**Holocene drainage systems of the English Fenland: roddons and their environmental significance**

Dinah M. Smith[a*], Jan A.Zalasiewicz[a], Mark Williams[a,b], Ian P.Wilkinson[b], Martin Redding[c], Crane Begg[d]

[a]*Department of Geology, University of Leicester, University Road, Leicester, LE1 7RH, UK*

[b]*British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK*

[c]*Witham Fourth District Internal Drainage Board, 47, Norfolk Street, Boston, Lincolnshire, PE21 6PP, UK*

[d]*Suffolk County Council, Graphics Officer, Field Team, Ford House, New Shirehall, Bury St. Edmunds, Suffolk, IP33 2AR, UK (present address)*

*Oxford Archaeology East, 15, Trafalgar Way, Bar Hill, Cambridge, CB23 8SQ, UK (previous address)*

*Corresponding author. *E-mail address:* dms23@le.ac.uk (D.M.Smith).

## Abstract

The roddons of the English Fenlands are fossilized silt and sand-filled tidal creek systems of mid to late Holocene age, incised into contemporaneous clay deposits. However, anthropogenic change (drainage and agriculture) has caused the former channels to become positive topographical features. Three stratigraphically discrete generations of roddon have been discriminated. They all show well-developed dendritic meander patterns, but there is little or no evidence of sand/silt infill during meandering; thus, unlike modern tidal creeks and rivers they typically lack laterally stacked point bar deposits, suggesting rapid infill. Major "trunk" roddons are rich in fine sands and there is little change in grain-size from roddon mouth to the upper reaches, suggesting highly effective sand transport mechanisms and uniform conditions of deposition. Tributaries are silt-rich, while minor tributaries also have a significant clay component. During infill, active drainage networks appear to have been choked by sediment, converting mudflat/saltmarsh environments into widespread peat-forming freshwater reed swamps.

Keywords: Holocene; sea-level change; eastern England; Fenland; fossil tidal creeks; roddon

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## 1. **Introduction**

The English Fenland covers areas of Lincolnshire, Cambridgeshire, north Norfolk and parts of Suffolk and is the largest area of Holocene deposits (some 4 000 km$^2$) in Britain. Fenland sedimentary deposits are up to 30 m (typically to 20 m) thick and they show evidence of a complex palaeoenvironmental history. Part of this story includes the development of drainage systems, the remarkable preserved remains of which are known as roddons. These are visible in the landscape as subtle ridges, up to 1 m high (e.g. Whittlesey [National Grid Reference: TL 270973] to Ramsey St. Mary [TL 256880]), Cambridgeshire, (Hayes and Lane, 1992; Hall, 1992, 1997; Zalasiewicz, 1996; Silvester, 1998). Their origin and infill remain enigmatic. However, developments in remote sensing techniques, coupled with new sedimentological and micropalaeontological analyses, reported here, allow improved insights into their nature and their relationship with the fine-grained deposits into which the channel systems are incised.

Three generations (separate networks) of roddons have been identified (Horton, 1989), two of which are recognised in the present study area and the third generation roddons are found in an area around the Wash (Fig. 1). Roddons are effectively part of and testament to a vanished, natural landscape, now obliterated by human activities harnessing the land for agriculture, domestic and commercial needs. Despite this, they represent an important repository of information regarding late Holocene environmental change and may be used to help predict future environmental change in the Fenland as global sea-level rises. Here we place the roddons in a stratigraphical, geological and palaeoenvironmental context and discuss their architecture, infill and evolution in terms of palaeoenvironmental change during the evolution of the Fenland Basin in the Holocene.

## 2. Methodology

### *2.1 Sediment sampling*

The roddon silts and host clays were hand-augered at six sites within Cambridgeshire to depths between ~2 m and ~6 m depending on the position of the water table and resistant material (Fig.1). Cores ~ ca 10 cm long were recovered in each auger head. Each sample was divided into three for: (1) archiving; (2) particle analysis [Buoyocos Method] for grain size analysis and distribution; and (3) microfossil sampling.

Roddons were sampled to find patterns of grain size distribution between different roddon systems, between different channel orders within a roddon system and between relatively proximal (nearer to coastline) and distal (further inland) part of the system (Fig.2).

### *2.2 Remote sensing of Fenland roddons*

Roddon systems were traced using aerial photographs from the University of Cambridge Air Photograph Library, which date from May 1975 at scale 1:13,650 and March 1982 at scale 1:10,000 and on average have a coverage of ~16 km$^2$ . The 2008 Oxford Terrain mapping images (courtesy of Oxford Archaeology East) have a complete coverage of Cambridgeshire and selected areas for Thorney and the Counter Drain area east of “Dog in a Doublet” road bridge, near Whittlesey, with a coverage of ~50 km$^2$. They complement the aerial photographs in showing surface elevation rather than soil colour, and therefore, pick out "buried" roddons – i.e. those of an early generation that were subsequently overlain by clay. Hence, they help resolve the different roddon generations when used in tandem with aerial photographs which show the type of surface sediment through tonal contrast.

The images from Oxford Archaeology East are derived from 3-dimensional surface models created using IFSAR digital surface model data at a horizontal posting or resolution of 5 m (DSM5) from the NEXTMap Britain dataset produced by InterMap. IFSAR (Interferometric Synthetic Aperture Radar) is a radar technique used in geodesy and remote sensing which uses two or more synthetic aperture radar (SAR) images to generate maps of surface deformation or digital elevation, using differences in the phase of the waves returning to the satellite or aircraft. A nearest neighbour algorithm was applied to the raw DSM data to generate the 3-dimensional grid which was then enhanced using colour scaling across elevation zones.

Data from remote sensing were used in conjunction with British Geological Survey field slips (mapped at 1:10 000 scale) and archived borehole data, East Anglian Archaeology Reports, local farmers knowledge and field walking to help constrain the field relationships and chronology of the roddon drainage patterns.

## 3. Geographical Framework

Skertchly (1877) discussed Holocene successions, identified various environments of deposition and attempted to determine palaeoenvironmental processes in terms of salinity change and marine transgression and regression (see also Waller, 1994). Skertchly recognised a tripartite Lower Peat/Basal Peat-Buttery Clay- Upper Peat stratigraphy (Fig.3) and the dendritic pattern of the sinuous “silthills” of the now-extinct water courses, and his work laid the foundation for all future Fenland stratigraphical studies (Godwin, 1978).

Godwin (1940) examined anthropogenic influences on the Holocene landscape and, using evidence from pollen analysis, developed a four-part stratigraphic division for the Southern Fenland: Basal or Lower Peat overlain by Fen Clay (Buttery Clay of previous authors), followed by Upper Peat (often the surface sediment) and, in some areas, Upper Silt (sometimes called Marine Silt and Romano-British Silt; see Waller, 1994, Fig. 2.3) at the top of the succession. The Upper Silt of Godwin (1940) seemingly relates in part to deposits in the fossilised drainage channel systems cut into the peat Fens, and forming the roddons. In part, it also relates to regionally distributed silt-rich deposits that form the slightly higher ground of the ‘Siltlands’, the Terrington Beds of Gallois (Horton, 1989; Waller, 1994) to seaward.

Godwin interpreted the roddons as levées besides channels that had drained alluvial marshes. This challenged Fowler’s theory (1932, 1933) that the roddon was “deposited in the form of a concave mass within the peat which would subside into a convex form with peat shrinkage” (Hall and Coles, 1994; Silvester, 1988). Coles and Hall (1998) continued mapping the Fenland roddon systems although French (1993) noted problems associated with the established stratigraphical nomenclature and the consistently younger than expected radiocarbon ages for the Basal Peat.

Horton (1989) identified three stratigraphically discrete generations of roddon in the Peterborough district (Fig. 4) related to a stratigraphy represented by clays, which were considered to represent a marginal saltmarsh environment, interbedded with peats, interpreted as formed in freshwater reed swamps (4). The Fen Clay was assigned to the Barroway Drove Beds, and divided into two units: the Lower Barroway Drove Beds (the bulk of the deposit), and the Upper Barroway Drove Beds, that thins and disappears southwards. These two units are separated by a thin peat, and overlain by the Upper Peat (that has now largely disappeared). We employ this stratigraphy, for the sampling executed in the Peterborough Thorney and Plash Drove areas as assembled in regional mapping, as it forms an effective framework for analysing and explaining roddon distribution (see below).

The interplay of sedimentary lithofacies in the Holocene sediments of Fenland partly reflects overall global sea-level rise consequent on deglaciation modified by local isostatic effects (Shennan, 1986; French and Pryor, 1993; Shennan and Horton, 2002).

## 4. The Holocene Fenland landscape

The pre-Holocene surface of the Fenland is mostly comprised of Jurassic clays (French, 1992). Overlying these are Pleistocene tills, sands and gravels (Wyatt, 1954) and the heterogeneous sandy clays of the Crowland Beds, of Late Pleistocene or early Holocene age, on which the Lower (= Basal Peat) lies (Horton, 1989; Brew *et al.*, 2000). More resistant chalk underlies the eastern and south-eastern part of the Fenland Basin and limestone occurs to the north and west. The palaeo-surface, on which the Holocene deposits rest, is uneven and areas of higher altitude formed “islands” such as Ely, March and Thorney. These “islands” are in effect inliers of older strata surrounded by Holocene deposits, and are overlain by Pleistocene gravels and till (Hall, 1996).

At the commencement of the Postglacial interval, the Fenland Basin was dry land with a few islands and crossed by river systems. During the Postglacial temperature increase, low-lying wooded areas began to establish themselves with lime as the main tree species, as deduced from pollen spectra (French and Pryor, 1993; French, 2003). Accumulation of Holocene deposits began when sea-level approached its present-day position after the release of water from the Devensian ice sheets (French and Pryor, 1993). During the period between 4000-3000 yr BP the marine transgression reached its maximum extent (Brew *et al*, 2000).

With sea-level rise, water tables rose and consequently the Fenland Basin became flooded as the drainage systems ceased to be effective. This allowed for localised eutrophic wood /reed peats to form in the freshwater marsh (French and Pryor, 1993). Horton (1989) dated the Basal Peat at 7690 $^{14}$C yr BP ±400 (BP calculated at 1950 AD);(8531 cal yr BP ± 447) (Fairbanks *et al*, 2005) at Elmtree Farm (TF 40101487).

The Fenlands were locally drained during Roman and medieval times, but the roddons became positive features after the phase of 17$^{th}$ century drainage due to the differential compaction of the silts, clays and peats, together with oxidisation and ablation of the peat. Thus, the modern landscape is dominated by anthropogenic activities associated with drainage and agriculture.

The relationship between roddon development and sea-level changes remains unclear. A Holocene sea-level curve for the Southern North Sea (Behre, 2007) shows similarities with the sequences of transgressions and regressions as described by Shennan (1986, Fig. 14; Waller, 1994, p.14) and the Horton and Edwards (2005) foraminifera studies in the Norfolk area are also consistent with regression at ca 3300 – 3000 yr BP. However, estimates of subsidence, and of the relative sea-level changes derived from the current height of stratigraphic contacts are complicated because the silts and sands compact at a slower rate than clays and peats. Currently, constraints on the timing of the roddon infill (mostly derived from $^{14}$C dates of the overlying peats) are insufficiently precise to say whether or not the infill events correlate with the inferred changes in sea level. French and Pryor (1993), Waller, (1994) and Hall, (1987) considered that the transgressions were not synchronous across the whole of the Fenland.

## 5. Roddon Architecture

### *5.1 Distribution*

Roddons are most clearly seen within an extensive inland belt of Fenland terrain which is dominated by fine-grained "Fen Clay" (Barroway Drove Beds) facies. The earliest recognised roddon generation is incised into the upper surface of the Lower Barroway Drove Beds, and the second roddon generation is incised into the top of the Upper Barroway Drove Beds (Fig.3). Both of these (sediment-filled) roddon networks are overlain by peat. A third, later roddon generation has been recognised (Horton, 1989) (British Geological Survey, 1984) (Fig. 3) associated with a silt-rich layer (the Terrington Beds or "Siltlands") in the extreme east and north-east of the Peterborough district, that stretches seawards to the Wash area. These form the uppermost unit. Formerly the entire area was covered by an Upper Peat layer, now almost entirely oxidised and depleted following drainage and ploughing, and it is the loss of this peat that has revealed the roddons.

The "Silt lands" is topographically slightly higher with silts and fine sands at the surface. That this is not a surface layer overlying Fen Clay, but a laterally equivalent facies, has been indicated by boreholes, which show more or less consistent sands and silts to the base of the Holocene succession (Fig. 5; cf. Wheeler and Waller, 1995, Fig. 5). The roddons traversing this area are harder to see, as the differences in soil-type and elevation are slight, but recent LiDAR images locally reveal them.

### *5.2 Channel morphology*

Roddons vary in channel width from ca 2 m to >1 km and in depth from ca 1m to >10 m. Channels may be placed in a hierarchy comparable to those established for fluvial networks (Morisawa, 1968; Bridge, 2003). The largest roddons – trunk roddons herein – are 250 to 1000m in width, and traverse the entire area. Some may have had a considerable freshwater input and be, therefore, related to the Fenland palaeo-river channels. One such example is the roddon of the now extinct course of the Little Ouse River near Lakenheath to the old course of the River Ouse between Ely and Littleport, Cambridgeshire. This roddon was visible in the 1980s at Plantation Farm (TL 642848) and its course can be traced from Old Decoy Farm (TL 665857) to Old Bank Farm, Littleport (TL579874) where it now forms a topographical high up to 2.5 m above the surrounding peats for approximately 8 km (Astbury, 1987).

Tributary roddons of at least two orders branch off from the trunk roddons, and these are referred to as "major" or "minor" tributary roddons herein (Fig. 6). These typically have blind endings inland and hence conform exactly to salt marsh channels, with both water and sediment sourced from the sea. Several of the roddons are straight and almost certainly artificial. These represent Roman and Medieval canals that appear to join together natural roddons, indicating that some roddons were open channels at these times and used for transport and/or drainage. One example can be seen as a straight raised ridge in fields along Plash Drove, near Guyhirn, Cambridgeshire (TF 3883905407).

Sections through the roddons are periodically exposed when the Fenland Internal Drainage Boards improve and clear drains and dykes. The smaller channels have a neat semi-circular outline exemplified by a roddon cut by the new bypass on the A47 road at Thorney, Peterborough, Cambridgeshire (TF 313790442) (7A and B). In nearby fields low ridges are visible after harvest time and sometimes the lighter silts/sands may be seen (Fig. 7C and D). Larger roddons locally show levée features while the sediments within the roddon can reveal contorted and slumped bedding and lamination (Fig. 7E and F).

### *5.3 Roddon generations and network architecture*

In the Peterborough district, the average trends of the two main Barroway Drove Bed roddon networks (Generations 1 and 2, Fig. 4) are almost orthogonal to each other. The Lower Barroway Drove Beds roddons drain dominantly north-eastwards while those in the Upper Barroway Drove Beds trend towards the north and northwest, the outfalls entering the Wash

(Horton, 1989). The Oxford Archaeology East IFSAR image (2008) places the two generations of roddon at different stratigraphical levels in the Thorney area (See also Hall, 1987). The direction, generations and size of the roddon channels in the Thorney and Wrydelands area (Fig. 8) are shown clearly by comparison of IFSAR imagery with aerial photographs. The "buried" roddons of the earlier generation, though covered by up to 1 m of clay, nevertheless form subtle ridges visible in the IFSAR images but not in the aerial photographs. The aerial photographs, by contrast, clearly show the pale surface silt of the later roddons that cross-cut those of the earlier "buried" generation (Fig. 8).

*5.4 Sedimentary structures*

Near-horizontal, planar bedding on a cm-scale is locally visible in exposures (largely cleaned banks of drains) through roddon infills, while fine (mm-scale) laminations may locally be discerned. Trunk roddons locally show contorted lamination, particularly near their margins and central sections caused by slumping of water-saturated silts and sands. The trunk roddon (Fig. 7E and F) shows a sharp contact with a layer of impersistent peat above the roddon sediments and indicates a change from a marine (roddon) to freshwater (peat) environment. This peat layer has been preserved by the newly deposited overlying Nene Wash sediments and the artificial leveés which have not been subjected to farming and erosion as in other Fenland areas.

Many roddons show, in aerial view, a more or less central dark linear structure. This appears to be a late-stage infill that is relatively organic-rich and at least locally (Smith, unpublished) shows freshwater influence.

*5.5 Grain size distribution*

The sedimentary infill of all the roddons augered to date shows distinct patterns in grain size trend (Fig. 9). The trends may be summarised as follows: 1) the infills of the two generations of roddon systems of the Barroway Drove Beds are, overall, very similar in grain size distribution; 2) trunk roddons were relatively sand-rich and carried substantial amounts of sands and silts far inland, and no significant landward diminution of grain size has been observed; 3) the grain size of any roddon is generally stratigraphically uniform except for the top metre or so, where a generally fining upwards trend is present. There is greater clay content in minor tributary roddons; 4) the most common component of the infill overall is silt.

The roddons of Generation 1 and 2 are incised into clays of the Barroway Drove Beds (Fig. 3). These clays are dark/grey brown in colour and much finer-grained than the roddon infill deposits, although containing small amounts of silts and sands. They show a general fining-up pattern in their surface (sampled) part (Fig. 10), while, seawards, the clays show a higher proportion of silts, perhaps having been affected by the marine transgression that deposited the Terrington Bed silts, although this might equally reflect proximity to the laterally equivalent facies of the "Silt lands" area (Fig 1) that remained silt- and sand-rich throughout the Holocene. Comparing the Fenland Holocene tidal creek (roddon) systems with a modern tidal system of The Wash (at Stiffkey, north Norfolk (TF 9727144158) shows considerable differences. The modern creeks display similar dendritic channel patterns, but they also show migrating channels, slumping bank sides, salt pan areas, ox-bow lakes and point bars - characteristics reminiscent of a typical fluvial system (Fig. 11). The sediments being deposited in a modern creek on the north Norfolk coast near to The Wash (Fig. 12) are considerably more sand-rich than are the roddon infills, and are considerably more poorly sorted, with a clay component derived from bank sides as they slump and erode, and deposited as drapes over the channel sedimentary structures.

## 6. Microfauna

The clays, silts and fine sands which accumulated in the Fenland of the Holocene yield rich and diverse calcareous microfauna, especially foraminifera and ostracods, which occur together with fragmentary fossils of echinoderms and bivalves. Preliminary examination shows the microfauna include both estuarine and saltmarsh taxa, but assemblages are dominated by distinctly marine and brackish-marine forms (Fig. 13). No freshwater taxa have been recognised. The finer grained, upper metre or so of roddon material is typically devoid of fossils, probably because of surface dissolution, while there appear to be fewer microfossils in the smallest, “minor tributary” roddons.

The foraminifera and ostracoda recovered in the roddon sediments typically are in pristine states of condition, indicating that they have not been reworked. Microfauna are dominated by benthonic foraminifera such as species of *Lagena, Oolina, Elphidium, Cibicides* and *Ammonia,* with saltmarsh assemblages being characterised by *Jadammina* and *Trochammina.* Ostracods are less common, but include shallow marine and brackish species of *Leptocythere* and *Hemicytherura.*

## 7. Controls on roddon evolution

### *7.1 Sediment infill*

Shennan (in Waller, 1994) discussed three models of deposition that may control the style of roddon infill: (i) a static barrier across the Wash (Swinnerton, 1931); (ii) migrating barriers or barrier islands; or (iii) an open coast. He concluded that an open coast was the most likely scenario due to: (a) the range of sediments being analogous to an open coast model; (b) that no large barriers exist in the Wash today; and that (c) the Holocene Wash embayment, being likely macro-tidal as at present, would be unlikely to generate and preserve substantial sedimentary barriers.

The above open marine hypothesis of Shennan is, in general, supported by our observations of the roddon sediment infill. Most importantly, the infill was marine-influenced as the sediments have substantial amounts of marine microfauna present. Furthermore, the roddons were almost certainly rapidly filled as no evidence has been seen of channel migration during infill. Thus, although the morphology of roddon channels resembles meandering rivers from the air, they show little or no evidence of lateral channel migration across the saltmarsh environment, in the form of laterally stacked point bars. This is one of the striking features of roddon systems and demonstrates their fundamental difference from the typical preserved records of rivers or of salt marsh creeks (Allen, 1964; Zalasiewicz, 1986). Other channel deposits have been described from Holocene coastal settings, but differ in detail, having for instance a generally finer-grained infill (Allen, 2000), or comprising straighter (anastomosing) fluvial networks (e.g. Törnqvist, 1993).

The roddons show a history of incision and then infill which reflects a changing balance between erosion and scouring of the roddon floor (its channel) and, shortly afterwards, landward transport and deposition of silt and fine sand to block the channel. Incision must have been in an overall ebb-dominant regime to allow scouring of the channel-forms. Subsequent infill must have marked a change to flood-dominance allowing sediment to rapidly accumulate. The grain size patterns obtained from the roddons demonstrate consistent and extremely efficient sediment transport mechanisms into these channel systems. Little or no clay settled in the main channels until the very latest stages of roddon infill. There was some limited sediment partitioning, though, between major and minor roddons, with finer sediment overall (and a minor clay component) in the latter.

There were repetitions of this distinctive pattern of roddon incision and subsequent infill represented in particular by roddon generations 1 and 2 (of the Barroway Drove Bed clays). This assemblage of sedimentary features is consistent with Shennan's conclusion that there was open access to the Holocene sea. We infer, though, that the palaeo-Wash, as today, possessed abundant shifting sandbanks that likely provided the sediment source.

*7.2 Marine transgressions*

Baeteman (2008) outlined two conflicting relative sea-level models for the relative sea-level changes for the southern North Sea during the latter part of the Holocene (the last 2500 years) – (1) fluctuating sea-level models such as Behre (2007) described below and (2) the smooth sea-level rise models as inferred by Kiden (1995) for the southwestern Netherlands and Denys and Baeteman (1995) for Belgian coastal plains. The latter authors suggest that the facies variations of coastal evolution were not the result of sea- level rise but were caused by tidal channels responding to changes in accommodation space, sediment supply and more latterly, human impact.

Holocene sea-level rise, modelled by Behre (2007), indicates a steep sea-level rise until ca 6950 yr BP, after which it levelled out, although several oscillations reflect short-lived transgressions and regressions. Several of the oscillations defined by Shennan (1986) are very similar, particularly that between ca 4500 and 4200 yr BP while Horton and Edwards (2005) also recognised a marked fall in sea-level about 3150 BP after investigating Norfolk foraminifera. Three main marine transgressions, all millennial scale, have been inferred for the Fenland (Coles and Hall, 1998; Waller, 1994) and their reconstructed palaeogeographies at the time of maximum local sea level are indicated in Figure 14. The distribution of the marine deposits gives the likely limit of the marine influence, Figure 14 (A,B,C).

The first major marine transgression resulted in the deposition of the Lower Barroway Drove Beds clays. This may in part have been diachronous across the Fenland (Hall, 1987; French, 2003). Dates for this earliest marine incursion range from ca 4200-3300 yr BP

(Shennan, 1986b; French and Pryor, 1993). The first generation of roddons formed at or near the end of deposition of these Lower Barroway Drove Beds clays. The Thorney area of Cambridgeshire was subject to a second marine incursion which deposited the Upper Barroway Drove Beds, forming the 'host' for the second generation of roddons. These beds are dated ca 3000 yr BP with possible continuation of sedimentation at 3300 to 2900 yr BP over the Western-central Fens, although the underlying peat markers are missing (Waller, 1994).

Given that the second main generation of roddons in the Barroway Drove Bed clays crosses the first generation roddons almost orthogonally, the prevailing drainage pattern in the Fenland must have altered course and direction, possibly due to a change in morphology of the evolving Wash coastline. Breaching would have taken place at different sites as the old roddon channels were silted up and would have given no access to the incoming tides. Also, the shifting of vegetation and sediment zones with the changes of marine/freshwater sedimentation likely influenced tidal creek development (Shennan, 1986). The effect of continued (and presumably differential) subsidence of the Fenland Basin since 6500 yr BP at a rate of 0.9/1000 years was likely also an influence on sedimentation patterns.

The third generation of roddons (the youngest) developed within the marine silts of the Terrington Beds which occur just north of Thorney "island" and south of Crowland "island" (Cambridgeshire), but mainly occur in the South Lincolnshire Fens. Shennan dated these deposits at 3000 – 1900 yr BP (Waller, 1994), thus in part overlapping the age of the second generation roddons. The silts of this third generation differ from the first two generations in being coarser-grained (Shennan, 1986) and deposited in a higher energy environment. These roddons however are not easily distinguished separately on aerial photographs.

The coincidence of the silted-up roddons of the first two generations and the respective transition from the Barroway Drove Beds clay to peat is striking. Silting up of the roddons, therefore, likely marked the end of an effective saltmarsh drainage system. This would have meant that the supply of water and sediment from seaward, which up until then would have been transported along the tidal creeks, would have been drastically reduced or even stopped. Such a "clastic sediment shut-off" from seaward could in itself have initiated peat accumulation, especially if a rising water table was occurring landward associated with ponding of river waters, whose access to the sea would have been equally hindered. If this suggestion has merit, then sea-level fluctuations might have had little direct fine–scale control on determining peat/clay transitions in this region. This mechanism resembles that inferred in part for the Dutch Holocene succession, which relates areas of peat and clay deposition to the changing position of tidal inlets in a barrier-bar system (De Mulder and Bosch, 1982; see also Kiden, 1995, Denys and Baeteman, 1995). This suggested mechanism reflects the delicate balance which likely existed in the natural Fenland environment, and its susceptibility to rapid environmental change across large areas, following what may have been a modest triggering process such as new tidal channels opening or being blocked which may have triggered geomorphological change inland.

*7.3 Future evolution*

The Intergovernmental Panel on Climate Change (IPCC) (2007) report predicts that sea level rise will be of the order of 0.18 – 0.58m by 2100. An additional 0.10 to 0.20 m is possible if the recent melting of polar ice sheets continues (Turner *et al*, 2009). Since the 17$^{th}$ century drainage and the attendant shrinkage and ablation of the Peat Fen area means that it is now -2 m below sea-level (Ordnance Datum) with the silt-dominated areas lying at or just above 0.3 m OD (Waller, 1994).

Over the coming decades and centuries, therefore, the Fenland is likely to be subjected to future marine transgressions beyond the norm for the Holocene. Future transgressions will take place over an extensive area which has already been anthropogenically modified. The subsidence caused by the drainage (compaction) and peat wastage (removal of surface sediment) is effectively irreversible. It is clear that roddons cannot be re-used as channels in future transgression events, but will concentrate water flow between them. The future geological record of the Fenland will thus, once more, be governed by these remarkable, geomorphological features.

**8. Conclusions**

Roddons in the English Fenlands are fossilized tidal creek systems of mid to late Holocene age (6000 to 2000 yr BP), incised into contemporaneous clay deposits. Sedimentation in major “trunk” roddons was predominantly of fine sands, while tributaries are silt-rich with a subordinate clay component. Sedimentation within the tidal creeks was dominated by the influence of marine conditions as indicated by the common shallow marine and brackish marine foraminifera and ostracods, although in some areas a salt-marsh community was established. The architecture of roddon generations and the pattern of their infill appear to have been affected by changes in the palaeogeography of the Wash and perhaps oscillations in local sea level. The roddons differ from modern tidal creeks in the Wash area: although they show well-developed dendritic meandering patterns, there is little or no evidence of sand/silt infill during active meandering; thus, unlike modern tidal creeks/rivers they typically lack laterally stacked point bar deposits and this suggests rapid infill. Choking of active drainage networks by sediment may have resulted in mudflat/saltmarsh environments being converted into widespread peat-forming, freshwater reed swamps as the fen deposits accumulated. The silt and sand infill formed a network of ridges (roddons) after the surrounding landscape underwent preferential subsidence and erosion largely due to anthropogenic drainage. This change is irreversible and will determine the pattern of future marine transgressions.

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**List of Figures**

**Fig. 1**. Location of the six roddon sites (nos. 1-6) sampled in Cambridgeshire. 1. National Grid Reference TL 230970 (1st Generation) 2. TF 2983900223 (1st Generation); 3. TF 313790442 (2$^{nd}$ Generation); 4. TF 313070 (2nd Generation); 5. TF 3869505292 (generation uncertain); 6. TL 5614491996 (generation uncertain). Modified after Malim (2005) and Redding in Pryor (2005).

**Fig. 2**. Diagram to illustrate the roddon sites sampled, generations, distance from palaeocoast, possible relationship to palaeo river systems, roddon orders and generations. Sources of information: [1] pers.com. Mark Knight, [2,3] Hall, 1987, [4] Hall, 1996, [5]Seale,1975.

**Fig. 3**. Stratigraphic nomenclature of the Fenland Holocene deposits. R1, R2 and R3 = generations of roddons; R1, oldest; R3, youngest. Sediments age in years BP: Terrington Beds – present to at least 2250; Nordelph Peat - present to at least 3250; Barroway Drove

Beds -? 2250 to about 7500 and Lower Peat/Basal Peat – 3390 to at least 7690. (Modified after Horton (1989).

**Fig. 4**. Diagram illustrating the relationship between the main elements of the Fenland Holocene succession. After Zalasiewicz, in Horton (1989).

**Fig. 5**. Collation of sedimentological data from British Geological Survey archived borehole data showing a "Siltlands" silt/sand-rich body of sediments that is laterally equivalent to the clay/peat of the area around Thorney, landward of Spalding and Wisbech.

**Fig. 6**. Disposition of roddons at Wrydelands Farm area, near Thorney (4 on Fig.1) showing position of sites augered (A, B and C) within the local roddon systems (Fig. 8) A=main trunk of roddon, B = a major tributary, and C a minor tributary. The site of the farm is indicated. (© CAM ARC/ Cambridgeshire County Council, 2008. Reproduced with permission).

**Fig.7**. A. View of roddon at Thorney by-pass road looking east, TF 3137904442, distance shown by dotted line is ~75m; B. Detail of roddon showing channel margin at Thorney by-pass road, TF 3137904442; C. Roddon ridges visible by sighting along drain, TF 297062, Thorney area, distance along dotted line is ~50m; D. Roddon ridge on Wrydelands Farmland, Cambs., looking north, TF 31930714, distance from foreground to horizon ~ 400m; E. Counter Drain near to Popley's Gull, "Dog in a Doublet" Bridge, Cambs., showing levee feature of roddon (lighter sediment), thin layer of peat (arrowed) on top of roddon and overlying clays, TF 2971700158, width of roddon ~20m; F. Contorted roddon sediment along the Counter Drain, east of "Dog in a Doublet" Bridge. TF 2855099817, width of roddon

imaged ~25m. Approximate visible limits of roddons on images A, C and D shown by dotted lines.

**Fig. 8**. Two images of the roddon system at Wrydelands Farm Thorney, Cambridgeshire TF 312071. A is an aerial photograph (RC8–AT 25) flown on the 17th May 1975. Copyright reserved (CUCAP). B. An IFSAR radar image. The main trunk roddon of generation 1 is overlain by a thin clay cover and so does not appear on A, while its subtle topographic expression is clearly captured by the radar image (B). The broken circle shows evidence of one roddon generation cross-cutting another. (© CAM ARC/ Cambridgeshire County Council, 2008. Reproduced with permission).

**Fig. 9**. Particle size analysis results for roddon sediments showing relative distal, intermediate and proximal (to coastline) roddon samples and roddon orders (Trunk (T) – widest; Major (M) and Minor (Mi) channel tributaries. See text for discussion. Map after Malim (2005) and Redding in Pryor (2005). (Fig.5 shows auger positions at Wrydelands Farm and Caves Farm graph (bottom right) for key to graphs).

**Fig. 10**. Particle size analysis of the Barroway Drove Bed clays which host the roddon system. Horizontal axis= percentage; vertical axis= depth -2.4m. Arrows indicate a general fining upwards trend.

**Fig. 11**. Stiffkey, north Norfolk TF 9727144158 (left) showing an active channel and sediment infill, slumping, erosion on outer bend and deposition on the inner bend, scale: narrowest section of channel in distance ~ 1.2m; right, aerial image of River Songhua, just

east of Harbin, north east China showing laterally stacked point bars of the meander belt; last accessed 30/05/09. http://en.wikipedia.org/wiki/Songhua_River.

**Fig. 12**. Top: a tidal channel at low tide, Stiffkey, north Norfolk TF9728944204. Bottom: relative proportions of clay, silt and sand at sites A (left bank area); B (left side of channel); C (middle of channel); D (right side of channel) and E (right bank of channel) looking east.

**Fig. 13**. Washed and sieved (125 µm) microfossil content of roddon sediments at Wrydelands Farm, Thorney, Cambridgeshire. Microfossils include: (a) foraminifera, (b) echinoid spines and (c) ostracods. Taken from depth of 1.5m.

**Fig. 14**. Summary map of palaeogeographies of the Fenland at the time of three major marine incursions and the marine Fen clay areas where the roddons may have formed. A. Neolithic (ca 4450 yr BP) - 1st marine incursion; B. Bronze Age (ca 3750 yr BP) –2nd marine incursion; and C. Iron Age (ca 2250 yr BP) - 3rd marine incursion. The Romano-British/Post-Roman event is not represented (after Waller, 1994, Coles & Hall, 1998 and French, 2003).

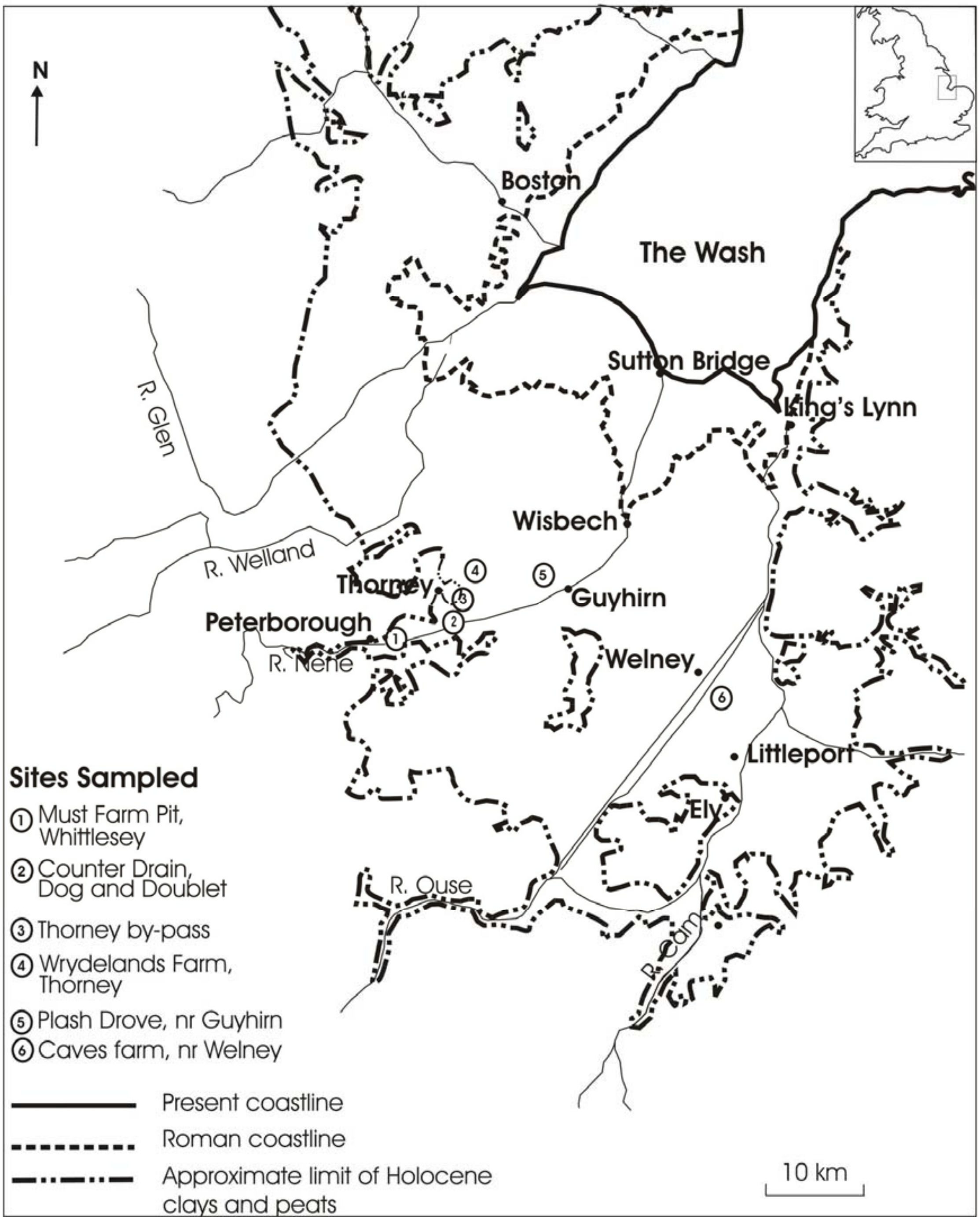
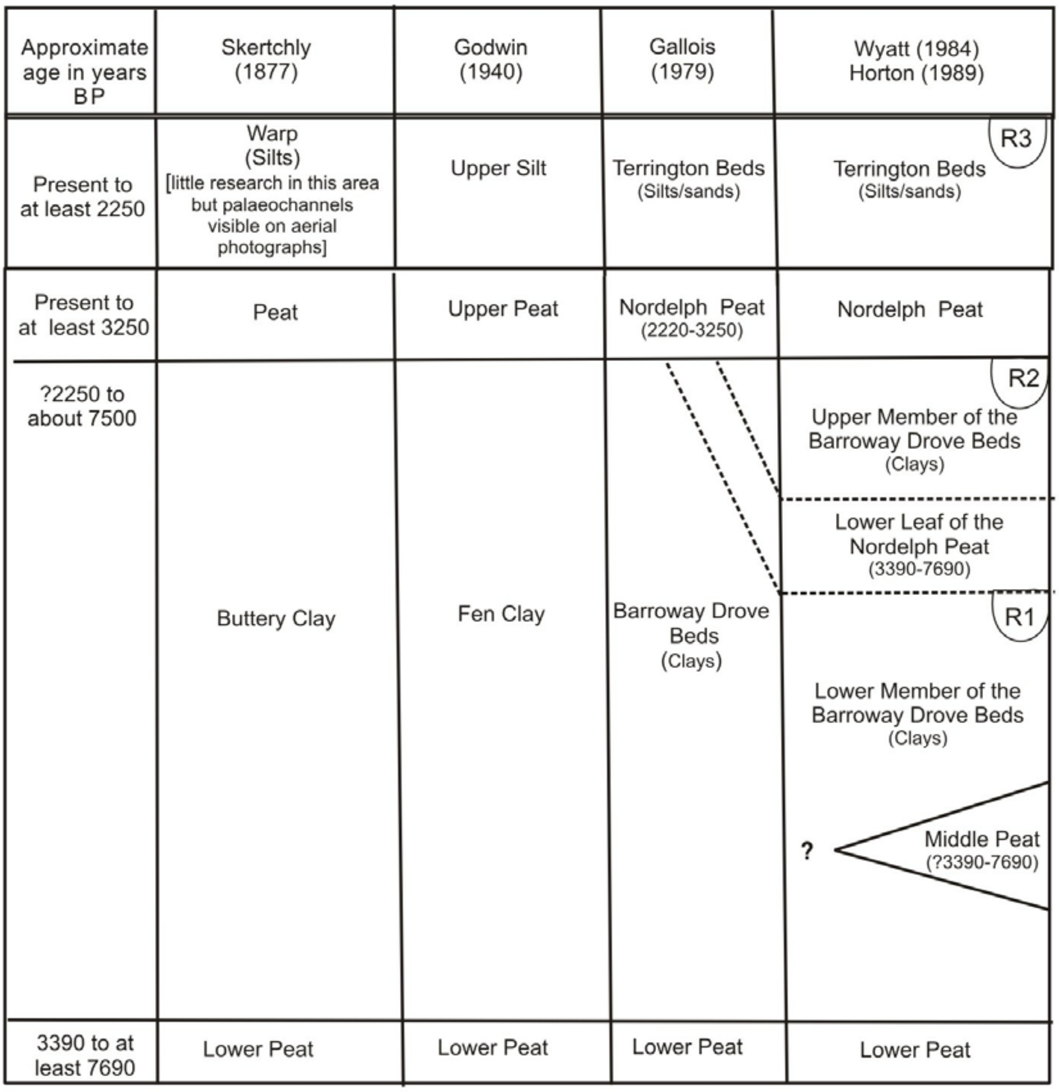

N
Boston
The Wash
Sutton Bridge
King's Lynn
R. Glen
Wisbech
R. Welland
Thorney
Guyhirn
Peterborough
R. Nene
Welney
Littleport
Ely
R. Ouse
R. Cam
Sites Sampled
1 Must Farm Pit, Whittlesey
2 Counter Drain, Dog and Doublet
3 Thorney by-pass
4 Wrydelands Farm, Thorney
5 Plash Drove, nr Guyhirn
6 Caves farm, nr Welney
Present coastline
Roman coastline
Approximate limit of Holocene clays and peats
10 km

**Fig. 1.**



Approximate age in years BP
Skertchly (1877)
Godwin (1940)
Gallois (1979)
Wyatt (1984) Horton (1989)
Present to at least 2250
Warp (Silts) [little research in this area but palaeochannels visible on aerial photographs]
Upper Silt
Terrington Beds (Silts/sands)
R3
Terrington Beds (Silts/sands)
Present to at least 3250
Peat
Upper Peat
Nordelph Peat (2220-3250)
Nordelph Peat
?2250 to about 7500
R2
Upper Member of the Barroway Drove Beds (Clays)
Lower Leaf of the Nordelph Peat (3390-7690)
R1
Buttery Clay
Fen Clay
Barroway Drove Beds (Clays)
Lower Member of the Barroway Drove Beds (Clays)
?
Middle Peat (?3390-7690)
3390 to at least 7690
Lower Peat
Lower Peat
Lower Peat
Lower Peat


**Fig. 2.**

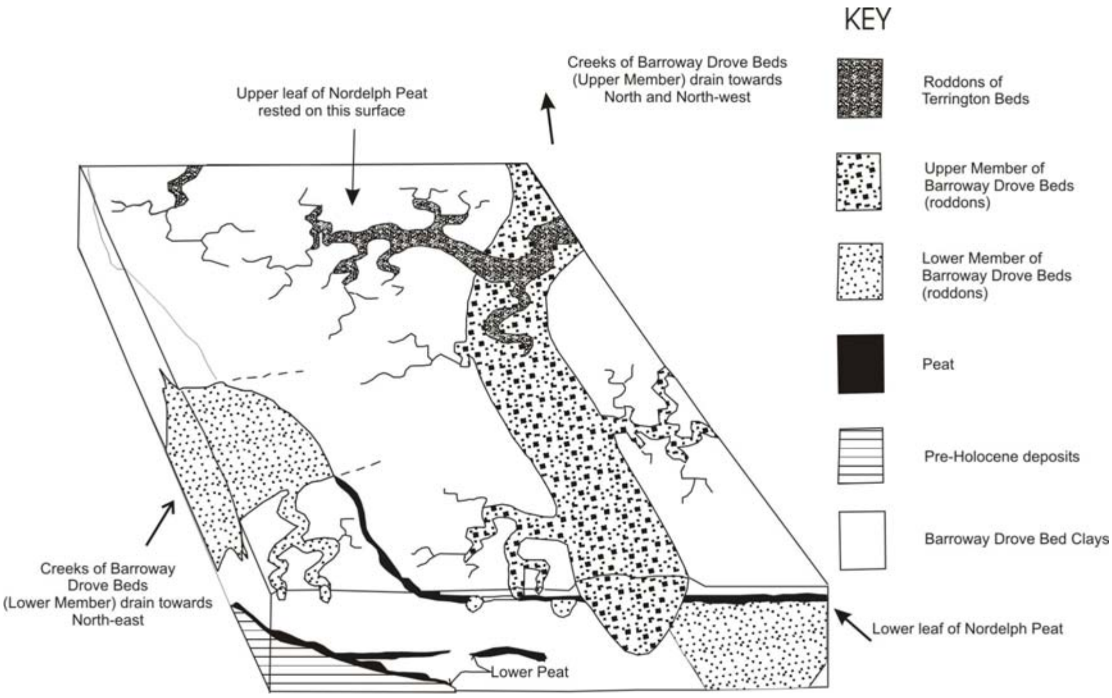

KEY
Roddons of Terrington Beds
Upper Member of Barroway Drove Beds (roddons)
Lower Member of Barroway Drove Beds (roddons)
Peat
Pre-Holocene deposits
Barroway Drove Bed Clays
Upper leaf of Nordelph Peat rested on this surface
Creeks of Barroway Drove Beds (Upper Member) drain towards North and North-west
Creeks of Barroway Drove Beds (Lower Member) drain towards North-east
Lower leaf of Nordelph Peat
Lower Peat

**Fig. 3.**

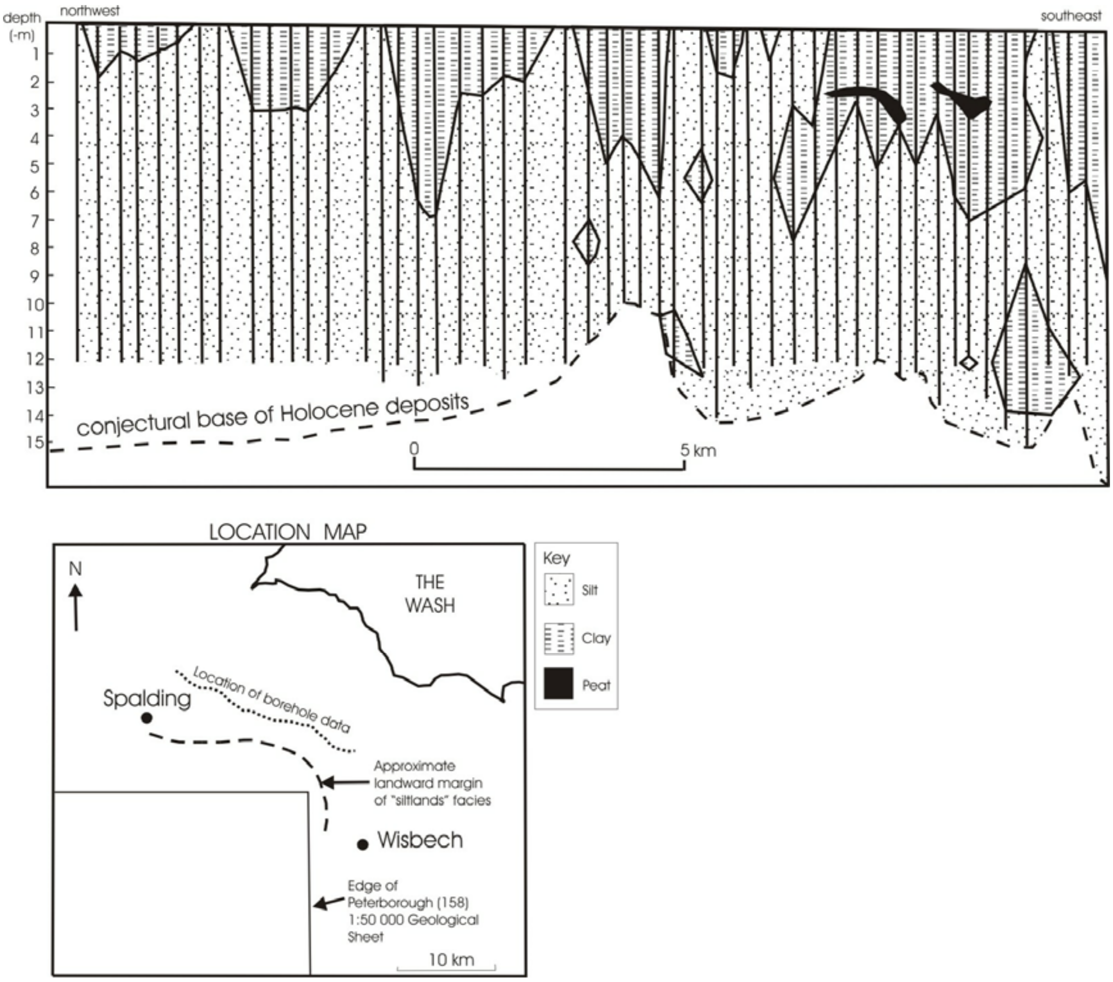
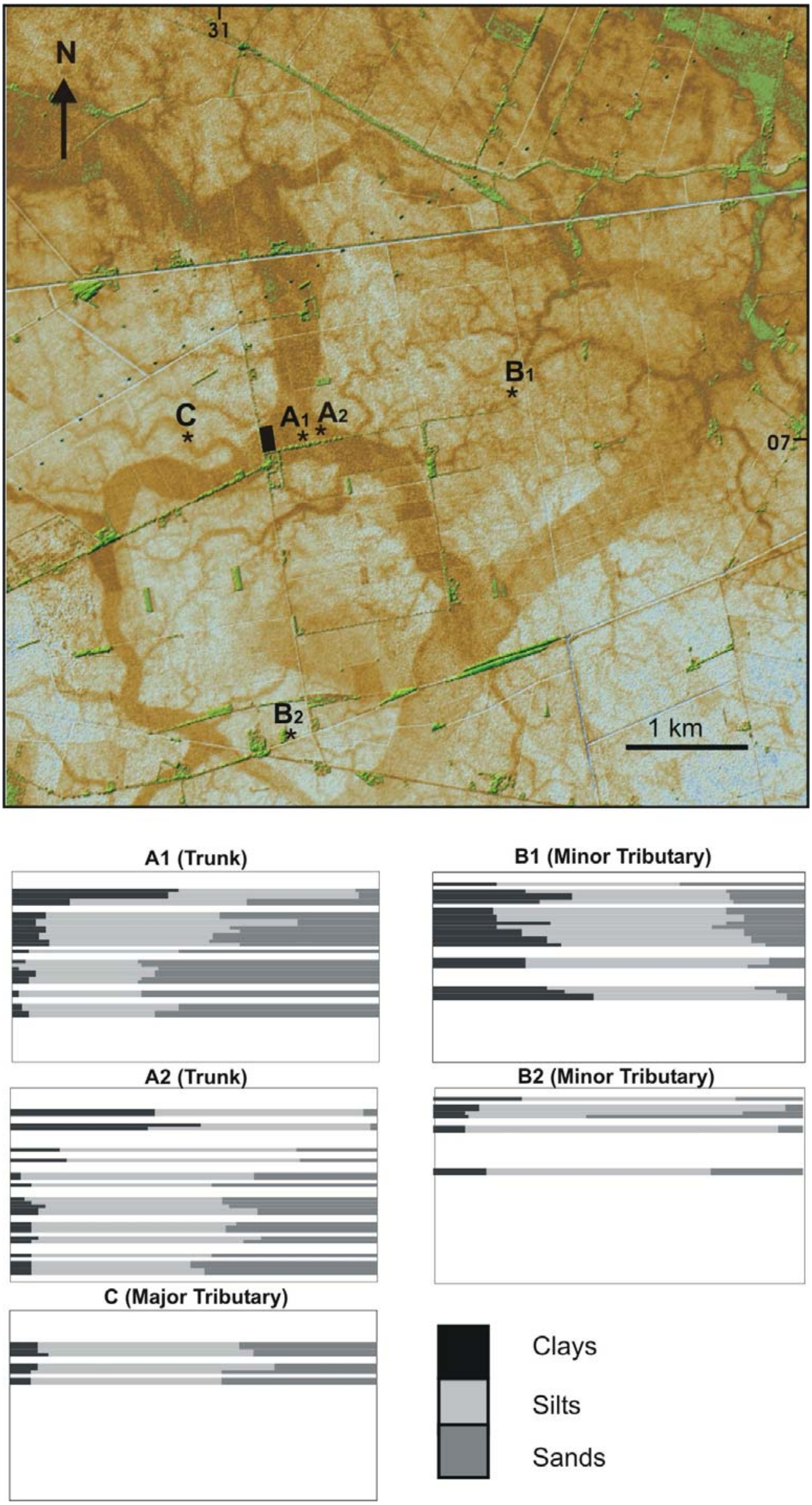

depth
(-m)
northwest
southeast
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
conjectural base of Holocene deposits
0
5 km
LOCATION MAP
N
THE
WASH
Spalding
Location of borehole data
Approximate
landward margin
of "siltlands" facies
Wisbech
Edge of
Peterborough (158)
1:50 000 Geological
Sheet
10 km
Key
Silt
Clay
Peat

**Fig. 4.**



31
N
B1
C
A1
A2
07
B2
1 km
A1 (Trunk)
B1 (Minor Tributary)
A2 (Trunk)
B2 (Minor Tributary)
C (Major Tributary)
Clays
Silts
Sands


**Fig. 5.**

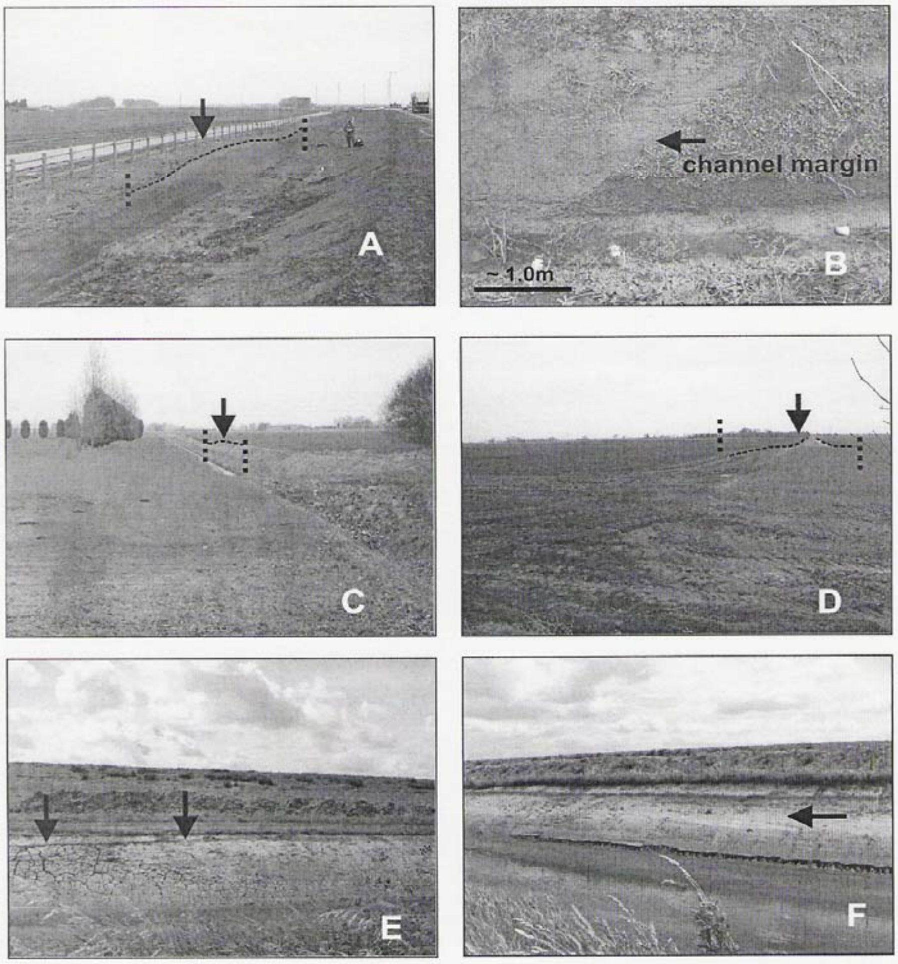



**Fig. 6.**

Fig. 7.

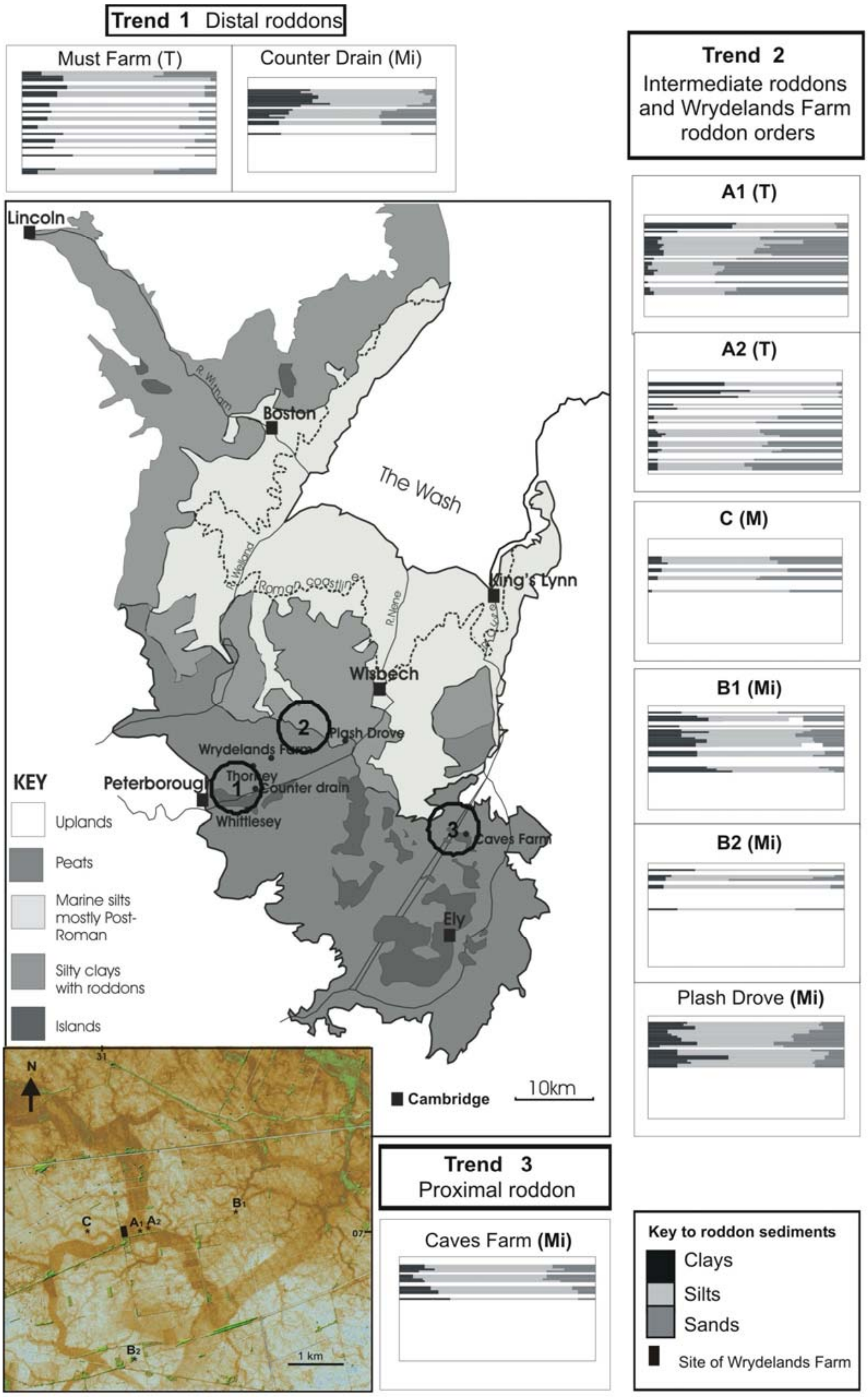

Trend 1 Distal roddons
Must Farm (T)
Counter Drain (Mi)
Trend 2
Intermediate roddons and Wrydelands Farm roddon orders
A1 (T)
A2 (T)
C (M)
B1 (Mi)
B2 (Mi)
Plash Drove (Mi)
Lincoln
Boston
The Wash
King's Lynn
Wisbech
Plash Drove
Wrydelands Farm
Peterborough
Thorney
Counter drain
Whittlesey
Caves Farm
Ely
Cambridge
10km
KEY
Uplands
Peats
Marine silts mostly Post-Roman
Silty clays with roddons
Islands
Trend 3
Proximal roddon
Caves Farm (Mi)
Key to roddon sediments
Clays
Silts
Sands
Site of Wrydelands Farm
1 km

**Fig. 8.**

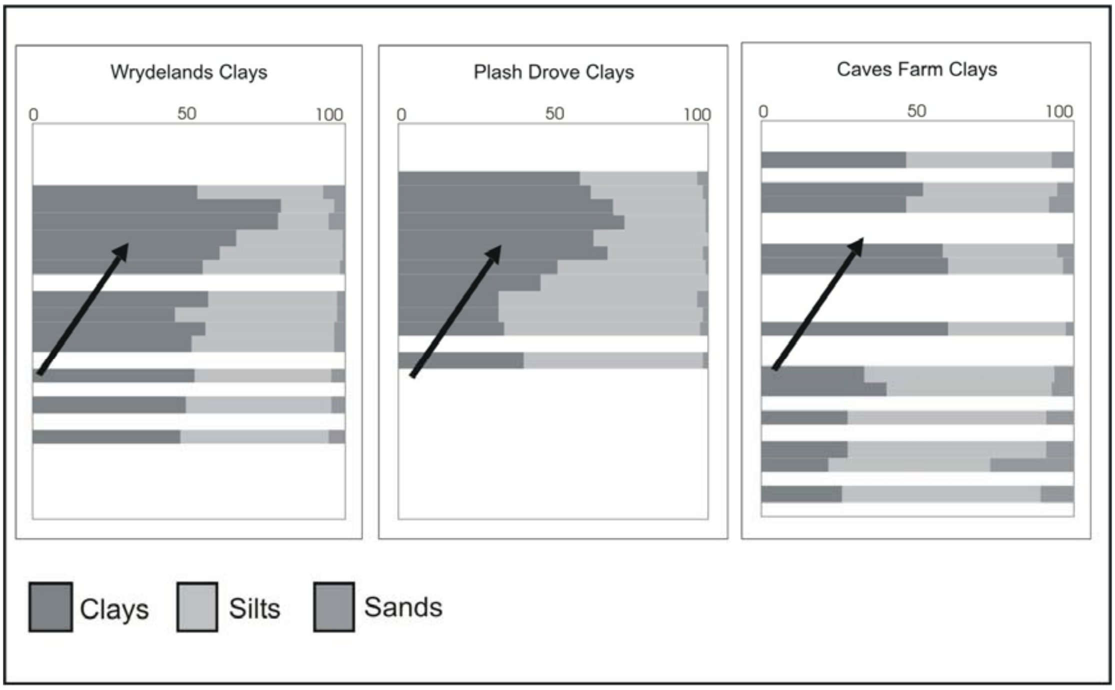

Wrydelands Clays
Plash Drove Clays
Caves Farm Clays
0
50
100
Clays
Silts
Sands

**Fig. 9.**

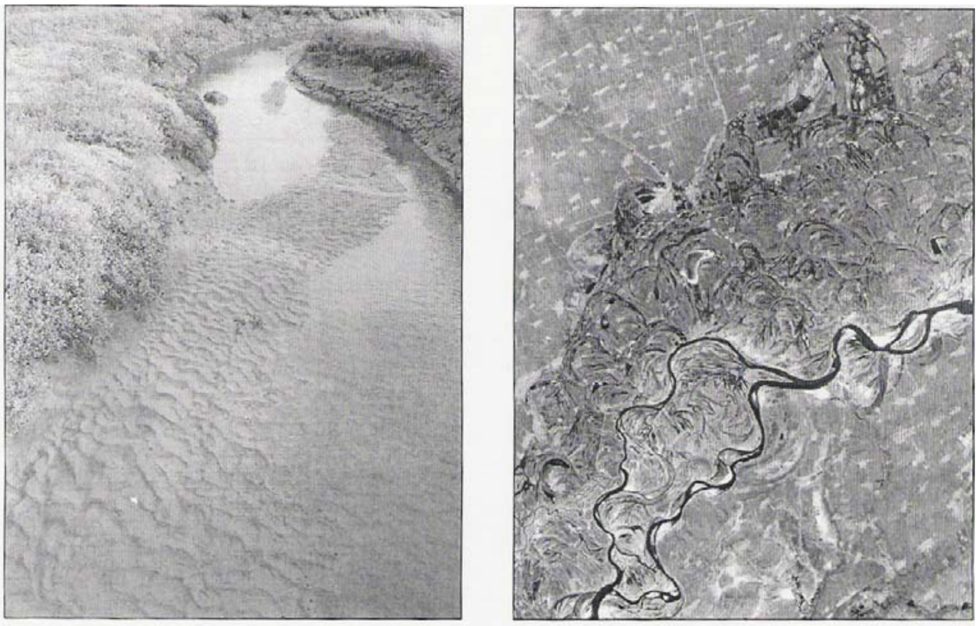
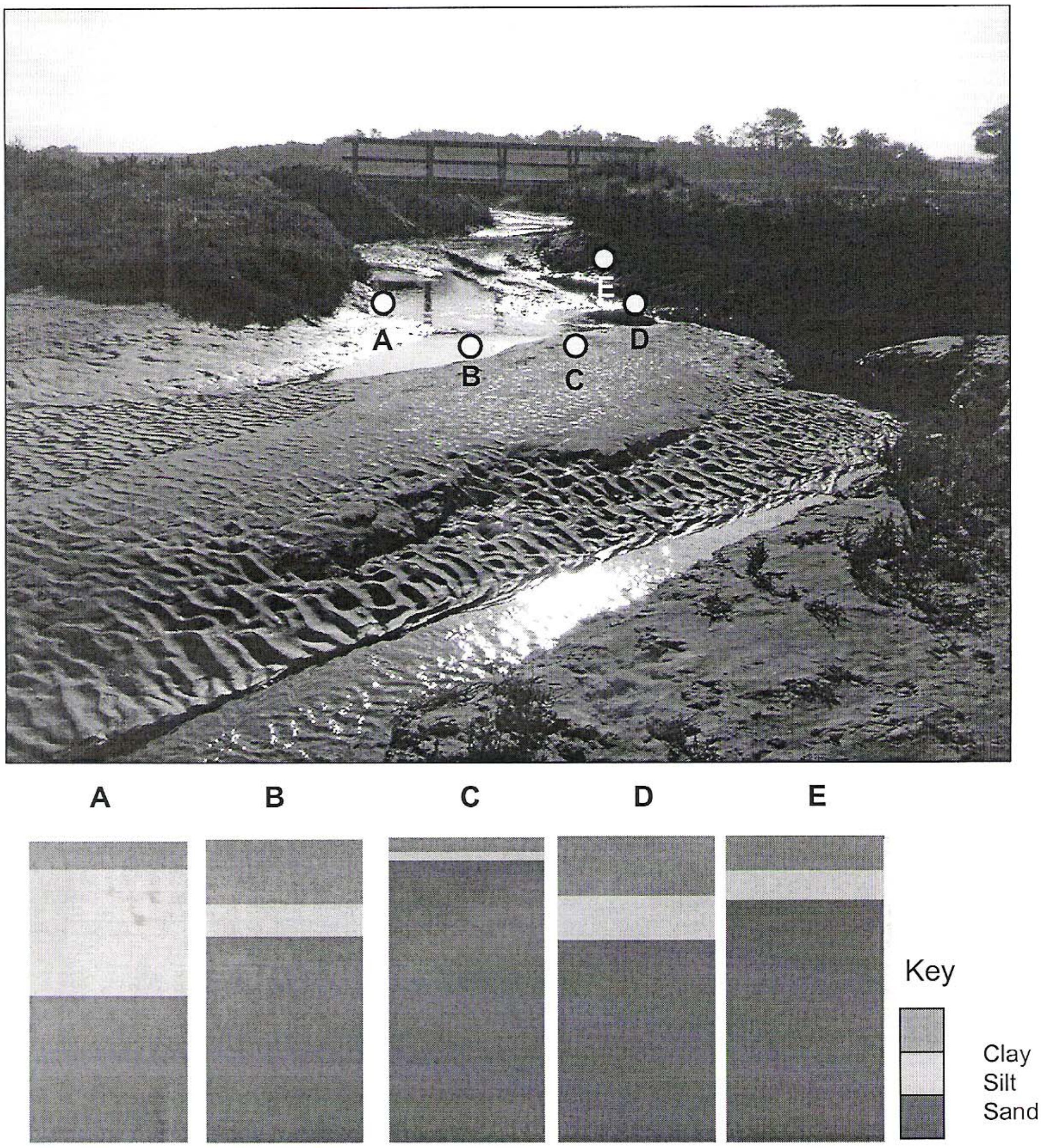


**Fig. 10.**

Fig. 11.



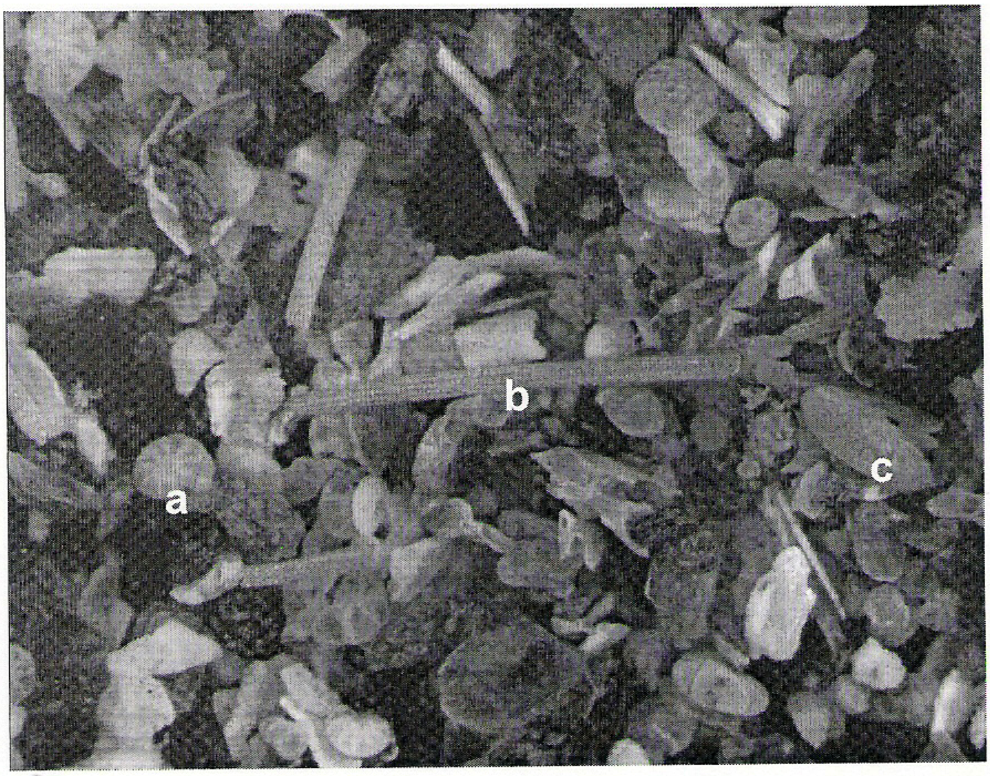



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**Fig. 12.**

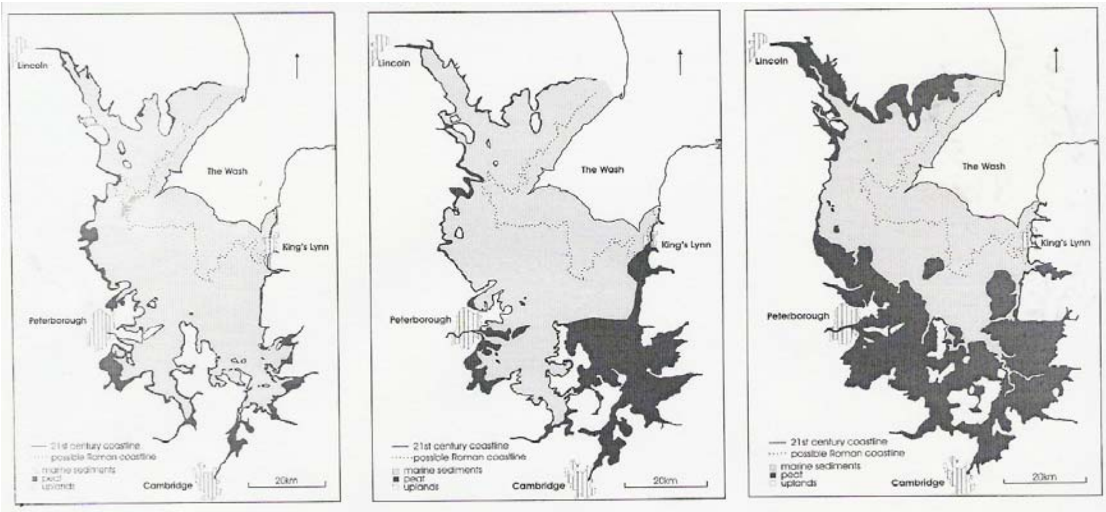
Lincoln
The Wash
King's Lynn
Peterborough
Cambridge
21st century coastline
possible Roman coastline
marine sediments
peat
uplands
20km
Lincoln
The Wash
King's Lynn
Peterborough
Cambridge
21st century coastline
possible Roman coastline
marine sediments
peat
uplands
20km
Lincoln
The Wash
King's Lynn
Peterborough
Cambridge
21st century coastline
possible Roman coastline
marine sediments
peat
uplands
20km

**Fig. 13.**