LEE, J R, PAWLEY, S M, ROSE, J, MOORLOCK, B S P, HAMBLIN, R J O, CANDY, I, BARENDREGT, R W, BOOTH, S J, AND HARRISON, A M. 2008. Pre-Devensian lithostratigraphy of shallow marine, fluvial and glacial deposits in northern East Anglia. *Quaternary of northern East Anglia - Field Guide*. CANDY, I, LEE, J R, AND HARRISON, A M (editors). (Edinburgh: Quaternary Research Association.)

Pre-Devensian lithostratigraphy of shallow marine, fluvial and glacial sediments in northern East Anglia

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Introduction

Historically, a wide range of stratigraphical approaches have been applied to examining the Early and Middle Pleistocene succession of northern East Anglia including conventional biostratigraphy and lithostratigraphy (Boswell, 1916; Banham, 1968; Perrin *et al*., 1979; West, 1980a; Bowen *et al*., 1986; Preece and Parfitt, 2000). Both of these approaches underpin the 'official' stratigraphic classification for Quaternary Deposits in the British Isles, published first in the mid-seventies (Mitchell *et al*., 1973), and then revised in the late-nineties (Bowen, 1999a).

Whilst both of these schemes are classical and important works they do possess several significant drawbacks that limit their general applicability. Firstly, little attempt has been made to describe the variability of the stratigraphic units away from their stratotype localities, and this makes determining their spatial extent and geometric inter-relationships problematic (McMillan, 2005). This is certainly the case in northern East Anglia, an area with arguably the best Early and Middle Pleistocene terrestrial record anywhere in north-western Europe, and where the stratigraphic scheme of Bowen (1999) is largely unworkable from a mapping perspective (McMillan, 2005). Secondly, although conventional biostratigraphy and lithostratigraphy have traditionally been used in the construction of Quaternary sequences, it is questionable as to whether their applicability to the Quaternary time-scale is appropriate. This is because both biostratigraphy and lithostratigraphy were conventionally devised for use within the Palaeozoic and Mesozoic time- scales (Salvador, 1994; Rawson *et al*., 2002). During these time periods, local and regional scale patterns of evolution, biodiversity and geological process were effectively masked by low temporal resolution—a function of both true age (tens to hundreds of millions of years) and the corresponding relative accuracy and precision of geochronometric dating techniques. Within a low-resolution pre- Quaternary sequence, it is relatively straightforward to make stratigraphic correlations over wide spatial areas because small-scale local and regional geological and ecological processes are relatively insignificant. The Quaternary time-scale is by contrast a higher-resolution period of time by several orders of magnitude, with many of the scientific themes and issues currently being addressed by the Quaternary community requiring chronologies to be constructed that relate to marine isotope stage / sub-stage scales. Accordingly, within the Early and Middle Pleistocene, Quaternary scientists are working with a chronological resolution of hundreds to tens of thousands of years, whilst within the Late Pleistocene and Holocene, they are working to thousands to hundreds of year's resolution—all of these time-scales operate well within the temporal scales of local and regional patterns of evolution, biodiversity and geological processes. Any biostratigraphic or lithostratigraphic attempt to correlate over and between large spatial areas must therefore, as a matter of course, conform to standard geological and ecological principles.

In northern East Anglia, the inter-relationship between geological processes and lithostratigraphy has been long recognised most notably with research focusing upon the preglacial river systems (Rose *et al*., 1976; Whiteman and Rose, 1992; Lewis, 1993; Bridgland, 1994) and glacial deposits (Banham, 1975; Hart and Boulton, 1991b; Lunkka, 1994). However, an integrated process-based lithostratigraphic approach linking the shallow marine, fluvial and glacial deposits of the region has not been attempted at a regional scale. The advantage of stratigraphically linking these three sedimentary systems together into a single model is that it provides a geological basis for understanding the dynamics of Early and Middle Pleistocene sedimentary systems in terms of their temporal and spatial response to neotectonic and climatic drivers. Within this overview paper, we present such a scheme based upon geological mapping, and the detailed lithological and sedimentological examination of Quaternary deposits in the region (Figure 1).

Pre-Anglian Fluvial Deposits

Thames River Sequence

The oldest lithostratigraphic unit of the Kesgrave Thames is the Nettlebed Formation. It consists of gravelly sand with occasional beds of organic material (Horton and Turner, 1983). The lithology of the gravel component is almost exclusively dominated by locally-derived flint with minor quantities of Greensand chert from the Weald and quartzose lithologies derived from the west of the London Basin (Rose *et al*., 1999b).

The Kesgrave (Group) Sands and Gravels are the main stratigraphic subdivision of pre-glacial Thames deposits and consist of stratified sands and gravels laid- down within a braided river complex. The sands and gravels occur extensively beneath Anglian till throughout southern East Anglia where they have been subdivided into two formations, the Sudbury and Colchester formations, based upon lithology—further lithostratigraphic subdivision into individual terrace members is based upon elevation (Whiteman and Rose, 1992; Rose *et al*., 1999b). The older of the two formations, the Sudbury Formation, is characterised by a high occurrence (up to 30%) of non-local white and colourless quartzose lithologies, with minor proportions of Greensand and Carboniferous chert, and acid igneous lithologies from North Wales such as rhyolite and ignimbrite. The white and colourless quartzose lithologies are distinct from coloured varieties within the latter Colchester Formation, a property considered by Hey (1965) to reflect *in situ* bleaching by acid groundwater. The younger unit, the Colchester Formation, is characterised by approximately 20% red and brown quartzose lithologies, with smaller proportions of Carboniferous and Greensand chert, and acid igneous lithologies. Differences in the proportions and colour of the quartzose lithologies are considered by Whiteman and Rose (1992) to reflect a significant change in the catchment dynamics of the Thames. The range of clast lithologies within the Sudbury Formation indicate that the Thames extended westwards from southern Eas tAnglia and the Weald into Midland England and north Wales. By contrast, during the deposition of the Colchester Formation, the Thames catchment had shrunk in size draining headwaters in the Cotswolds and West Midlands (Rose *et al*., 1999b). The occurrence of igneous lithologies in significant proportions was considered by Whiteman and Rose (1992) to suggest that Welsh glacier ice encroached into the headwaters of the Thames.

Bytham River Sequence

The Bytham River system was a major river system that drained the West and East Midlands and East Anglia until it was overridden and destroyed by ice during the Anglian Glaciation (Rose, 1987, 1994). The river has no surface expression within the modern landscape and evidence for its existence, in the form of extensive tracts of sand and gravel, are buried beneath Anglian till (Lewis, 1993). The terrace sequence of the river system was first established across the Midlands and the western end of the Waveney Valley by Lewis (1993), and later extended across to the North Sea coast in the vicinity of Great Yarmouth and Lowestoft by Lee *et al*. (2004a). Within East Anglia, a total of six separate river terraces have been identified on the basis of elevation and the presence of soil horizons signifying a stabilised terrace surface (Lewis, 1993; Lee *et al*., 2004a). Typically, the Bytham sands and gravels are dominated by durable clast lithologies derived from the Triassic of the West Midlands—most notably red or brown vein quartz, quartzite and sandstone. Carboniferous chert from the Pennines and Spilsby (glauconitic) Sandstone from the Lower Cretaceous of Lincolnshire are present in only minor quantities (Lewis, 1993; Lewis *et al*., 1999; Rose *et al*., 1999b). Clasts of soft lithologies such as Mercia Mudstone and Chalk are locally present but degrade rapidly away from source. Heavy minerals from Bytham River sands are also distinctive from other pre-glacial deposits in EastAnglia (Lee, 2003). Common diagnostic minerals include zircon, tourmaline and kyanite from Triassic strata of the West Midlands, rutile from the Carboniferous and cryptocrystalline apatite (collophane) from Jurassic and Lower Cretaceous mudstones (Bateman and Rose, 1994; Lee *et al*., 2004a). Glacial input into the Bytham River is recognised within the third Timworth Terrace where glacially-derived erratics, heavy minerals and reworked till clasts have been identified (Rose *et al*., 2000; Lee *et al*., 2004a). Fluvial deposits of the Cromer Forest-bed Formation at Corton and Pakefield on the coast (West, 1980a), and Norton Subcourse further inland (Lewis *et al*., 2004), are likely to be alluvial deposits of either the Bytham itself or its tributaries.

Ancaster River Sequence

The Ancaster River is inferred to have drained a catchment extending from the Pennines and East Midlands, across Lincolnshire and the present offshore area between Lincolnshire and north Norfolk during the Early and Middle Pleistocene (Rose *et al*., 2001). No deposits of the Ancaster River have been formally recognised however it is likely that some of the fluvial elements of the Cromer Forest-bed Formation of north Norfolk including the Cromer Forest-bed *sensu stricto*, may be deposits of this river system. In the absence of firm, direct evidence, the existence of the Ancaster River has been inferred based upon the reconstructed form of the pre-glacial land surface (Clayton, 2000), and the presence of northern-derived clast lithologies. These include white vein quartz in higher proportions than in Bytham and Kesgrave deposits—presumably derived from the Pennines (Hey, 1976; Green and McGregor, 1990; Rose *et al*., 1999b), *Rhaxella* chert from east Yorkshire (Rose *et al*.,1999b) and Lias limestone from Lincolnshire in stratigraphically equivalent shallow marine deposits (Lee, 2003).

Pre-Anglian Marine Deposits

Norwich Crag Formation

The Norwich Crag Formation comprises several sand, sand and gravel and clay shallow marine units. These include several members that were deposited within a nearshore or beach environment, such as the Chillesford Sand and Westleton Bed members (Mathers and Zalasiewicz, 1988, 1996; Richards *et al*., 1999), and the Chillesford Clay Member, which was deposited within an estuarine or tidal-flat environment (Allen and Keen, 2000). The clast composition of the Westleton Bed Member is dominated by locally-derived flint, with minor quantities of far-travelled colourless vein quartz and quartzite, and *Rhaxella* chert (Rose *et al*., 2001). Riding *et al*. (1997, 2000) and Moorlock *et al*. (2002b) noted the presence within the Norwich Crag of Silurian palynomorphs from the Welsh Borders, and Carboniferous and Jurassic palynomorphs from the Pennines and East Midlands.

Wroxham Crag Formation

The Wroxham Crag Formation is a stratigraphic term recently introduced to describe quartz-bearing shallow marine deposits in northern EastAnglia that outcrop between the Norwich Crag Formation and the Lowestoft Formation.They includes the Bure Valley Beds of Cambridge (1978a,b), marine elements of the Cromer Forest-bed Formation (West, 1980a), and quartz-bearing sands and gravels previously attributed to the Kesgrave Thames (Hamblin and Moorlock, 1995; Green and McGregor, 1996; Hamblin *et* al., 1996; Rose *et al*., 1996a). Four separate members of the Wroxham Crag Formation have been defined. The basal two members, the Dobbs Plantation Member and the How Hill Member, have been mapped extensively throughout the Waveney Valley and southern Norfolk (Rose *et al*., 2001, 2002; Lewis *et al*., 2004; Lee *et al*., 2006a). The basal member is the Dobbs Plantation Member—flint-rich gravels with up to 10% far-travelled clast lithologies including quartz and quartzite (mainly colourless), Greensand and *Rhaxella* cherts. This passes upwards into the How Hill Member, and this contains up to 30% far-travelled clasts including quartz and quartzite (mainly red and brown); Greensand, *Rhaxella* and Carboniferous cherts; Spilsby (glauconitic) sandstone; and far-travelled northerly-derived sandstones and crystalline rocks from North Wales and northern Britain (Rose *et al*., 1996b, 2001, 2002; Lee *et al*., 2006a). The Mundesley Member occurs in north Norfolk and has been mapped in the Aylsham district, as well as in coastal sections between Happisburgh and Weybourne. The unit consists of flint-rich gravels with up to 30– 40% far-travelled clasts including vein quartz and quartzite (mainly colourless), *Rhaxella* and Carboniferous chert, Carboniferous sandstone, Jurassic limestone and erratics of northern provenance (Briant *et al*., 1999; Davies *et al*., 2000; Lee, 2003; Pawley *et al*., 2004). The Pakefield Member consists of shallow marine deposits that occur between the glacial Happisburgh and Lowestoft formations and has been recognised both at Pakefield (Lee *et al*., 2006a, this guide) and on the southern outskirts of Norwich (Read *et al*., 2007).

Pre-Devensian Glacial Deposits

Since the last QRA field trip to East Anglia in April 2000, a new stratigraphy for the glacial deposits of the region has been proposed (Figure 2) (Hamblin *et al*., 2000, 2005; Lee *et al*., 2004b). Central to this new scheme is the fact that the Walcott Till ('Second Cromer Till') does not occur stratigraphically beneath the Lowestoft Till (Moorlock *et al*., 2000a) as previous models suggest (Banham, 1968; Bowen *et al*., 1986; Ehlers *et al*., 1991 Lunkka, 1994). Instead the two tills are laterally equivalent, forming a single mappable till sheet that extends from north Norfolk southwards into Suffolk and Essex (Hamblin *et al*., 2000, 2005). Beneath this regionally extensive till sheet, which forms the Lowestoft Formation, the 'First Cromer Till' of Banham (1968) has been sub-divided into two separate and mappable till units, and together with associated outwash deposits, are assigned to the Happisburgh Formation. The 'Third Cromer Till' and 'Marly Drift' of Banham (1968), which now overlie the Lowestoft Formation, are assigned to the Sheringham Cliffs Formation, and sands and gravels associated with the Cromer Ridge and ice- marginal landforms of the Glaven Valley belong to the Briton's Lane Formation. In addition to this, detailed examination of the lithology of these tills has demonstrated that previous assertions that the sandy 'Cromer Tills' are of Scandinavian origin (Perrin *et al*., 1979; Bowen *et al*., 1986; Ehlers and Gibbard, 1991) are incorrect, and they were actually deposited by the British Ice Sheet (Lee *et al*., 2002, 2004b; Pawley *et al*., 2004). A schematic diagram showing the glacial stratigraphy exposed within the coastal sections is shown in Figure 3, and its correlation with other sites within northern East Anglia in Figure 4.

Happisburgh Formation

The Happisburgh Formation consists of two principal till units, the Happisburgh Till and Corton Till members, separated and overlain by outwash lithofacies. The Happisburgh Till Member ('First Cromer Till' of Banham (1968)) is the basal lithofacies of the Happisburgh Formation and crops-out as far south as Happisburgh, and westwards to Wickmere approximately 8km south of Cromer (Moorlock *et al*., 2002a). The diamicton consists of a grey, massive, matrix-supported diamicton that was deposited subglacially (Hart, 1987; Lunkka, 1994; Lee, 2001) by the British Ice Sheet flowing down the east coast of England (Lee *et al*., 2002). The till is separated from the Corton Till Member by a sequence of laminated clays and sands that record a phase of deglaciation following this initial ice advance (see Happisburgh—this guide).

The Corton Till Member represents a major, more extensive readvance of the British Ice Sheet across the region (Lee *et al*., 2002). The unit crops-out extensively from Happisburgh across north Norfolk to Sparham 25km west of Norwich, and southwards into the Waveney Valley as far south as Diss and Lowestoft (Arthurton *et al*., 1994; Lewis *et al*., 1999). The diamicton is brown and sandy in appearance with abundant flint clasts. It is generally massive, matrix-supported, and highly consolidated and was deposited subglacially by grounded ice (Hopson and Bridge, 1987; Lee, 2003). Locally, for example at Corton near Lowestoft, the diamicton is weakly stratified and comprises beds of reworked diamicton and stratified sand. At this locality the deposit has been interpreted as representing the eroded remnants of a subaqueous grounding-line position (Lee, 2001). At its Corton stratotype and throughout the Waveney Valley, the Corton Till Member is overlain by coarse- and fine-grained glaciofluvial outwash deposits called the Leet Hill Sand and Gravel and Corton Sand members (Hopson and Bridge, 1987; Rose *et al*., 1999a; Lee *et al*., 2004a). The Corton Sand Member in particular is a distinctive unit comprising chalky fine sands and these have been traced extensively northwards from the Waveney Valley to Happisburgh and Aylsham.

Lowestoft Formation

The Lowestoft Formation defined here is different to that defined by Bowen (1999), and comprises two principal till units within northern East Anglia. Firstly, the Lowestoft Till Member, which is equivalent to the 'Jurassic Boulder Clay' recognised on the coast around Lowestoft by Baden-Powell (1948). It consists of a massive, matrix-supported diamicton with its characteristic battleship grey colouration and a clay-rich matrix containing numerous chalk and flint clasts (Baden-Powell, 1948; Banham, 1971; Pointon, 1978; Perrin *et al*., 1979). Analysis of the derived microfossil content of the matrix demonstrates that is almost exclusively composed of Kimmeridge Clay from the Fen Basin (Lee *et al*., 2004b). The Walcott Till Member equates to the 'Second Cromer Till' of Banham (1968) or the 'Walcott Diamicton' of Lunkka (1994). It is a weakly stratified matrix-supported diamicton with a silt-rich matrix texture and pebble assemblage dominated by flint and chalk. The derived microfossil content (Moorlock *et* al., 2000a)enables components of the matrix to be provenanced to the Carboniferous of northern England and the Midland Valley of Scotland, and Jurassic and Lower Cretaceous strata in the Yorkshire Basin. Both tills are widely considered to be subglacial in origin. Lithological differences between the two tills reflect separate ice flow trajectories within the same ice sheet and the subsequent erosion and incorporation of different bedrock materials into the till.

Sheringham Cliffs Formation

The Sheringham Cliffs Formation consists of all sediments overlying the Walcott Till Member, up to and including the chalky 'Marly Drift' of Perrin *et al*. (1979). This includes the 'Mundesley Sands' and 'Third Cromer Till' of Banham (1968), and the glaciolacustrine clays, marl and sands described at

Trimingham by Hart (1992). Within this stratigraphy, the 'Third Cromer Till' is sub-divided into two separate till units based upon structure and genesis, and these crop-out in north Norfolk north of a line linking Dereham and Bacton. The basal till unit is the subglacial Runton Till Member—a dark grey matrix-supported diamicton containing brecciated and attenuated inclusions of chalk and 'Walcott Till Member' material. The upper till unit is the subaqueous Bacton Green Till Member—a stratified diamicton containing beds of sorted sand and sandy diamicton. Clast and derived microfossil assemblages from both tills are similar to some of the older tills in the region, indicating ice flow through and the erosion and transportation of bedrock lithologies from the Midland Valley of Scotland and Yorkshire Basin (Lee *et al*., 2004b). The 'Marly Drift' is renamed the Weybourne Town Till Member (Lee *et al*., 2004b). It consists of a highly calcareous, chalky, subglacial till with abundant brecciated chalk, both assimilated into the diamicton matrix and as clasts. Locally, such as at Weybourne Town Pit (Fish *et al*., 2000; Fish and Whiteman, 2001) and Weybourne Cliffs, the Weybourne Town Till overlies and has partially incorporated Bacton Green till as part of a subglacial deforming bed till, giving the till a distinctly stratified appearance. Provenance analysis of chalk clasts from the Weybourne Town Till demonstrate that chalk was derived from the northwest and west of the site (Fish *et al*., 2000, 2001) supporting clast lithological and structural observations (Banham and Ranson, 1965; Fish *et al*., 2000; Fish and Whiteman, 2001; Pawley *et al*., 2004).

Briton's Lane Formation

The Briton's Lane Formation is a complex succession of outwash sands and gravels that drape the pre-existing geology north of a line linking NorthWalsham in the east and Thursford in the west (Moorlock *et al*., 2002a; Pawley, 2006). Two principal phases of outwash development comprising different stratigraphical units can be recognised, and these can be distinguished based upon their tectonostratigraphic relationship to the formation of the Cromer Ridge push moraine complex (*sensu* Hart, 1990). The first outwash phase consists of four outwash units that exhibit a range of compressive structural features reflecting deposition prior-to and during the formation of the Cromer Ridge push moraine (Lee *et al*., 2004b). The most extensive of these units is the Briton's Lane Sand and Gravel Member. This unit is over 40m thick at its Beeston Regis stratotype locality, but thins progressively southwards and westwards towards Norwich and Thursford (Pawley *et al*., 2005). The unit is important because in addition to a British erratic suite, it also contains a range of igneous and metamorphic clast lithologies from southern Norway including rhomb porphyry (Moorlock *et al*., 2000), and this represents a fresh and new lithological input into the sedimentary system (Lee *et al*., 2004b; Pawley *et al*., 2004, 2005). The second outwash phase equates to the outwash deposits and ice contact landforms on the northern seaward side of the Cromer Ridge.These include the Blakeney esker and the kames and kame terraces of the Glaven Valley which record successive ice-marginal retreat phases (Straw, 1975; Pawley, 2006; Pawley *et al*., 2006).

Lithostratigraphic and Chronostratigraphic Correlation

An integrated lithostratigraphic model for the fluvial, shallow marine and glacial deposits of northern EastAnglia can be attempted by linking the lithology and genesis of particular deposits into time-equivalent land systems. Put simply, the lithological signature of fluvial systems can be traced through the terrace deposits of the catchment and into their equivalent shallow marine offshore deposits (Figure 5). In a similar manner, fresh input of far-travelled material into northern East Anglia by glaciers can also be recognised within and traced through the sedimentary sequence.

Nettlebed Formation and Norwich Crag Formation

The Nettlebed Formation of the Thames River System can be stratigraphically linked to the Norwich Crag Formation. This is based upon the presence of a dominantly local (flint) clast assemblage and far-travelled fine sediment fractions within the Norwich Crag Formation, consisting of Silurian and Carboniferous palynomorphs that can be provenanced to the Thames catchment (Riding *et al*., 1997, 2000; Rose *et al*., 2001; Moorlock *et al*., 2002b). However, despite possessing extensive river catchments, the dominance of locally-derived clast lithologies suggests that these rivers were relatively sluggish at this time, and did not possess the energy regime or sediment budgets to recycle large quantities of bedload either quickly or over extensive distances. This reflects the climate dynamics during the Early Pleistocene that were driven by high frequency-low magnitude climatic oscillations (41ka and 21ka Milankovitch cycles).

Sudbury Formation, Bytham Sands and Gravels, Dobbs Plantation Member

The relative abundance of white quartzose lithologies, Carboniferous chert, *Rhaxella* chert, Greensand chert and Spilsby (glauconitic) sandstone characterise bedload input into the Wroxham Crag basin by the Thames, Bytham and Ancaster river systems (Whiteman and Rose, 1992; Rose *et al.*, 1999a,b, 2001, 2002). The dominance of white and colourless quartzose lithologies, coupled with the relative abundance of *Rhaxella* chert suggest that the Thames and Ancaster rivers were the dominant river systems of central and eastern England at this time, and the Bytham by contrast, was comparatively small (Rose *et al.*, 2001). The Thames catchment, the largest river in southern and central Britain, probably extended westwards into Wales as indicated by the presence of acid volcanic rocks from North Wales (Whiteman and Rose, 1992). The mixed assemblage of local and far-travelled lithologies suggests that clasts were being recycled relatively efficiently through all of the major river systems as bedload. This transition from suspension- to bedload-dominated rivers represents a fundamental shift in the drainage dynamics of southern Britain and is considered to coincide with the gradual intensification of the global climate signal through the Early Pleistocene. The presence of the marine bivalve *Macoma balthica* within the Dobbs Plantation Member of the Wroxham Crag Formation at Wroxham provides a chronological handle to this fluvial and marine sequence, as it makes its first appearance in TC4c within the Netherlands (Meijer, 1993), which is broadly equivalent to MIS 68 (Gibbard*et al.*, 1991; Funnell, 1995).

Colchester Formation, Bytham Sands and Gravels, How Hill and Mundesley Members

The lower frequency of far-travelled fluvially-derived clast lithologies and the progressive increase in the proportions of coloured quartzose clasts characterise the input of the Thames and Bytham rivers into the North Sea Basin. The How Hill Member of the Wroxham Crag Formation is the coastal equivalents to the Colchester Formation and the Bytham sands and gravels, and crop-out between How Hill and the Waveney Valley in southern Norfolk. The lateral equivalent of the How Hill Member in North Norfolk is considered to be the Mundesley Member, and this represents a separate offshore area receiving colourless quartzose materials, Jurassic and Carboniferous limestone from the Pennines and Lincolnshire via the Ancaster River.

The relative abundance of coloured quartzose lithologies within the How Hill Member and equivalent fluvial lithofacies indicates derivation from the Triassic conglomerates of the West Midlands. This suggests that a major reorganisation of drainage had occurred in southern Britain, with the headwaters of the Bytham River extending further westwards at the expense of the Thames catchment. It is probable that this drainage reorganisation was driven by the transition of climate in the late Early Pleistocene to one dominated by high magnitude-low frequency eccentricity- driven climatic fluctuations. This change, recognised within the marine isotope record, occurs at approximately 1.2 Ma—broadly equivalent to MIS 30. The overall effect of this climatic regime was to enhance both seasonality and major changes in surface and catchment processes between temperate and cold stages, and this appears to have exerted a major influence of patterns of river terrace aggradation and incision and cycles of sea-level change observed within the region (Bridgland, 1994, 2000, 2006; Lee *et al.*, 2004a, 2006a; Rose, 2006).

Happisburgh Formation and Bytham Sands and Gravels

The age of the Happisburgh glaciation is highly controversial but it based upon correlation of till units with the reconstructed Bytham terrace sequence. This correlation is possible because reworked clasts of Happisburgh Formation till, and glacially-derived heavy minerals and erratics occur within the Bytham sands and gravels (Rose *et al.*, 2000; Lee *et al.*, 2004a). This glacial input into the Bytham river system coincides with the aggradation of the third youngest terrace of the Bytham—the Timworth Terrace Member of Lewis (1993), which, through the application of terrace generation models, is suggested to have been deposited during MIS 16 (Hamblin *et al.*, 2000; Lee *et al.*, 2004a). The correlation of Happisburgh Formation deposits with MIS 16 disagrees strongly with the mammalian and molluscan biostratigraphy of the early Middle Pleistocene (see Banham*et al.* 2001 and Preece and Parfitt, this volume). Specifically, the Happisburgh till overlies a range of temperate deposits that contain a variety of biological assemblages and which are all normally magnetised. The deposition of the Happisburgh till during MIS 16 would, therefore, require the underlying Cromerian complex deposits at sites such as Pakefield, Happisburgh, Sidestrand and Ostend, and by implication West Runton, to have been deposited during either MIS 19 or 17 (Preece and Parfitt, this volume). Palaeontologists and biostratigraphers argue that such a short period of time and limited number of interglacial episodes is too restrictive to explain the diversity of assemblages present and the evolutionary trends that are observed, in particular the evolution of the ancestral *Mimomys savini* to its descendant *Arvicola terrestris cantiana* (see Koenigswald and Kolfschoten, 1996) However, the absolute timing of evolutionary change within this lineage is currently poorly understood, particularly in the highly fragmented sequences of northwest Europe, and correlation with the more detailed sequences of eastern Europe is frequently proposed (i.e. the LAD of *Mimomys pusillus*, Parfitt *et al.*, 2005). Such correlations require the evolution and/or dispersal of these species to be essentially synchronous over large geographic areas and does not allow for regional differences in biological variations. Furthermore, the complex pattern of substage forcing that is clearly seen in the marine isotope record, could potentially allow the existence of a large number of discrete temperate substages within which different biological assemblages could occur (Bassinot *et al.*, 1994; EPICA, 2004). We therefore believe that the lithostratigraphic model is as robust as any other currently proposed stratigraphical system and that further work is required to resolve the complexities of the early Middle Pleistocene.

Pakefield Member and Bytham Sands and Gravels

Whilst the age of the Happisburgh Formation remains a controversial issue, a growing body of geological information now exists that demonstrates active geological processes following the deposition of the Happisburgh Formation, but prior to the deposition of the Lowestoft Formation in MIS 12. Shallow marine deposits of the Wroxham Crag (Pakefield Member) have been recognised at Pakefield by Lee *et al*. (2006a) cropping-out between Happisburgh Formation outwash and Lowestoft Till. Further to the north near Norwich, Read *et al*. (2007) has also recognised shallow marine deposits, and these include an indigenous marine fauna characteristic of sea temperatures similar to those of the modern day Southern North Sea. At Leet Hill in the Waveney Valley, two horizons of calcrete have been developed within the Corton Sand Member. The lower horizon consists of a rhizogenic calcrete that formed during a climatic amelioration where a near-surface water table formed and vegetation cover became established (Candy, 2002).

Lowestoft Formation and Bytham Sands and Gravels

The Lowestoft Formation in northern East Anglia comprises two tills—the Lowestoft Till and Walcott Till members, deposited by a British Ice Sheet flowing southwards from Central England and the western margins of the North Sea Basin (Figure 6, Lee *et al*., 2004b). It corresponds with the aggradation of the youngest terrace of the Bytham sequence as the river system was overridden and destroyed by glacier ice (Lewis, 1993; Rose, 1994). The Lowestoft Formation is widely considered to correspond to the MIS 12 Anglian Glaciation—its age being constrained by correlation with the Thames terrace sequence (Bridgland, 1994), and radiometric age determinations of organic remnants that overlie the till (Rowe *et al*., 1999; Grün and Schwarcz, 2000; Preece *et al.*, 2007).

Sheringham Cliffs Formation

The Sheringham Cliffs Formation of northern East Anglia consists of three tills and associated outwash sediments (Lee *et al*., 2004b). These were deposited in association with an advance of British ice from the north and west (Figure 6, Lee *et al*., 2004b; Pawley, 2006). Current debate surrounds the chronological significance of this formation—specifically whether it equates with a younger post-Anglian MIS 10 glaciation (Hamblin *et al*., 2000, 2005), or whether it corresponds, as traditionally defined, to the MIS 12 Anglian Glaciation (Bowen, 1999).

The assertion of a post-Anglian MIS 10 age of the Sheringham Cliffs Formation is based upon two lines of evidence. Firstly, that in the Nar Valley, the Weybourne Town Till forms part of a sedimentary continuum with overlying glaciolacustrine, shallow marine and freshwater facies that spans the transition from a cold to warm stage (Ventris, 1996). Peats within these freshwater beds, the Nar Valley Freshwater Beds, have be dated by U-series to MIS 9 (Rowe *et al*., 1997), implying that the till at the base of the sequence is MIS 10 in age (Scourse *et al*., 1999). Secondly, based upon the modelling of ice sheet flow paths, that the Weybourne Town Till is stratigraphically equivalent to the Oadby Till of the Midlands (Hamblin *et al*., 2000, 2005; Clark *et al*., 2004). An MIS 10 age has been suggested for the Oadby Till, based upon its correlation with terrace sequences within the Thame and Thames (Sumbler, 1995, 2001; Keen, 1999). Evidence for the possibility that the Sheringham Cliffs Formation may be Anglian in age is based upon OSL dating of Briton's Lane Formation sands and gravels, which dates them to MIS 12 (see Chapter 14).

Briton's Lane Formation

The Briton's Lane Formation consists of outwash sands and gravels that crop-out in northern Norfolk and exhibit a new input of Scandinavian lithologies not seen in earlier parts of the glacial sequence (Lee *et al*., 2004b). Presently it is unclear whether this new input of Scandinavian material into the sedimentary system is derived directly from the Scandinavian Ice Sheet or whether it has been reworked from the North Sea basin by British ice (Pawley *et al*., 2005; Hoare *et al*., 2006; Lee *et al*., 2006b). This Scandinavian presence has however been used as a crude chronological marker. Hamblin *et al*. (2000) have considered this fresh input and the relative abundance of Scandinavian erratics within the Briton's Lane Formation to suggest a chronological correlation with the Scandinavian-bearingWarren House Gill and Basement tills of County Durham and East Yorkshire (Trechmann, 1915). Hamblin *et al*. (2000, 2005) also considered the level of preservation associated with the outwash landforms of the Glaven Valley and the Cromer Ridge to be analogous to the Saalian-age landforms of the Netherlands, and considered that their good preservation state precluded them from being as old as theAnglian. The inferred MIS 6 'Saalian' age of the Briton's Lane Formation, based upon a 'lithostratigraphic' correlation with the pre-Devensian tills of north-eastern England, and a 'morphostratigraphic' correlation with landforms in the Netherlands is not supported by geochronology. However, initial OSL dating of the outwash gravels that form the Cromer Ridge indicate a MIS 12 Anglian age (Chapter 14). Dates for the outwash deposits and landforms of the Glaven Valley by the OSL method are not yet available, and it remains a possibility that these may be post-Anglian but pre-Devensian in age.

Conclusions and Points for Discussion

- Conventional litho- and biostratigraphic approaches when applied to the Quaternary exhibit poor resolution making them insensitive to spatial and temporal complexities such as geological and ecological processes— understanding these processes at the relevant time-scale is fundamental to the construction of robust stratigraphic models.
- A process-lithostratigraphic approach provides a stratigraphical framework for the Early and Middle Pleistocene of northern East Anglia consisting of three fluvial formations, three shallow marine formations, and four glacigenic formations.
- 'Cromer Forest-bed Formation'—the application of this stratigraphic term should be restricted to its stratotype area of the north Norfolk coast and alluvial deposits of the Ancaster River. Whilst organic deposits from the Bytham River should be formalised as part of the Bytham group of sediments.
- Applying robust chronologies to this sequence is the most controversial issue and realistically, specific issues regarding the timing of particular events will only be resolved with geochronology.

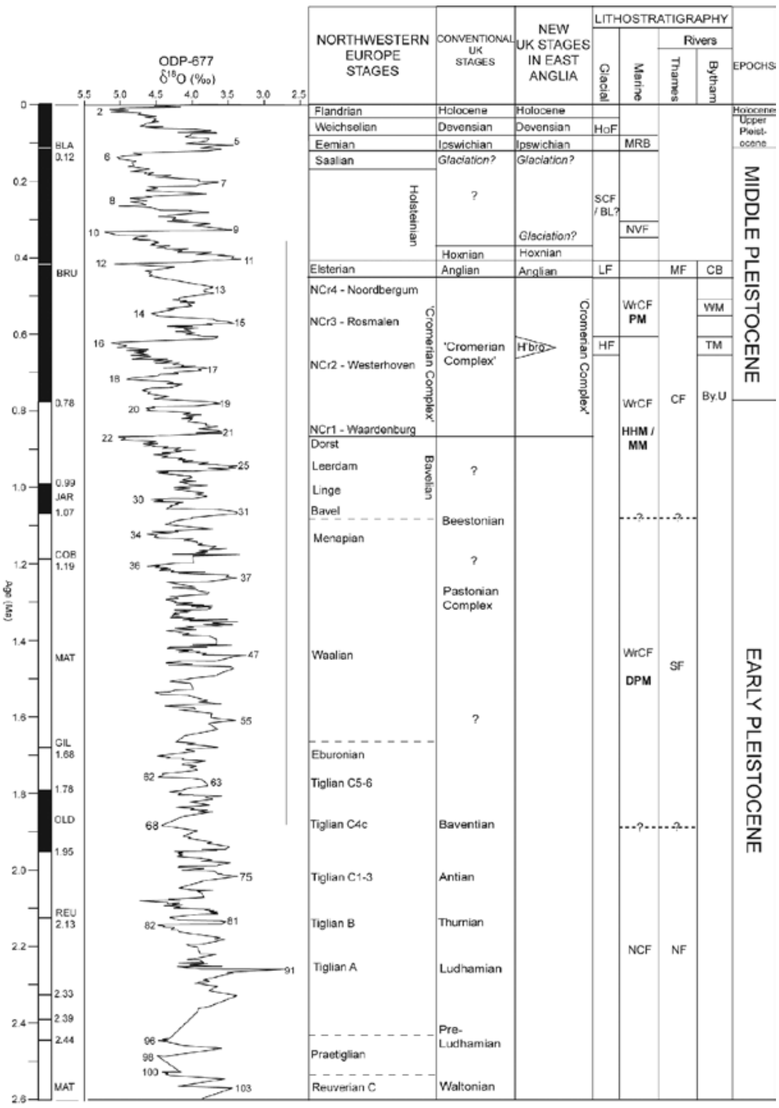

Figure 1. Quaternary lithostratigraphy of northern EastAnglia showing the temporal distribution of shallow marine, fluvial and glacial deposits relative to the marine isotope record. Key ofAbbreviations: HoF—Holderness Formation; SCF—Sheringham Cliffs Formation; BL—Britons Lane Formation; LF—Lowestoft Formation; HF—Happisburgh Formation; MRB—Morston Raised Beach deposit; NVF—Nar Valley Formation; WrCF—Wroxham Crag Formation; PM—Pakefield Member; HHM / MM—How Hill and Mundesley members; DPM—Dobbs Plantation Member; NCF—Norwich Crag Formation; MF—Maidenhead Formation; CF—Colchester Formation; SF—Sudbury Formation; NF—Nettlebed Formation; CB—Castle BythamTerrace; W—Warren Hill Member; TM—Timworth Member; By.U—Bytham sands and gravels (undifferentiated). Modified from Funnell (1995) and Rose *et al.* (2001).

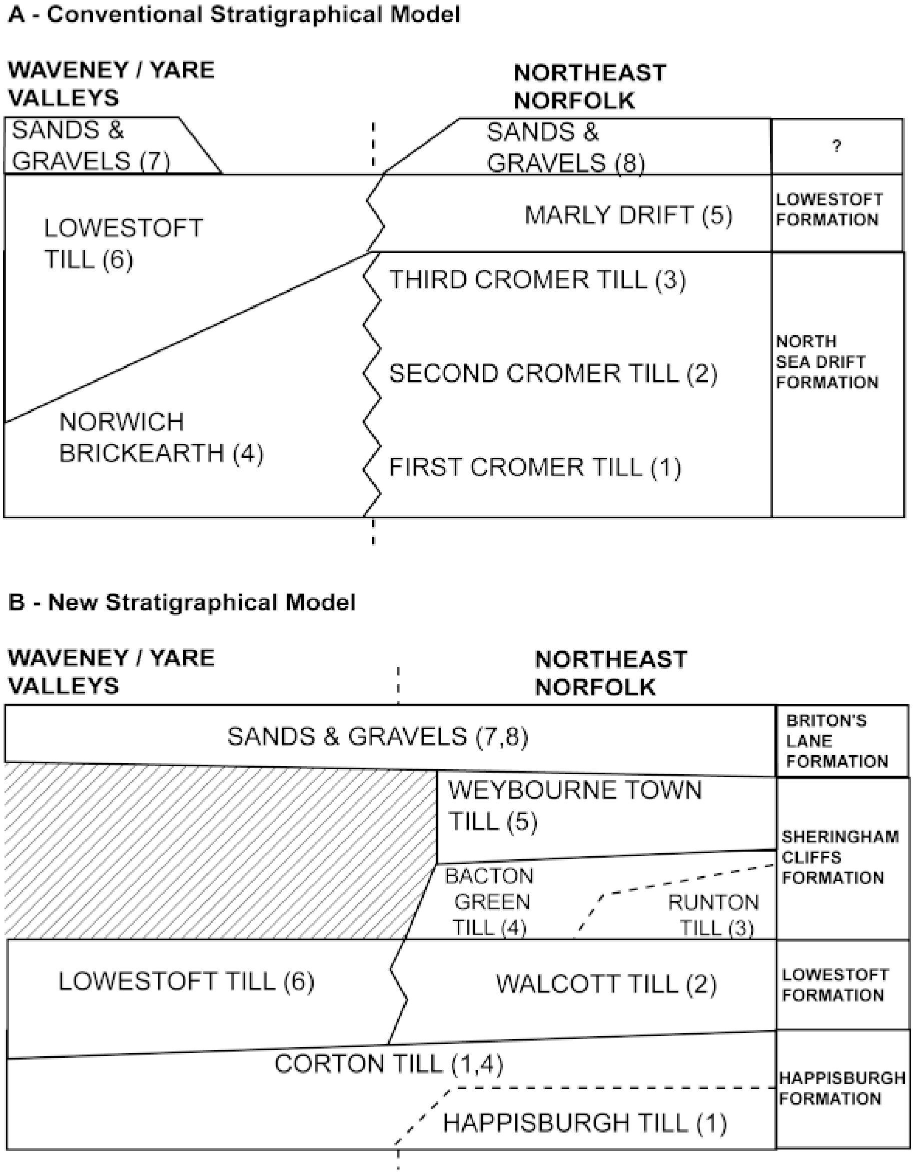

Figure 2. Diagram showing the 'Conventional' and 'New' stratigraphical models for the glacial deposits of northern East Anglia (from Lee *et al*., 2004b).

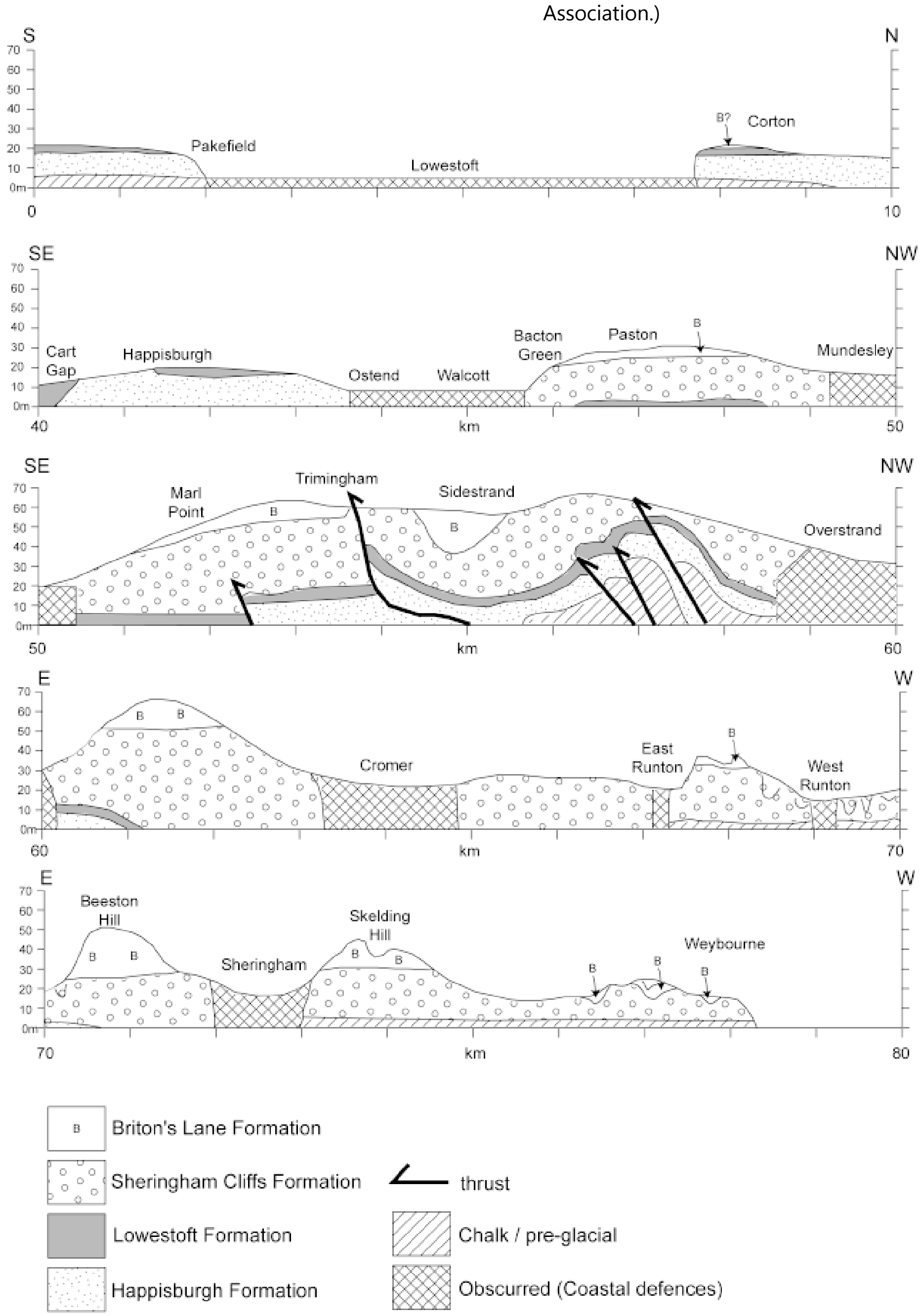

Figure 3. Distribution of glacial lithofacies within the coastal cliffs of Suffolk and Norfolk (from Lee *et al*., 2004b)

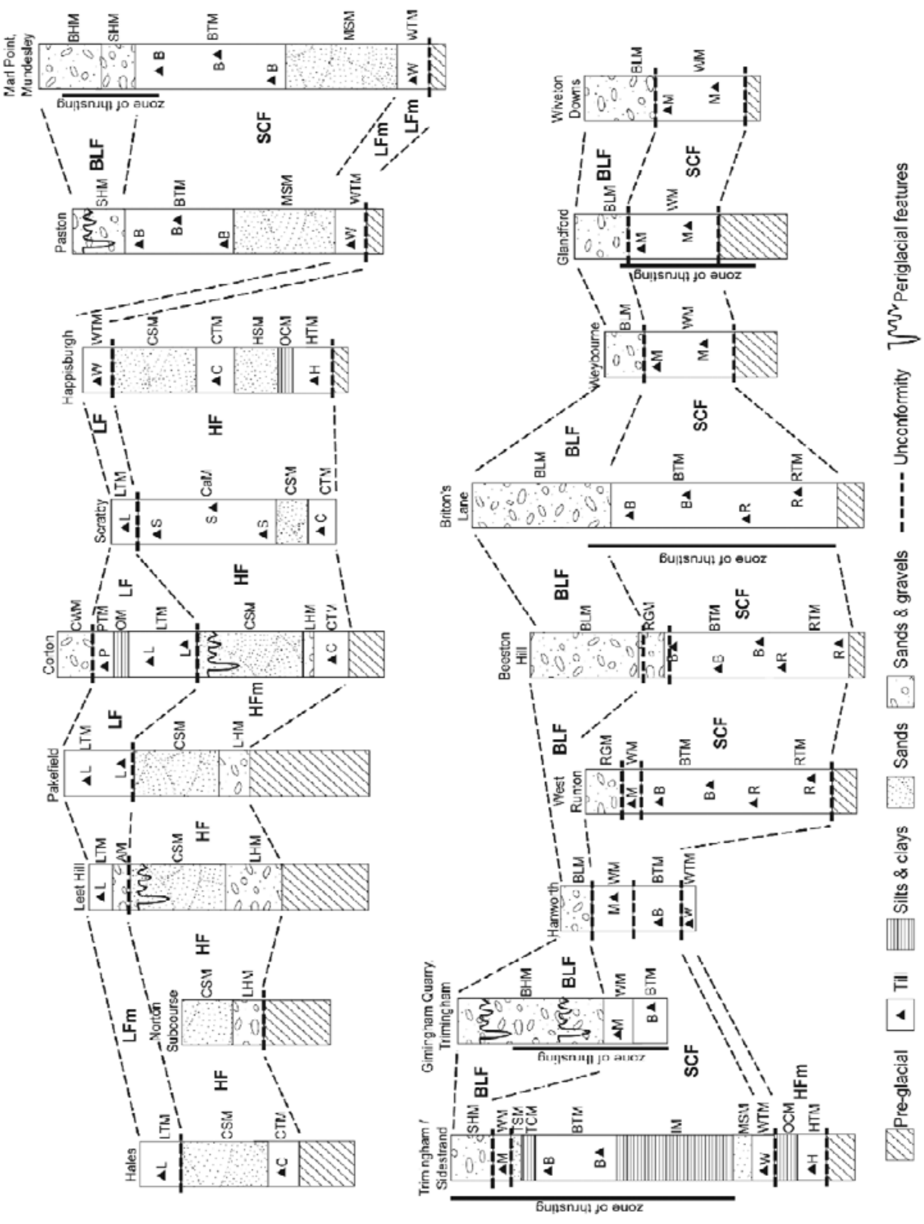

Figure 4. Schematic diagram showing the correlation of the glacial stratigraphy between sites in northern East Anglia. Abbreviations to stratigraphical terms – formations: HF – Happisburgh Formation; LF – Lowestoft Formation; SCF – Sheringham Cliffs Formation; BLF – Briton's Lane Formation. Abbreviations to stratigraphical terms: HTM – Happisburgh Till Member; OCM – Ostend Clay Member; HSM – Happisburgh Sand Member; CTM – Corton Till Member; LHM – Leet Hill Sand and Gravel Member; CSM – Corton Sand Member; CaM – California Till Member; LTM – Lowestoft Till Member; WTM – Walcott Till Member; OM – Oulton Clay Member; PTM – Pleasure Gardens Till Member; AM – Aldeby Sand and Gravel Member; MSM – Mundesley Sand Member; IM – Ivy Farm Laminated Silt Member; RTM – Runton Till Member; BTM – Bacton Green Till Member; TCM – Trimingham Clay Member; TSM – Trimingham Sand Member; WM – Weybourne Town Till Member; RGM – Runton Sand and Gravel Member; SHM – Stow Hill Sand and Gravel Member; BHM – Beacon Hill Sand and Gravel Member; BLM – Briton's Lane Sand and Gravel Member; CWM – Corton Woods Sand and Gravel Member. After Lee *et al*. (2004b) and Pawley (2006).

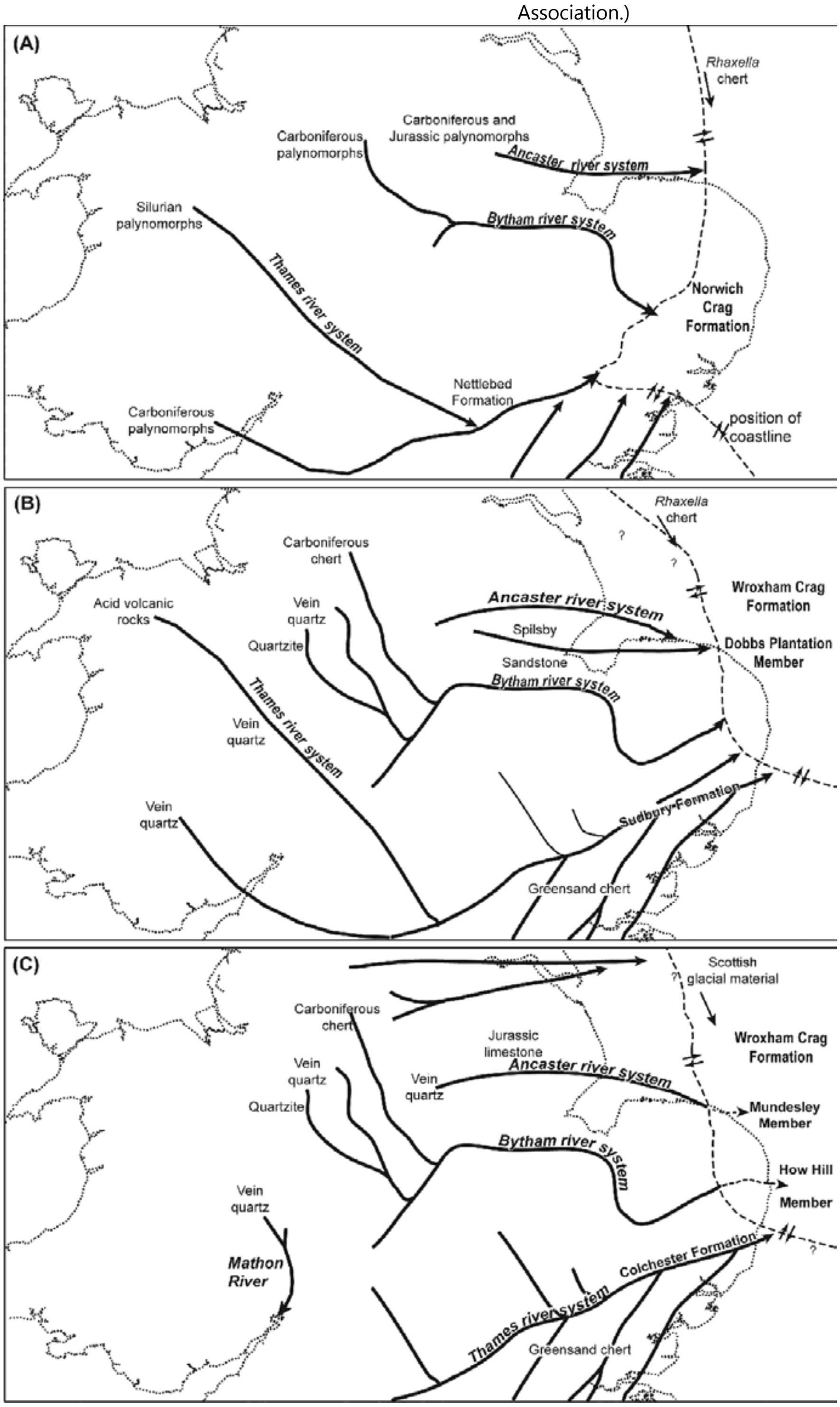

Figure 5. Palaeographic evolution of central and eastern England during the Quaternary. (a) Deposition of the Norwich Crag and Nettlebed formations; (b) Deposition of the Sudbury Formation, Bytham sands and gravels and the Dobbs Plantation Member of theWroxham Crag Formation; (c) Deposition of the Colchester Formation, Bytham sands and gravels and the How Hill and Mundesley members of the Wroxham Crag Formation (modified from Rose *et al*., 2001).

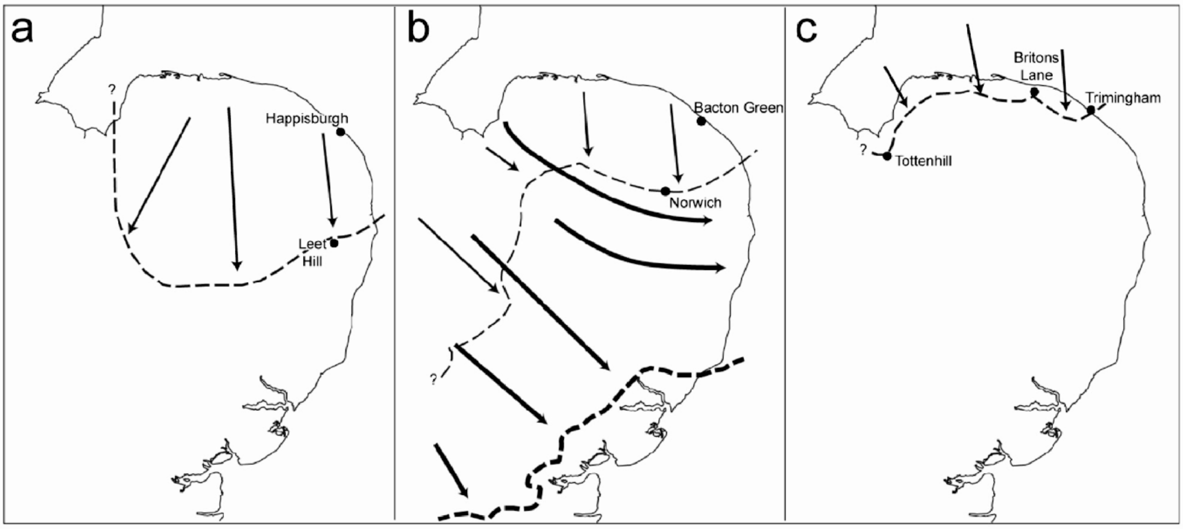

Figure 6. Maximum ice limits in northern East Anglia during the deposition of the Happisburgh Formation (a), Lowestoft and Sheringham Cliffs formations (b) and Britons Lane Formation (c). After Hamblin *et al*. (2005).