 cal. BP). After this 'transgressive maximum', the area was subject to a regressive phase resulting in formation of further salt marsh and marked by peat growth *c*. 3500 cal. BP (Figure 10C). By contrast, local changing conditions in the Wainfleet basin resulted in a more complicated history comprising three transgressive-regressive cycles represented by alternations of salt marsh and intertidal mudflat sediments, before the formation of peat *c*. 3650 cal. BP (Figures 4 and 11C). The different histories recorded in each of the basins are possibly related to differences in local rates of sediment supply or ease of access of marine waters due to the irregular morphology of the underlying till surface.

3800-2000 cal. BP

After *c*. 4000 cal. BP the rate of relative sea-level rise slowed to less than 2mm/yr (Figure 9), which coincides with the onset of intercalated peat formation in the north-western Fenland. With a constant supply of sediment and the slowing down of the rate of sea-level rise, the embayments of the north-western Fenland eventually silted-up leading to the accumulation of peat (Figures 10C and 11C). In the Wainfleet basin, accumulation of peat in the Low Grounds replaced silici-clastic deposition at about 3650 cal. BP. Pollen assemblages from the peat describe a salt marsh environment followed by freshwater bog (Figure 5). The accumulation of peat was replaced by clay deposition *c*. 2300 cal. BP, indicating the start of a marine episode, which extended into the Low Grounds (Figure 11D). The peat was partially eroded prior to deposition of the clay.

In the Wrangle-Friskney basin, intercalated peat growth (salt marsh then freshwater reed swamp and sedge fen, Waller *et al*., 1994) began *c*. 3500 cal. BP. This regressive phase was short-lived in the Low Grounds, being replaced by a transgressive phase and deposition of marine-brackish clays on top of the peat (partially eroded in places) at *c*. 3350 cal. BP. This transgressive phase was synchronous with the regressive phase in the Wainfleet basin, and the marine influence probably invaded from the south or south-west to reach as far inland as the southern edge of East Fen (Figure 10D). A period of increased erosion (or lowering of the rate of sediment supply) in the Wrangle-Friskney basin compared to the Wainfleet basin may explain the occurrence of synchronous regressive and transgressive episodes in adjacent areas. Most of East Fen became covered with peat *c*. 3500 cal. BP, and thereafter, a long-lasting freshwater fen (beyond the limit of any marine influence) became established maintained mainly by a high groundwater table (Lane 1993) (Figure 10D).

The transgressive phase in the Low Grounds of the Wrangle-Friskney basin ended with the development of another peat in a sedge fen, reed swamp and bog (Waller *et al*., 1994) and finally a buried soil *c*. 2800 cal. BP which marked the onset of another regressive phase (Figure 10D). This ended with deposition of marine-brackish clays *c*. 2350 cal. BP, coinciding with the marine incursion in the Wainfleet basin around 2300 cal. BP (Figures 10D and 11D). It would appear that about this time a regional marine phase began, inundating both the Wainfleet and Wrangle-Friskney basins (Simmons, 1978, 1980). Lane (1993) proposed that the marine waters entered the area from The Wash from the direction of the River Steeping and, in the Wrangle-Friskney basin, reached just inland of Wrangle. In contrast, Simmons (1978, 1980) placed the coastline further inland, almost at the present-day Fen edge, and interpreted the area north of Wrangle as a small island. The inland extent of marine influence postulated by Simmons (1978, 1980) is not supported by the new stratigraphic evidence which shows that the inland parts of the north-western Fenland was a freshwater fen from about 3500 cal. BP onwards.

2000 cal. BP-present

A further landward (i.e. westward) extension of the intertidal and subtidal areas of The Wash caused erosion of the underlying salt marsh and intertidal mudflat deposits beneath the Marshes and Tofts and buried them with intertidal and subtidal nearshore silts and sands, that had begun earlier in the Holocene (Figures 10D and 11D). The erosional surfaces of the Marshes and Low Grounds (outer part) may be coincident with similar surfaces recorded in the central part of The Wash (Brew, 1997a). Dates of peats below the marine sequence at Wainfleet Tofts define the timing of the erosion to post-2100 cal. BP (Brew and Evans, unpublished data). The landward edge of the Tofts marks the inland limit of the silt-sand deposition in this area (Figures 10D and 11D). The area landward of the Tofts was unaffected by this erosion and continued as salt marsh (inner Low Grounds) and freshwater fen (East Fen).

5.3 Regional correlations

The Holocene chronology of the southern Fenland is well established (Godwin and Clifford, 1938; Godwin, 1940; Godwin and Vishnu-Mittre, 1975; Shennan, 1986a, b; Waller, 1994;

Shennan *et al*., 2000a, b; Brew *et al*., 2000), whereas the chronologies of The Wash (Brew, 1997a), Lincolnshire Marsh (Brew, 1997b) and Humber Estuary (Long *et al*., 1998; Rees *et al*., 2000) are limited in their coverage, and correlations with the north-western Fenland sequences are difficult. Nevertheless, some general statements can be made regarding The Wash and Humber Estuary.

Southern Fenland

Waller (1994) suggested that positive sea-level tendencies dominated the Fenland for most of the Holocene, whereas most negative tendencies were merely local in nature. However, several brief periods of regional negative sea-level tendency were indicated, *c*. 3640-3360, *c*. 3170-2780 and *c*. 1710-1530 cal. BP. The first regional regressive phase correlates well with the beginning of a regressive phase which has been established across both the Wainfleet and Wrangle-Friskney basins of the north-western Fenland (*c*. 3650-3500 cal. BP). However, whereas the end of the regional phase correlates with the end of freshwater conditions in the Wrangle-Friskney basin (*c*. 3350 cal. BP), the dates from the Wainfleet basin suggest continuation of the regressive phase beyond 3360 cal. BP, to *c*. 2600-2100 cal. BP (Brew and Evans, unpublished data). Continuation of freshwater conditions in the Wainfleet basin appears to have more in common with the Lincolnshire Marsh sequence (unpublished data) rather than with the Fenland sequence. There is little evidence in the north-western Fenland for a response to the regional regressive phase recognised between 3170 and 2780 cal. BP. However, a later regressive phase was recorded in the Wrangle-Friskney basin *c*. 2800 to *c*. 2350 cal. BP. Unfortunately, chronological data from the period 1710 to 1530 cal. BP is lacking in the north-western Fenland.

The Wash

The Holocene sequence in the submarine parts of the central Wash reveals periods of widespread subtidal sandy sedimentation separated by periods of both local and regional erosion (Brew, 1997a). The earliest Holocene deposits preserved in The Wash were interpreted as estuarine. Brew (1997a) estimated that this initial marine influence would have reached the inner parts of The Wash before *c*. 7800 cal. BP. The preservation of these deposits is limited, as most of any other estuarine units were eroded as the shoreface migrated landward with the marine flooding. The supposed estuarine sediments in The Wash are considered to be similar in age to the early Holocene intertidal mudflat deposits recognised in core F5 below the seaward part of the Marshes, both having been deposited during the initial transgression into the area. A phase of sand bank deposition followed the erosion, only for the sediments to be largely removed by a phase of tidal scour, after which further deposition of large volumes of sand took place. The thick sands and silts preserved beneath the Marshes are interpreted as the intertidal equivalents of the submarine sands in The Wash.

Humber Estuary

Long *et al*. (1998) and Metcalfe *et al*. (2000) described the occurrence of positive and negative sea-level tendencies at a number of sites along the Humber Estuary. Parts of the estuary were inundated with marine waters before *c*. 7400 cal. BP. This initial inundation was followed by a general relative sea-level rise, punctuated by local regressive phases (*c*. 6730 and *c*. 4720 cal. BP), until *c*. 2700 cal. BP. After *c*. 2700 cal. BP a major regressive phase was proposed which began at different places between 2750 and 1990 cal. BP. Given the fragmented chronology of the Humber Estuary sequence (Long *et al*., 1998) it is difficult to establish reliable correlations with the north-western Fenland sequence.

6. Conclusions

Detailed analyses of lithostratigraphy, foraminiferal and pollen assemblages, and a suite of 18 radiocarbon dates have been used to reconstruct the Holocene history of sea-level and palaeoenvironmental evolution for the north-western Fenland between the Rivers Witham and Steeping, Lincolnshire. The area has been influenced by marine conditions since *c*. 7700 cal. BP after which a series of transgressive and regressive events took place in what appears to have been two basins centred on Wainfleet and Wrangle-Friskney. In the Wainfleet basin three transgressive-regressive cycles were recorded up to *c*. 3650 cal. BP, whereas, during the same time period in the Wrangle-Friskney basin, the initial transgressive event was followed by a single regressive event. Between *c*. 3650 and 2600 cal. BP a regressive event continued to affect the Wainfleet basin whereas in the Wrangle-Friskney basin the equivalent regressive event was punctuated by a short-lived transgressive episode between *c*. 3350 and 2800 cal. BP. Around 2600 cal. BP, a regional transgressive marine phase began which inundated both basins simultaneously.

Palaeoenvironments were dominated by salt marsh and intertidal mudflats in the inner parts of the area, whereas the outer parts were dominated by intertidal sandflat and subtidal nearshore sands. The sandy sequence of the Tofts ridge marks the landward edge of this wedge of sandy intertidal and subtidal deposits which at this location is dated post-2100 cal. BP (Brew and Evans, unpublished data).

This investigation shows that the influence of regional sea-level can be detected in the north-western Fenland sequences. However, it is clear that other factors, such as variations in rates of sediment supply, and erosion and deposition related to extension of the marine environments of The Wash throughout the Holocene, may have been the significant factors in controlling the overall evolution of the area.

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Table

Table 1. Sea-level index points from the north-western Fenland. Relative sea level (RSL) is calculated as elevation minus the reference water level (RWL). The RSL error range is calculated as the square root of the sum of squares of the elevation error, sample thickness, tide-level error, and indicative range. The indicative range (given as a maximum) is the most probable vertical range in which the sample occurs. Every index point has been age dated using radiocarbon techniques and calibrated to sidereal years with a 2σ confidence interval using the calibration programme 3.0.3 of Stuiver and Reimer (1993). MHWST = mean high water spring tides.

Site	Stratigraphical postion	Laboratory code	^{14}C age ± 1σ	Calibrated age			Elevation (m OD)	RWL (m OD)	RWL	Tendency	RSL (m) ± error
				Min	Med	Max					
Wrangle Lowgate, F5	Top basal peat	AA22365	6920 ± 75	7558	7682	7898	-9.70	3.15	MHWST 0.00	+	-12.85 ± 0.40
Butterwick Ings, C1	Top basal peat	SRR4637	5365 ±45	5993	6178	6283	-4.46	3.60	MHWST -0.20	+	-8.06 ± 0.20
Baker's Bridge	Top basal peat	SRR4634	4950 ±40	5597	5658	5842	-2.89	3.60	MHWST -0.20	+	-6.49 ± 0.21
Wrangle Bank, F4	Top basal peat	AA26373	4495 ±85	4864	5185	5445	-2.5	2.95	MHWST -0.20	+	-5.45 ± 0.20
Butterwick Ings, D5	Top basal peat	SRR4635	4465 ±45	4873	5122	5291	-1.67	3.60	MHWST -0.20	+	-5.27 ± 0.20
Lade Bank	Top basal peat	Q2543	4250 ±70	4567	4833	4973	-2.19	3.60	MHWST -0.20	+	-5.79 ± 0.20
Midville	Top basal peat	Q2525	3825 ±70	3986	4184	4415	-1	3.60	MHWST -0.20	+	-4.60 ± 0.20
Thorpe Culvert	Intercalated peat	Q2807	3425 ±70	3473	3664	3839	-0.14	3.68	MHWST 0.20	-	-3.82 ± 0.69
Hobhole B	Intercalated peat	Q2564	3390 ±70	3465	3629	3829	0.13	4.00	MHWST 0.20	-	-3.87 ± 0.20
Hobhole A	Intercalated peat	Q2562	3310 ±65	3378	3514	3690	-0.44	4.00	MHWST 0.20	-	-4.44 ± 0.20
Friskney	Intercalated peat	Q2828	3260 ±50	3367	3467	3621	-0.03	3.68	MHWST 0.20	-	-3.71 ± 0.68
Eastville, F3A	Intercalated peat	AA26356	3180 ±65	3219	3378	3549	-0.06	3.94	MHWST 0.40	-	-4.00 ± 0.81
Midville	Intercalated peat	Q2526	3170 ±70	3214	3373	3549	-0.19	4.00	MHWST 0.20	-	-4.19 ± 0.21
Friskney	Intercalated peat	Q2827	3135 ±50	3214	3356	3462	0.03	3.28	MHWST -0.20	+	-3.25 ± 0.68
Thorpe Culvert, F1	Intercalated peat	AA26355	2920 ±60	2870	3065	3248	-0.10	4.13	MHWST 0.20	-	-4.26 ± 0.20
Friskney	Intercalated peat	Q2826	2735 ±60	2750	2824	2952	0.27	3.68	MHWST 0.20	-	-3.40 ± 0.68
Thorpe Culvert	Intercalated peat	Q2805	2460 ±80	2334	2623	2751	0.23	3.28	MHWST -0.20	+	-3.05 ± 0.69
Friskney	Intercalated peat	Q2825	2385 ±60	2320	2353	2713	0.4	3.28	MHWST -0.20	+	-2.88 ± 0.68

Figure and table captions

Figure 1. Location of the core sites in the north-western Fenland. Unlabelled sites are borehole logs archived at the British Geological Survey. Limit of the Tofts (stippled) is modified from British Geological Survey (1996, 1997). Section C-D is shown in Figure 3. HWM=Mean High Water Mark. LWM=Mean Low Water Mark. Horizontal coordinate system is British National Grid square TF, 10 km intervals. The terms Marshes, Tofts, Low Grounds and East Fen are those used by Robson (1985) to differentiate provinces of the north-western Fenland.

Figure 2. Percentage foraminifera in core F5 and palaeoenvironmental interpretation. Location of core is shown in Figure 1. See Figure 3 for lithological key. SM = salt marsh, MF = mudflat.

Figure 3. Section of cores across the Low Grounds at Wainfleet. Location of section is shown in Figure 1. See Figure 3 for lithological key.

Figure 4. Percentage foraminifera in core F1 and palaeoenvironmental interpretation. Location of core is shown in Figure 1. See Figure 3 for lithological key. zc = silty clay, cz = clayey silt, SM = salt marsh, MF = mudflat.

Figure 5. Percentage pollen in the intercalated peat of core F1. Location of core is shown in Figure 1. See Figure 3 for lithological key.

Figure 6. Percentage foraminifera in core F4 and palaeoenvironmental interpretation. Location of core is shown in Figure 1. See Figure 3 for lithological key. SM = salt marsh, MF = mudflat, C = creek, Br = brackish.

Figure 7. Percentage pollen in the basal peat of Butterwick Ings core C1 and calibrated radiocarbon dates. Location of core is shown in Figure 1. See Figure 3 for lithological key.

Figure 8. Percentage pollen in the intercalated peat of core F3A. Location of core is shown in Figure 1. See Figure 3 for lithological key.

Figure 9. Sea-level index points for the Fenland. Grey crosses are previously published dates (Shennan *et al*., 2000). Black squares (top basal peats) and triangles (intercalated peats) are sea-level index points reported in this paper for north-western Fenland (Table 1).

Figure 10. North-west to south-east cross-sectional model across the ‘southern (Wrangle-Friskney) basin’ of the north-western Fenland to illustrate the postulated Holocene evolution at various time-slices. Caption A represents a snap-shot about 7300 cal. BP, B=3800 cal. BP, C=2600 cal. BP, D=2000 cal. BP and E represents the modern situation.

Figure 11. North-west to south-east cross-sectional model across the ‘northern (Wainfleet) basin’ of the north-western Fenland to illustrate the postulated Holocene evolution at various time-slices. Caption A represents a snap-shot about 7300 cal. BP, B=3800 cal. BP, C=2600 cal. BP, D=2000 cal. BP and E represents the modern situation.

Figure
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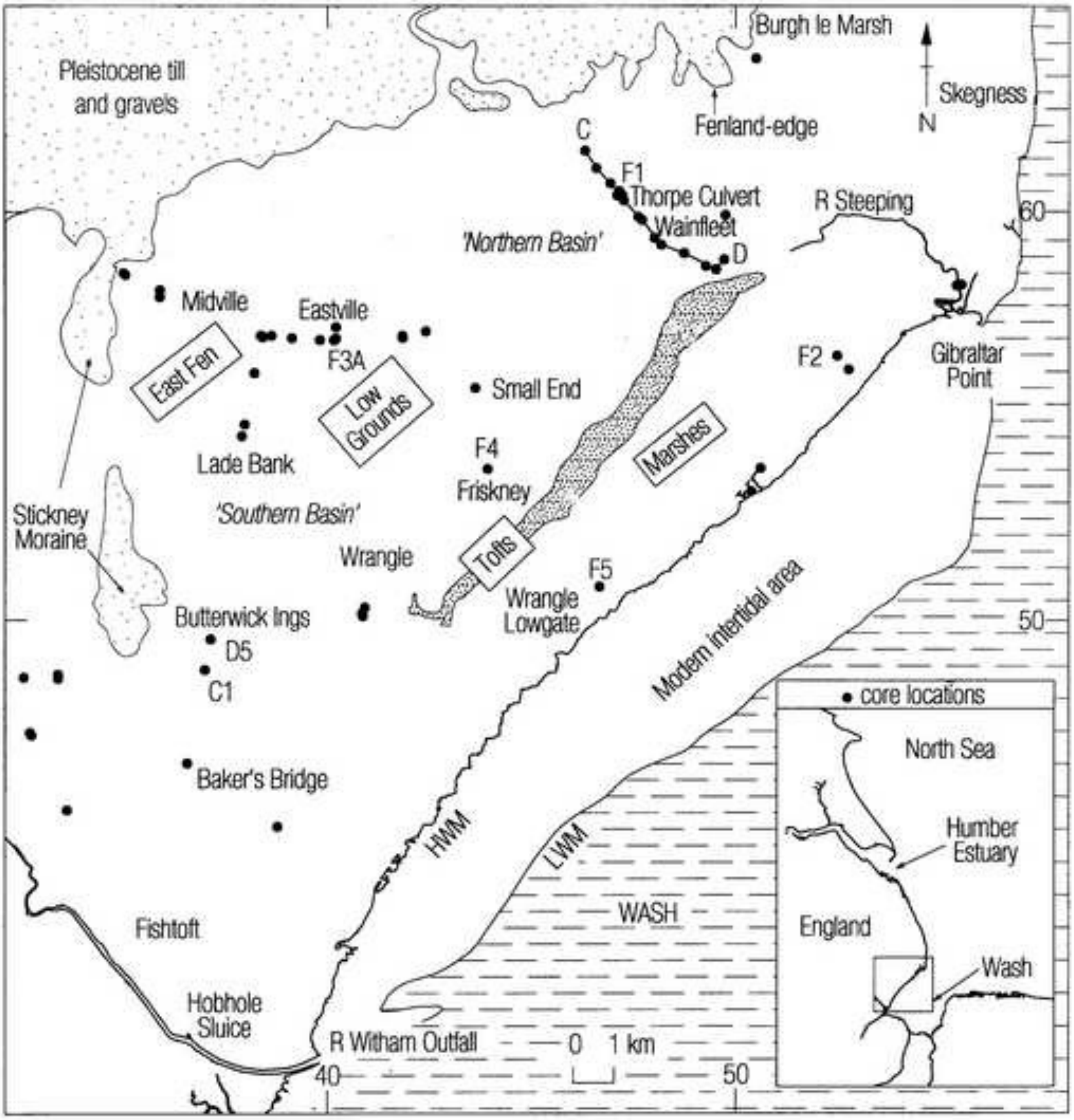

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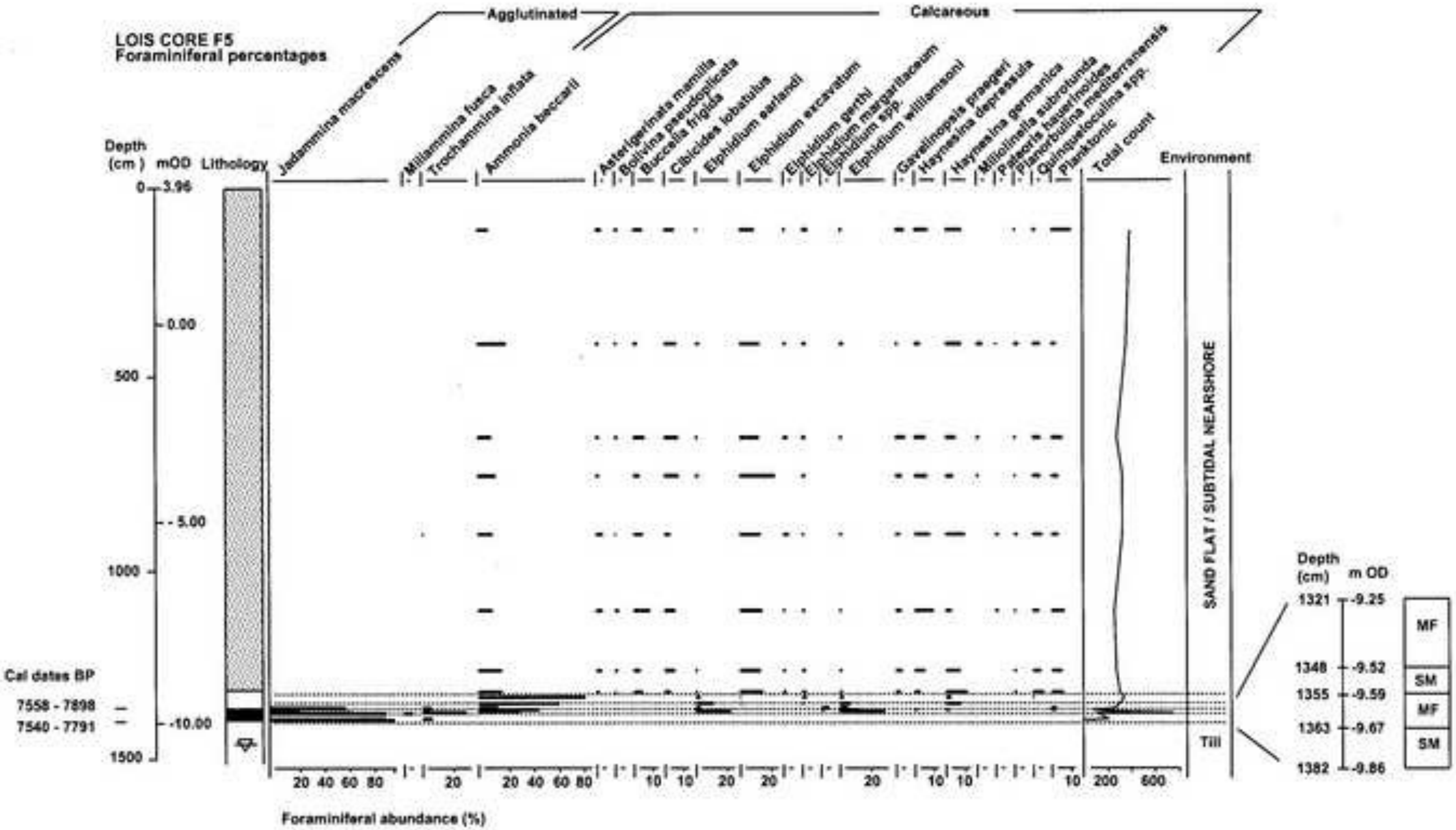

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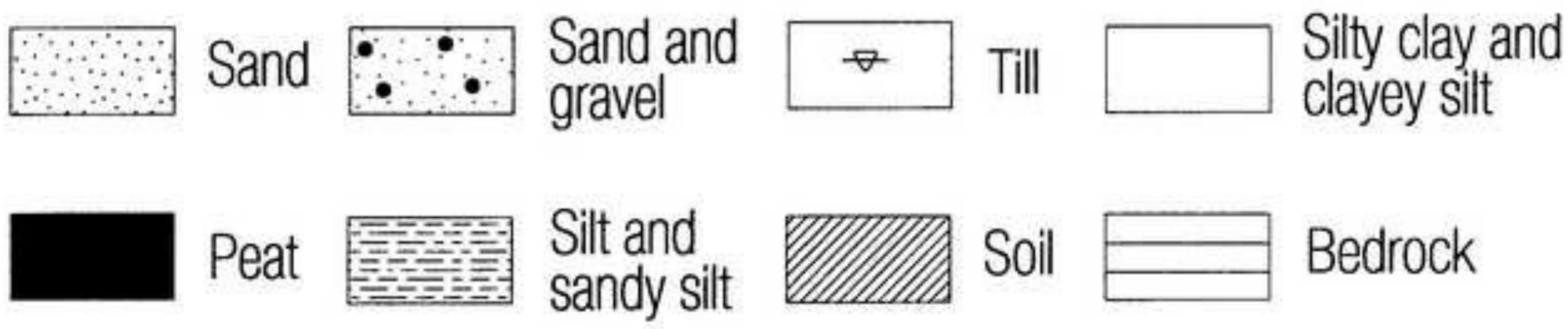
Sand
Sand and gravel
Till
Silty clay and clayey silt
Peat
Silt and sandy silt
Soil
Bedrock

Figure
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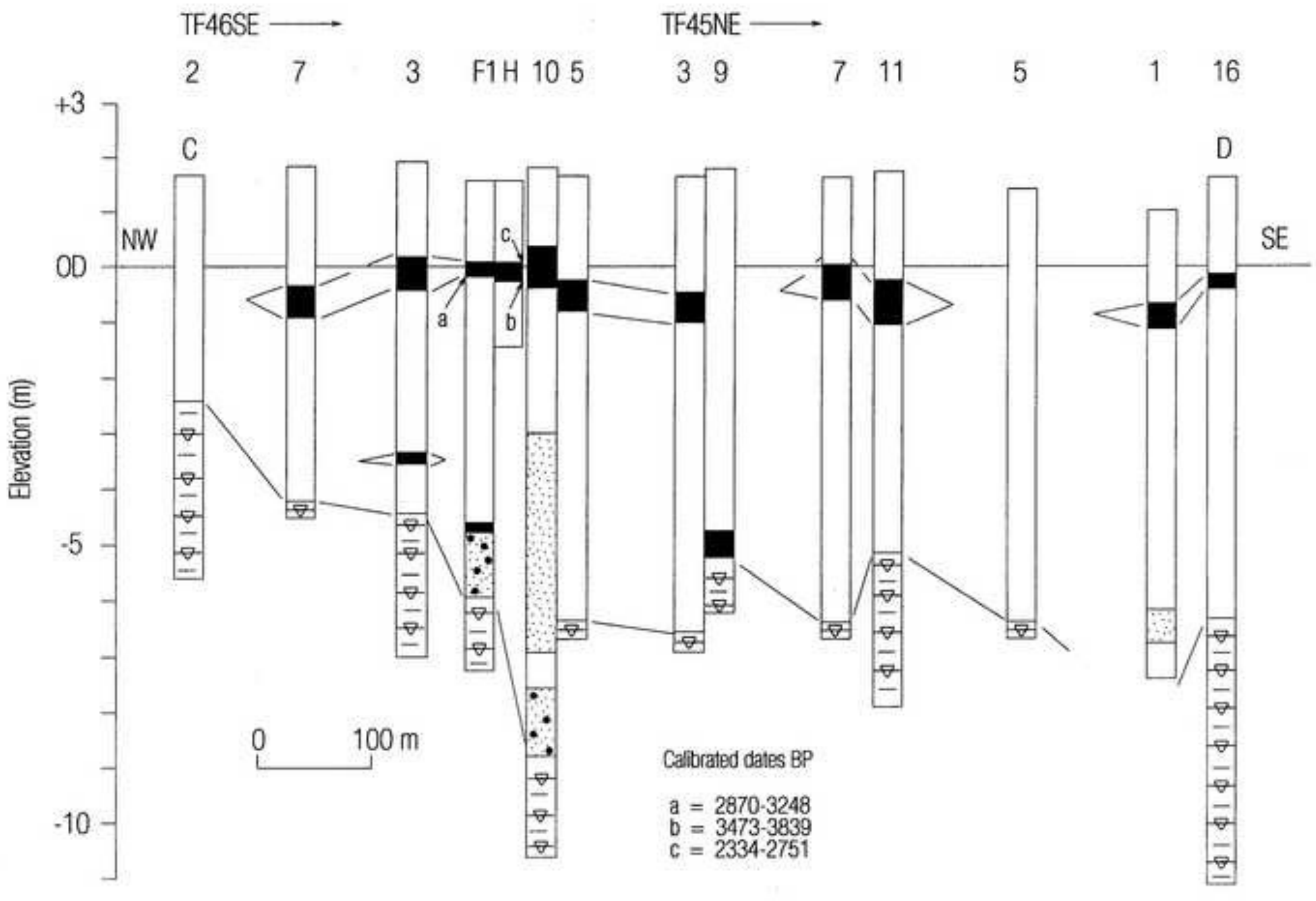

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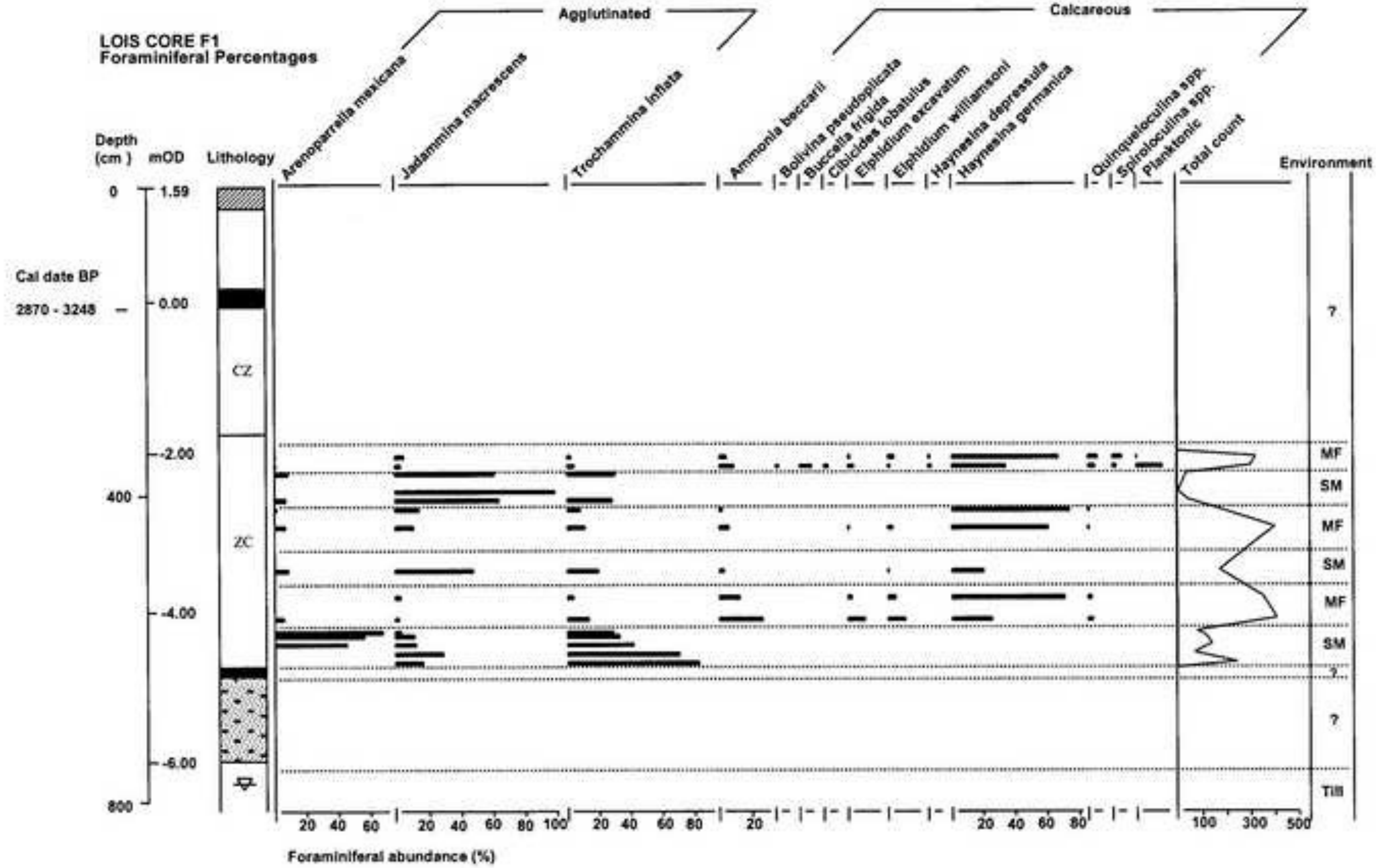

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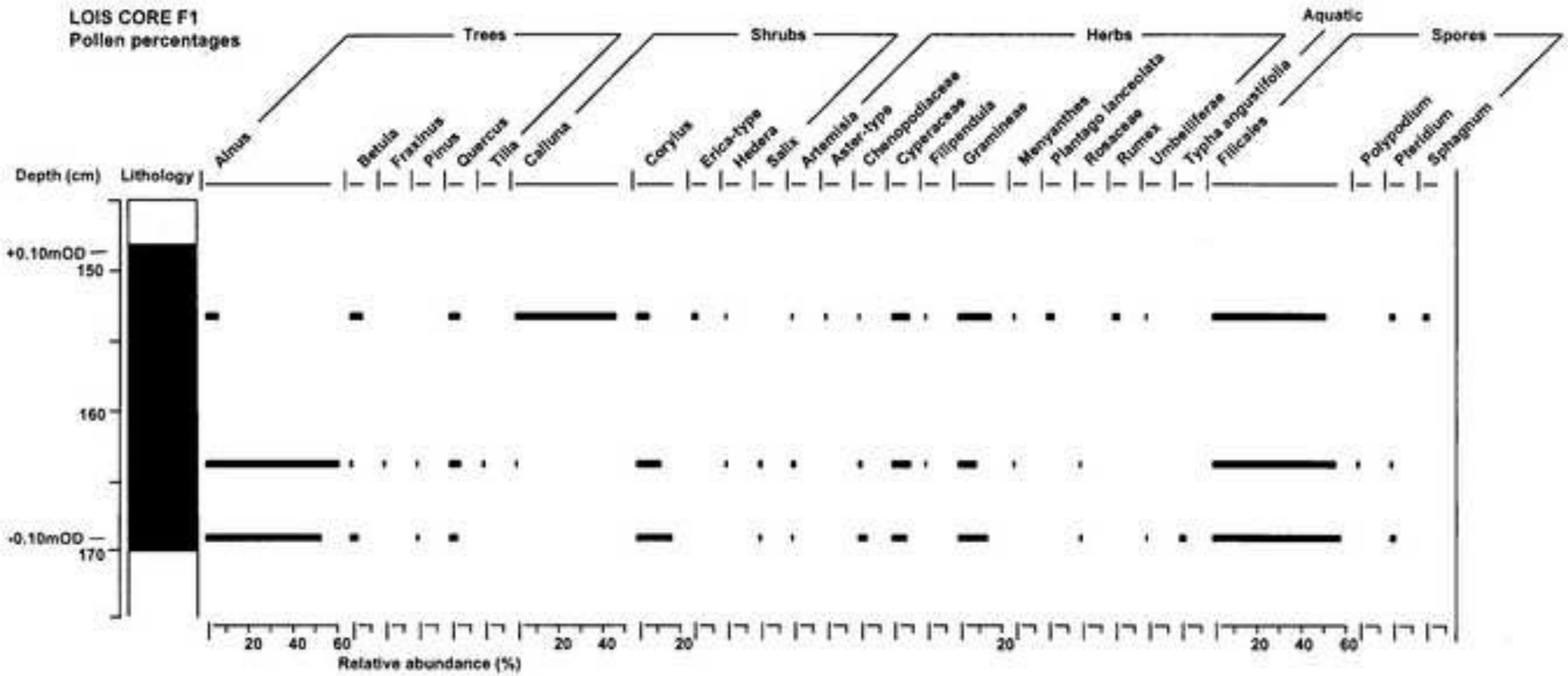

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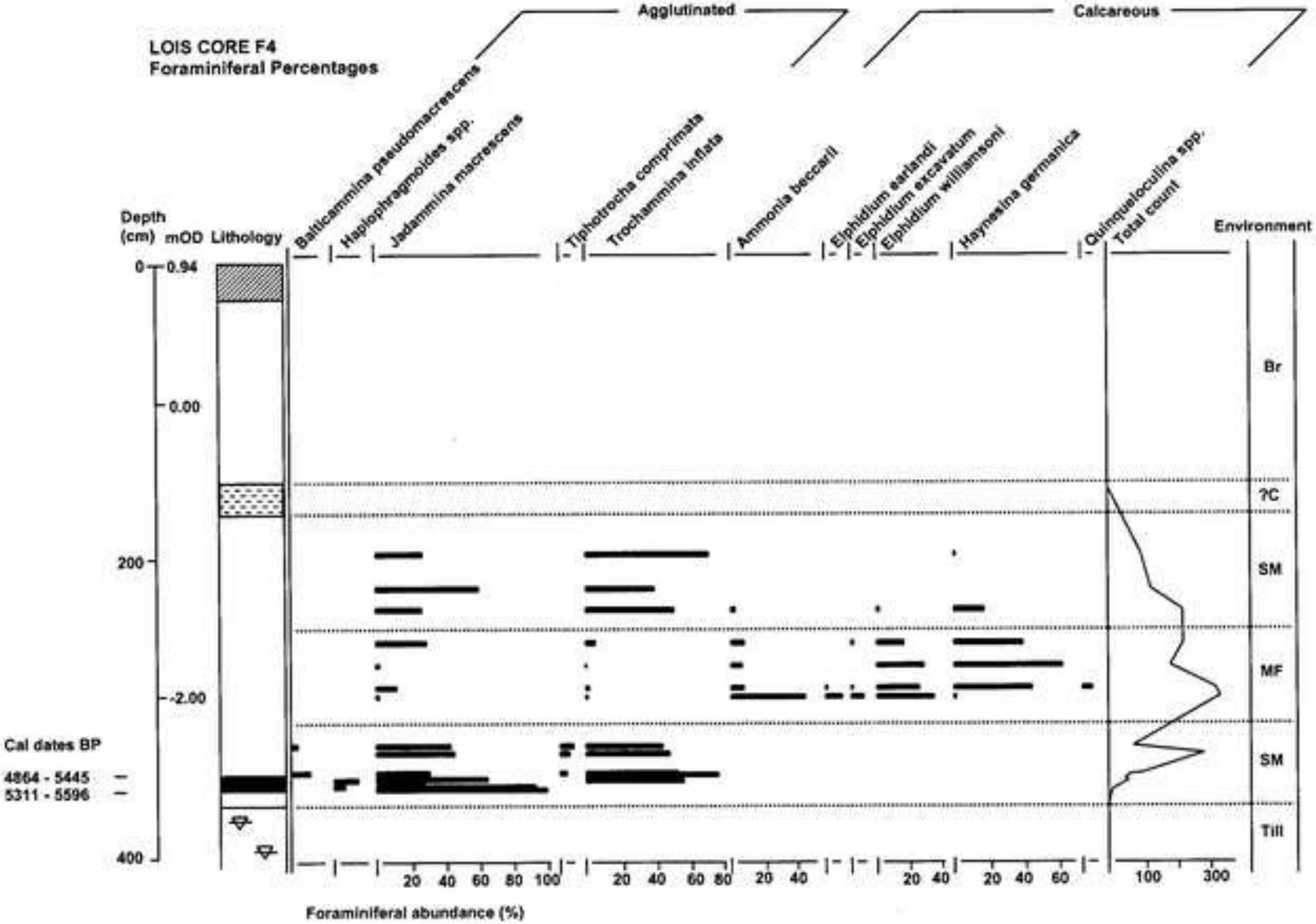

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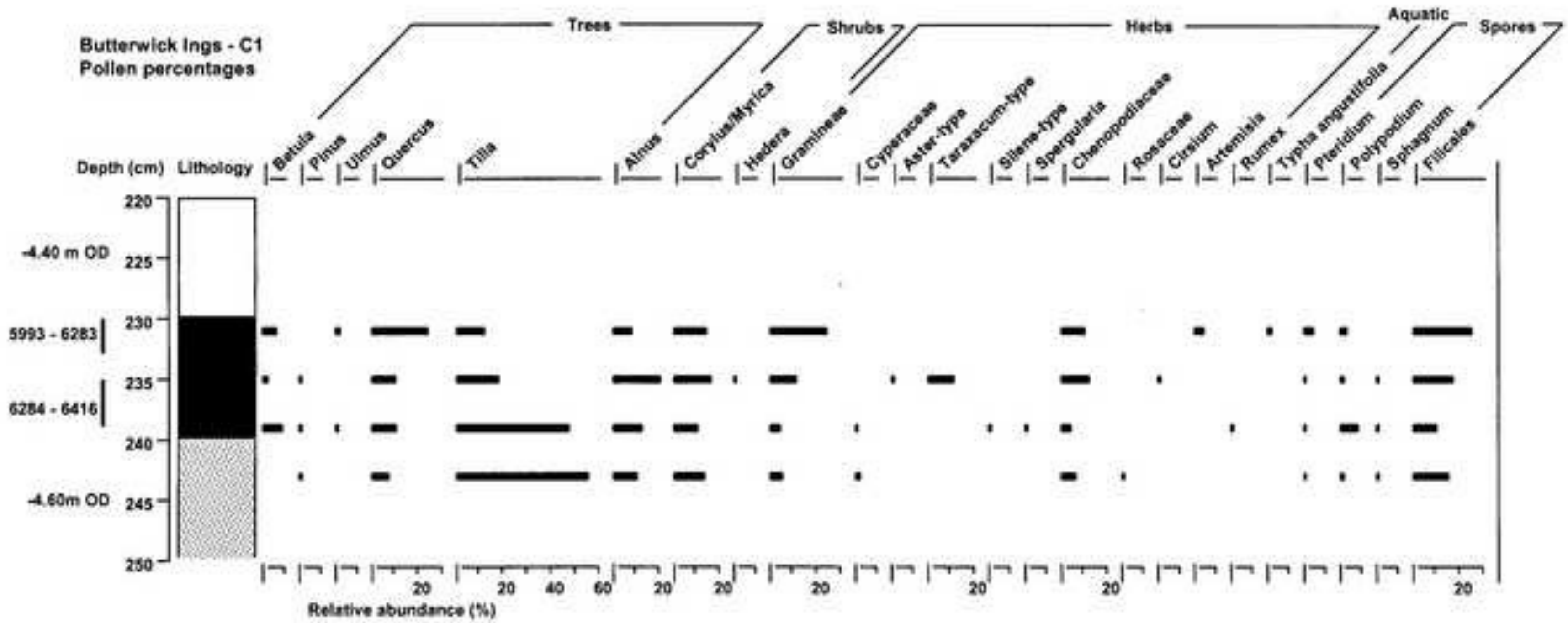

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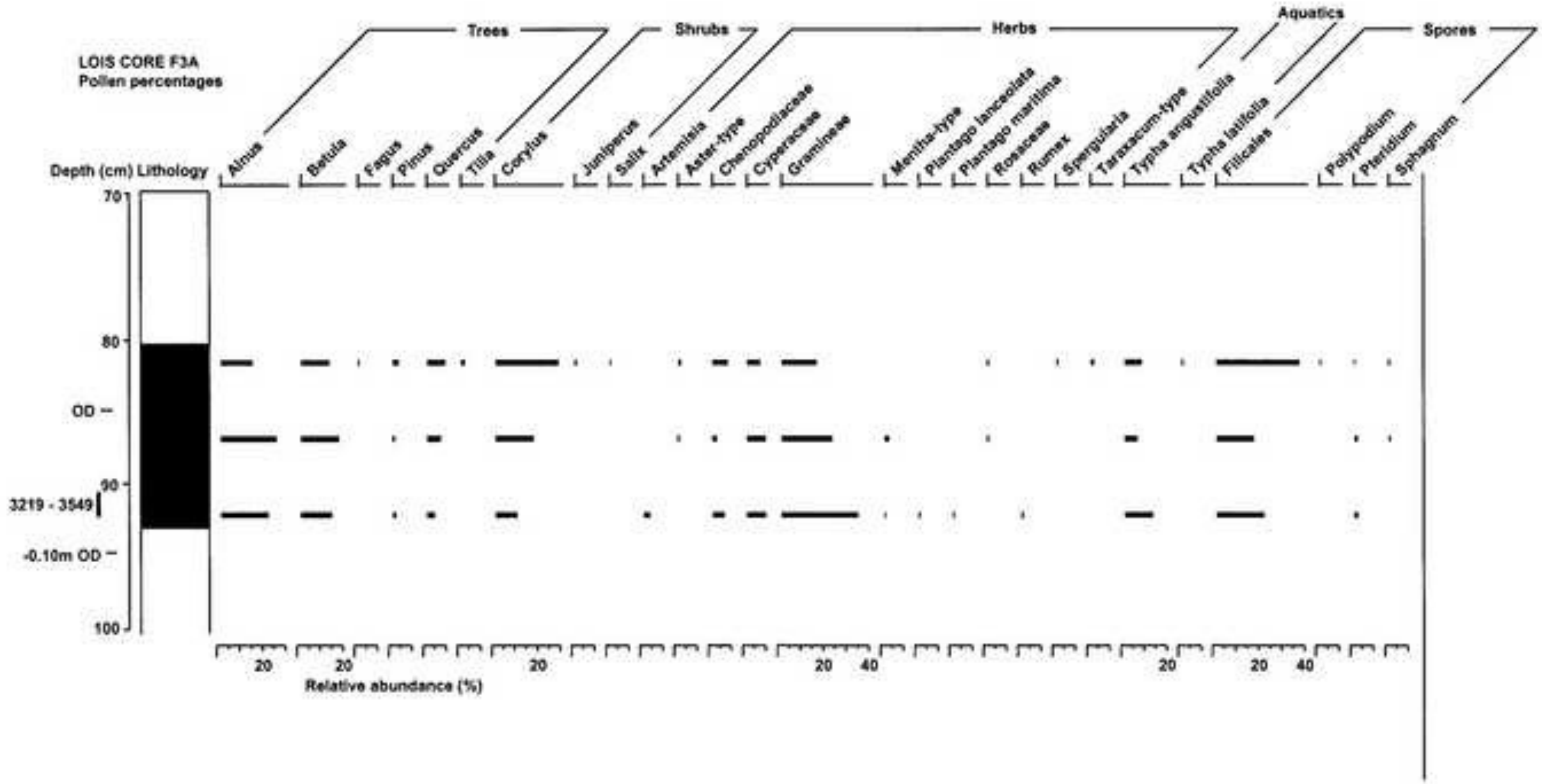

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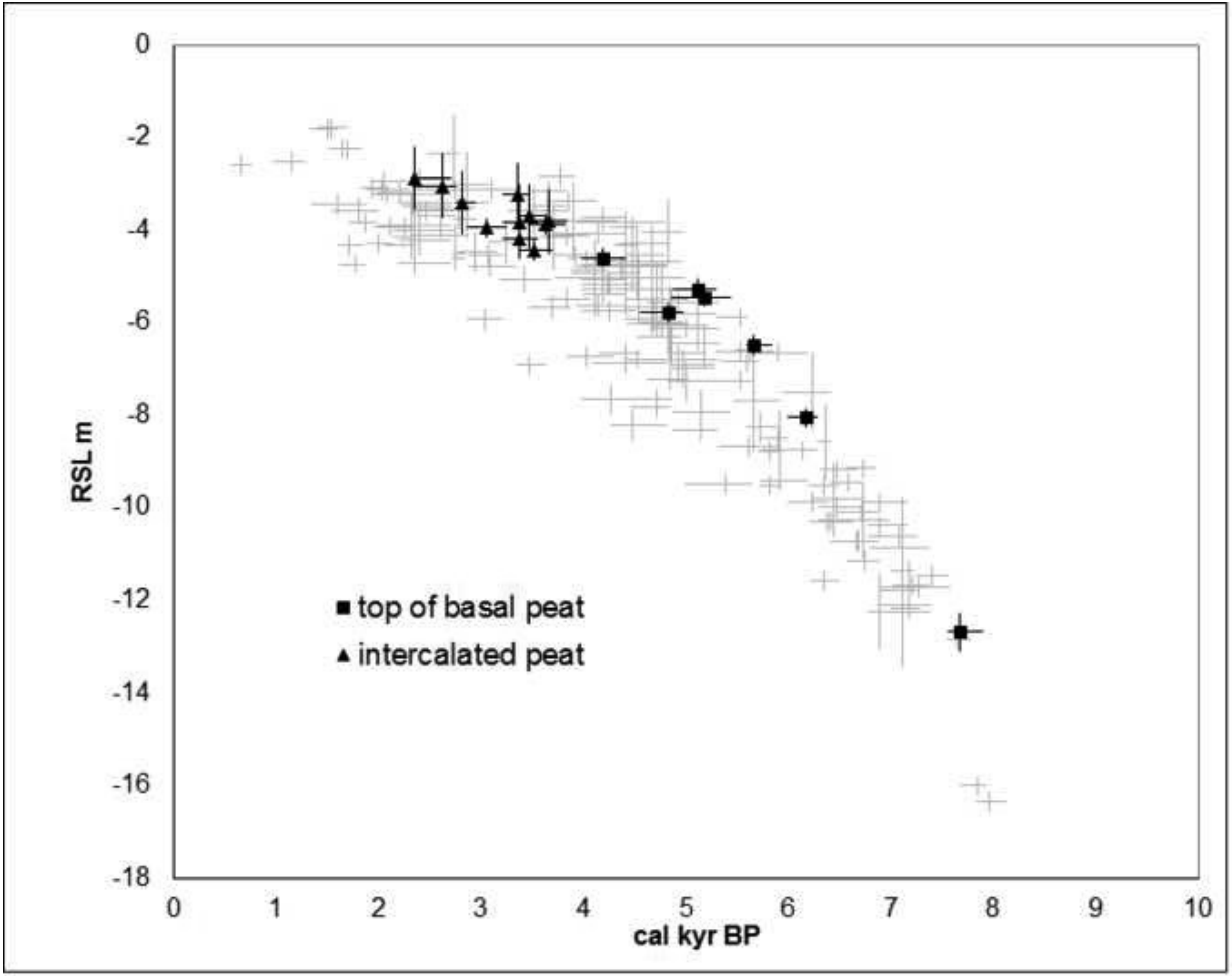
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top of basal peat
intercalated peat

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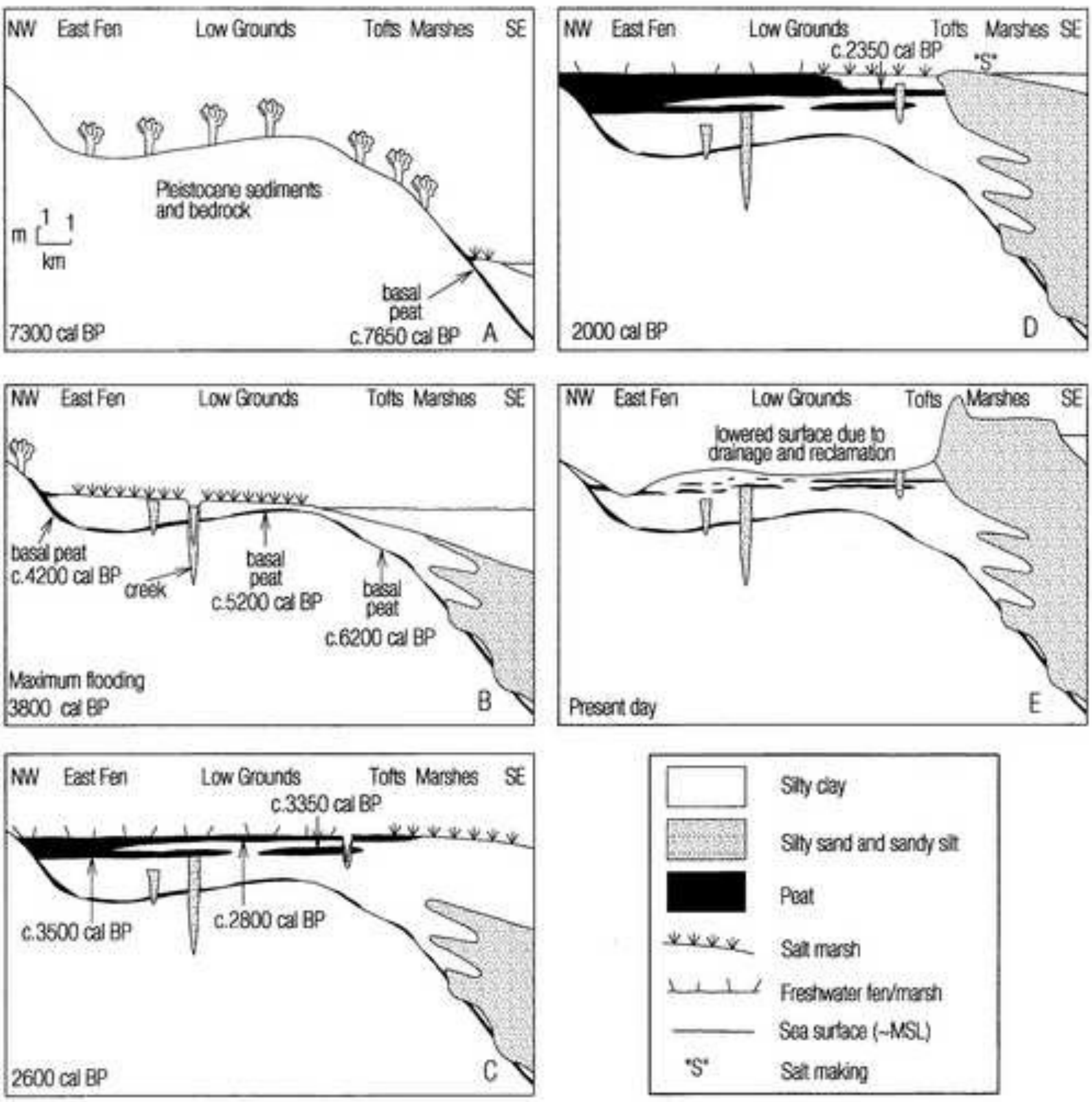

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