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The Glacial History of the British Isles during the Early and Middle Pleistocene: Implications for the long-term development of the British Ice Sheet

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INTRODUCTION

The Early and Middle Pleistocene (ca. 2.6–0.125 Ma) was a period of major climate and earth system change driven by a progressive trend of global cooling. This include the so-called Middle Pleistocene Transition (MPT) (Head and Gibbard, 2005a) which represents a shift (1.2–0.7 Ma) from global climate forcing driven by 41 ka (obliquity) cycles to a pattern of forcing driven by 100 ka (eccentricity) cyclicity (Clark *et al*., 2006). The global effects of the MPT on various physical, chemical and biological systems have been documented by a number of papers within Head and Gibbard (2005b). However, one of its most obvious global consequences was to produce longer and more intense 'cold' periods, which changed both the long- and short-term development of ice sheets and the timing and scale of glaciation (Ehlers and Gibbard, 2007). A large number of Pleistocene ice sheets, including the Scandinavian (SIS), Laurentide and Greenland ice sheets, plus several smaller maritime ice sheets, lie adjacent to the climatically sensitive North Atlantic region. Recent research has demonstrated that each of these ice sheets underwent a step-wise amplification in both the frequency and scale of glaciation across the MPT (Jansen *et al*., 2000; Sejrup *et al*., 2005; Knies *et al*., 2009). However, it remains unclear how the British Ice Sheet (BIS) fits into this regional trend as its long-term development is poorly understood. This is due largely to the fragmentary and sometimes ambiguous nature of the evidence for glaciation in Britain, difficulties with correlating evidence between terrestrial and offshore sequences and major problems regarding chronology and correlation with geological sequences in other countries in northwestern Europe (Clark *et al*., 2004; Ehlers and Gibbard, 2004, 2007; Rose, 2009; Lee *et al*., 2010).

The scope of this chapter is to examine spatial and temporal patterns in the scale of glaciation within the Early and Middle Pleistocene British Isles. This will provide a greater understanding behind the controls of the long-term development of glaciation in Britain, and whether it was in-phase with global climate change and other Northern Hemisphere Ice Sheets. This has important implications for understanding the sensitivity of the British land-mass and the level of coupling to climate change. Particular focus is placed upon: (1) reviewing and evaluating the evidence for Early and Middle Pleistocene glaciations; (2) identifying long-term trends in the development of glaciation in Britain; (3) drivers of glaciations and their wider context.

EARLY AND MIDDLE PLEISTOCENE GLACIAL HISTORY OF THE BRITISH ISLES

Long-Term Sedimentary Archives

Long-term sedimentary archives provide the best means by which the Quaternary evolution of glaciation in Britain can be evaluated. However, records that span the Early and Middle Pleistocene are relatively few in number and discontinuous in nature (Fig.1).

UK Continental Shelf and Margin

Offshore sediment sequences developed along the North-western European Continental Margin offer a detailed insight into glacial processes operating both on and adjacent to the continental shelf, and at the shelf edge with the development of glaciogenic fan complexes (Sejrup *et al*., 2005). Extending westwards from the Norwegian Channel to Ireland, the continental margin to the north of Scotland reveals evidence for several Pleistocene expansions of the Scottish sector of the BIS (Sejrup *et al.*, 2005; Bradwell *et al.*, 2007). BGS borehole 88/7,7a from the Hebrides Slope records layers of Scottish-derived dropstones between the Gauss–Matuyama palaeomagnetic boundary (ca. 2.6 Ma) and the base of the Anglian (Marine Isotope Stage (MIS) 12) (Stoker *et al.*, 1994, 1993). Whilst the specific number of ice-rafting events is unclear, the fact that they span several different normalised and reversed palaeomagnetic horizons suggests multiple ice-rafting events associated with the extension of Scottish ice into coastal areas. The first shelf- edge glaciation, associated with MIS 12, is represented by a major seismic unconformity that can be traced across the Hebrides Shelf, and several of the glaciogenic fan complexes including the Sula Sgeir Trough Mouth Fan and the Rona Wedge (Stoker *et al.*, 1994, 1993; Stoker, 1995; Holmes *et al.*, 2003; Sejrup *et al.*, 2005). A further expansion of Scottish ice onto the continental shelf during MIS 6 has been recognised by Hibbert *et al.* (2009) form core MD04-2822 near the Barra-Donegal Fan. Sejrup *et al.* (2005) has suggested additional shelf-edge glaciations of Scottish ice during MIS 10 and 8 although these require further verification.

The North Sea and 'Crag' Basins

The North Sea is a marine basin fed during the Quaternary by rivers and ice sheets that emanated from Britain and continental Europe (Zagwijn, 1989, 1996; Gibbard, 1995; Sejrup *et al.*, 2000; Rose *et al.*, 2001; Carr, 2004; Busschers *et al.*, 2008). The 'Crag' Basin represents the pre-MIS 12 extension of the North Sea Basin into parts of eastern and southern East Anglia (Funnell, 1995; Rose *et al.*, 2001; Rose, 2009).

The first possible evidence for glaciation within the North Sea region corresponds to 'Baventian' (ca. MIS 68/ 1.8 Ma) marine clays from Easton Bavents and Covehithe in the 'Crag' basin of East Anglia. These clays exhibit a 'semi-glacial' fauna (West *et al.*, 1980) and contain possible ice-rafted hornblende heavy minerals from Scandinavia (Soloman, 1935). However, the provenance and significance of the hornblende identified by Soloman is ambiguous due to the absence of a full suite of provenance-diagnostic heavy minerals. Alternatively, the hornblende could be ice -rafted from northern Britain; or introduced by rivers eroding hornblende-bearing igneous rocks or Tertiary strata in Europe (Berger in Gibbard *et al.*, 1991a) or southern Britain.

The earliest *direct* evidence for the expansion of British ice into the margins of the northern North Sea coincides with the first shelf-edge expansion of the SIS during the Fedje Glaciation (ca. MIS 34/1.1 Ma) (Sejrup *et al.*, 1987) (Fig. 2). Evidence consists of large influxes of out- wash-derived pre-Quaternary palynomorphs within BGS boreholes 81/29 and 81/34 (Devil's Hole). These palynomorphs are believed to be eroded from lowland bedrock strata along the western fringes of the North Sea offshore from northern Britain (Ekman, 1999). Several additional in- fluxes of glacial outwash into the northern North Sea from northern Britain occurred during the Jaramillo Sub-Chron dated to ca. 1.07–0.99 Ma (Ekman, 1999).

Further small expansions of the BIS in northern Britain during the 'Cromerian Complex' (ca. MIS 22–13/0.9–0.48 Ma) are indicated by several strands of evidence. First, far-travelled erratics (Green and McGregor, 1990; Larkin, Lee and Connell, unpublished data) and heavy minerals (Lee *et al.*, 2006; Lee, 2009) from northern Britain have been found at several different localities and stratigraphical levels within coastal deposits (Wroxham Crag) in northern East Anglia. Many erratics exhibit a fresh morphology and weigh several kilos and are believed to be the product of ice rafting from a calving BIS in the northern North Sea with localised reworking by coastal processes (Larkin *et al.*, 2011). The precise timing of these ice-rafting events is tenuous; however, their stratigraphical position relative to temperate organic facies of the Cromer Forest- bed Formation suggests deposition during several different cold stages. Further north within the Moray Firth and Firth Approaches, glaciomarine deposits occur in the Aberdeen Ground Formation that contains dropstones (Stoker and Bent, 1985). They directly overlie the Brunhes–Matuyama (B/M) palaeomagnetic boundary that is dated to ca. 0.78 Ma (MIS 19), suggesting that they may be as old as MIS 18 (Merritt *et al.*, 2003). Additional evidence for a pre-MIS 12 expansion of ice into the northern North Sea is suggested by a series of subglacial 'tunnel valleys' and channels cut into the top of the Aberdeen Ground Formation that are partially infilled by 'Cromerian Complex' sediments (Holmes, 1997).

Large-scale expansion of the BIS into the North Sea region during the Middle Pleistocene occurred during MIS 12 (Balson and Jeffrey, 1991; Carr, 2004). Evidence for this glaciation is generally in the form of an extensive seismic unconformity that has been interpreted as a glacial erosion surface

(Cameron *et al*., 1992), and a series of over-deepened subglacial tunnel valleys produced by coeval glaciofluvial erosion and deposition during ice-marginal retreat (Praeg, 2003). Sedimentary evidence for the Anglian expansion of the BIS consists of tills, glaciolacustrine and glaciomarine deposits of the Swarte Bank and Aberdeen Ground formations (Cameron *et al*., 1992; Gatliff *et al*., 1994). The configuration of the BIS and SIS within the North Sea during this glaciation is unclear. It is possible that many of the glacial features and deposits assigned to the Elsterian in the Dutch Sector (Laban, 1995) may not be equivalent to the MIS 12 Anglian glaciation of the UK, but instead, a younger MIS 10 glaciation (see Lee *et al*., 2010 for an overview of this subject).

The extent of the BIS within the North Sea during post- Anglian/pre-Ipswichian cold stages is poorly understood. A till of Scottish origin was recognised within core 81/26 from the Fladen Ground area and assigned to the Late Saalian (ca. MIS 6) (Sejrup *et al*., 1987). However, no intervening British glacial deposits have been recognised in the North Sea suggesting that the BIS did not extend far eastwards during these cold stages (Long *et al*., 1988).

Kesgrave Proto-Thames Terrace Sequence

The pre-Anglian terraces of the proto-Thames sequence contain evidence for several possible phases of mountain- scale glaciation in western highland and lowland Britain during the Early and early Middle Pleistocene (Whiteman and Rose, 1992; Rose *et al*., 1999a).

Deposits of the proto-Thames are collectively called the Kesgrave Sands and Gravels (Kesgrave Group). They have been subdivided into the Sudbury (older) and Colchester (younger) Formations based upon lithology and individual terrace aggradations determined by geomorphology and elevation (Whiteman and Rose, 1992). Within the Early Pleistocene, during the deposition of the Sudbury Formation, the headwaters of the Thames drained parts of southern and central Wales. However, during the late Early Pleistocene, the headwaters of the proto-Thames catchment were beheaded and the subsequent terrace aggradations represent deposition by a much smaller river with headwaters to the east of the Cotswold escarpment (Whiteman and Rose, 1992). Far-travelled erratics from north Wales, including frequently outsized and sub-angular clasts of acid porphyry, tuff and banded rhyolite (Hey and Brenchley, 1977; McGregor and Green, 1978), and glacially-abraded sand grains (Hey, 1980), have been found throughout both the Sudbury and Colchester formations (Whiteman and Rose, 1992), and recently, a glacially striated oversized block of rhyolitic tuff has been discovered *in situ* in the Colchester Formation (Roseetal *et al*., 2010). The lithology of the Sudbury Formation terraces, with high quantities (up to 35%) of far-travelled quartz and quartzite (Whiteman, 1992), suggests a direct link to north and south Wales, the Welsh borders and the West Midlands. However, with the exception of the Ardleigh Terrace which shows an increased level of far-travelled material (Whiteman and Rose, 1992), the lithology of the Colchester Formation terraces, with much lower quantities (15–20%) of far-travelled quartz and quartzite (Whiteman, 1992), supports the idea of a more restricted catchment with the far-travelled component of these gravels being recycled from older terrace aggradations (Rose *et al*., 1999a).

From a temporal perspective, the presence of lithologies from north Wales in Sudbury Formation gravels has been interpreted as reflecting a glaciofluvial input into the proto-Thames catchment from a Welsh ice cap (Whiteman and Rose, 1992; Rose *et al*., 1999a; Clark *et al*., 2004). This would indicate the existence of restricted mountain-scale glaciation during the Early Pleistocene. In terms of major landscape evolution, one of the most significant events during the history of the proto-Thames was the beheading and truncation of its headwaters to the west of the Cotswold Hills prior to the deposition of the Colchester Formation terraces. Multiple explanations could be proposed for this event including, for instance, enhanced soft-rock erosion within the headwaters of the Bytham River catchment, how- ever, several authors have indicated that it could reflect a major glaciation (see Whiteman and Rose, 1992). In such a model, the advance of a major ice sheet into Midland England would override the upper reaches of the proto- Thames, disrupting the drainage system and truncating the catchment in the region of the Cotswold escarpment. This is a plausible explanation but is difficult to prove, largely due to the absence of unambiguous glacigenic deposits within the pre-Anglian Thames catchment (see Clark *et al*., 2004 for a review of the evidence). The increased influx of north Welsh erratic lithologies into the Ardleigh Terrace aggradation has been attributed to a glaciation reaching the Cotswold Hills after the truncation of the Thames catchment, and this is supported by the recent discovery of a striated, oversized clast of rhyolitic tuff in these terrace gravels (Rose *et al*., 2010).

Developing a chronology for these major events and spatial changes within the pre-Anglian Thames catchment is thus crucial to developing an understanding of the long-term evolution of the

Welsh sector of the BIS. This must be viewed as tentative due to the absence of *in situ* biostratigraphical evidence and the dependence upon geo- morphological geochronometry although this has similar validity, resolution and possibly more robustness than other chronometers for the period of time under consideration (Lee *et al.*, 2004a). The crude chronological framework developed by Whiteman and Rose (1992), Rose *et al.* (1999a) and Westaway *et al.* (2002) is based upon climate forcing of river aggradation and incision, linked to shallow crustal adjustment and, where possible, correlation with First Appearance Datum (FAD) and Last Appearance Datum (LAD) mammal and molluscan assemblage biostratigraphy. Within this chronological model, the earlier Sudbury Formation was deposited between ca. 1.87 and 0.87 Ma, with individual terrace aggradations tentatively assigned to MIS 68 (Stoke Row terrace), MIS 62-54 (Westland Green terrace), MIS 54-36 (Satwell terrace), MIS 36-32 (Beaconsfield terrace) and MIS 22 (Gerrards Cross terrace); providing the first evidence for a Welsh ice cap at around MIS 68. Terraces within the Colchester Formation were, by contrast, formed during single cold stages between ca. 0.87 and 0.48 Ma, with individual aggradations and corresponding Welsh glaciations occurring during MIS 20 (Waldringfield terrace), MIS 18 (Ardleigh terrace, with ice reaching the Bruern region in the Cotswold Hills), MIS 16 (Wivenhoe terrace), MIS 12 (St Osyth terrace), although see Rose *et al.* (2010) for a more recent assessment of these age attributions. Critically, this chronological interpretation places the first lowland expansion of Welsh ice and the beheading of the Welsh headwaters of the Thames, into MIS 20, although there is no specific influx of erratic material into the Thames at this time to suggest that ice reached the present Thames catchment.

Middle Pleistocene Glacial Sequence of Eastern England and the Midlands

During the Middle Pleistocene, it was widely accepted that East Anglia and the Midlands were glaciated extensively on two occasions—during the Anglian Glaciation, and a later pre-Devensian glaciation known as the 'Wolstonian' (West and Donner, 1956; Mitchell *et al.*, 1973; Shotton, 1983; Straw, 1983). However, detailed examinations of the preglacial and till successions subsequently led to the proposal that there was only one extensive Middle Pleistocene glaciation—the Anglian (Perrin *et al.*, 1979; Bowen *et al.*, 1986; Rose, 1987, 1989a, 1992). Evidence from the Holderness and County Durham areas also suggests a later minor extension of ice along the North Sea coast of England believed to be equivalent to the Late Saalian (MIS 6) glaciation (Catt and Penny, 1966; Bateman and Catt, 1996) which is equated to the 'Wolstonian'. Ice is believed to have extended to the margins of the Wash Basin depositing a complex sequence of outwash (Gibbard *et al.*, 1991b, 1992, 2009; Lewis and Rose, 1991). Recently, the glacial model for East Anglia and the Midlands has been challenged by new work that challenges: (1) the regional glacial succession; (2) the provenance of some of the deposits; (3) the number of Middle Pleistocene glaciations and their ages. Each of these issues has courted controversy, and the evidence and de- bates are presented within the following sections.

Regional Glacial Lithostratigraphy

As stated above, 'conventional' interpretations of the Middle Pleistocene glacial succession of East Anglia and the Mid- lands provide evidence for two separate glaciations. It was proposed that during the Anglian Glaciation, the BIS extended across much of southern Britain north of the present river Thames. It deposited Mesozoic-rich tills in the Mid- lands that include the Thrussington and Oadby tills of the Wolston Formation, and the Lowestoft Till of the Lowestoft Formation in central and southern East Anglia (Rice, 1968; Perrin *et al.*, 1979; Bowen *et al.*, 1986). In northern East Anglia, the three 'Cromer Tills' ('North Sea Drift Formation') were laid down contemporaneously by the SIS (Reid, 1882; Banham, 1968; Lunkka, 1994), with a intermediate- stage retreat enabling the BIS to extend eastwards across the region depositing a chalk-rich facies of the Lowestoft Formation called the 'Marly Drift' (Figs. 3A and 4) (Per- rin *et al.*, 1979; Ehlers *et al.*, 1991). This was subsequently covered in northeast Norfolk by a re-advance of the SIS.

Over the past 10 years, the robustness of the regional lithostratigraphy—especially the complex relationship between the 'North Sea Drift' and Lowestoft formations in northern East Anglia—has been challenged by new geo- logical mapping, sedimentological and stratigraphical studies and subsurface modelling of borehole data. Within northern East Anglia, the local stratigraphical schemes of Reid (1882), Banham (1968) and Lunkka (1994) developed largely on coastal and occasional inland sections are robust. However, when attempting to map this stratigraphical scheme inland, it became clear that the geometric relation- ship between the North Sea Drift and Lowestoft formations as defined by the conventional stratigraphical scheme (i.e. Fig. 3A) was erroneous. Common artefacts of mapping to this scheme included various stratigraphical spirals of tills and unit geometries that were geologically implausible.

Based upon new field data collected across several thou- sand square kilometres of northern East Anglia, a new lithostratigraphy was presented for the region (Hamblin *et al*., 2000; Lee *et al*., 2004b) and later extended more widely (Hamblin *et al*., 2005) across into the Midlands (Clark *et al*., 2004; Lee *et al*., 2008a; Rose, 2009) (Fig. 2B). The revised glacial succession consists of four broad mappable stratigraphical subdivisions. The lowest subdivision is the Happisburgh Formation of northern East Anglia which includes two tills—the Happisburgh and Corton tills, formerly attributed to the First Cromer Till. The second subdivision is the redefined Lowestoft Formation with some elements of the Wolston Formation.

It consists of a laterally persistent till sheet that can be traced from the Midlands into central and northern East Anglia to the Midlands and includes: (a) the Thrussington Till rich in Carboniferous, Permian and Triassic materials (Shotton, 1953; Rose, 1989a); (b) a Lias and Early-Middle Jurassic- rich/chalk-free till (Rose, 1992) now called the Bozeat Till (Barron *et al*., 2006; Carney and Ambrose, 2007); (c) a Late Jurassic (Kimmeridgian)-rich till with chalk clasts—the Lowestoft Till (*s.s.*) (Pointon, 1978; Perrin *et al*., 1979) and local equivalents in southern East Anglia (Allen *et al*., 1991); (d) the Walcott Till (Second Cromer Till) of northern East Anglia (Banham, 1968; Lunkka, 1994). The third stratigraphical subdivision in northern East Anglia is the Sheringham Cliffs Formation which includes two till facies, the Bacton Green Till (Third Cromer Till) and the Weybourne Town Till (Marly Drift) (Banham, 1968; Perrin *et al*., 1979; Ehlers *et al*., 1987; Lunkka, 1994). It is believed, on the basis of lateral continuity, that this formation is equivalent to the Oadby Till of the Wolston Formation of the Midlands. The fourth, and stratigraphically highest subdivision is the Briton's Lane Formation of northern East Anglia. This formation consists of a series of outwash sands and gravels deposited during a series of ice-marginal oscillations that formed the Cromer Ridge push moraine complex (Hamblin *et al*., 2005; Rose, 2009). Whilst, the dominant clast lithologies within the outwash sands and gravels are derived from northern Britain, they also contain a very small (< 2%) but persistent clast assemblage derived from Scandinavia (Moorlock *et al*., 2000; Pawley *et al*., 2004). On the northern ice proximal side of the Cromer Ridge are a further series of outwash deposits and landforms formed during several phases of ice-marginal standstill and retreat including the Kelling and Salthouse outwash plains (Pawley, 2006), the Blakeney Esker (Gray, 1997; Gale and Hoare, 2007) and some possible kame terraces within the Glaven Valley.

Till Provenance

Whilst many of the tills within the stratigraphical succession of the Midlands and East Anglia are of British provenance, it is widely considered that other tills within the region were deposited by the SIS, due to the reported presence of Norwegian erratics from the Oslofjord area of Norway. This includes tills previously attributed to the 'North Sea Drift' (i.e. 'Cromer Tills') in northern East Anglia (Perrin *et al*., 1979; Bowen *et al*., 1986; Ehlers and Gibbard, 1991), the Basement Till of East Yorkshire (Catt and Penny, 1966) and the Warren House Till further north in County Durham (Trechmann, 1916; Catt, 2007).

In northern East Anglia, despite claims that '… [rhomb porphyry and larvikite] are found at all exposures of North Sea Drift Cromer Tills. . .' (Ehlers and Gibbard, 1991: 18), very few *in situ* Scandinavian erratics have actually been reported from the tills (Moorlock *et al*., 2001; Hoare and Connell, 2005; Lee *et al*., 2005). Recent analyses have demonstrated that the tills are actually derived from bedrock sources in northern and eastern Britain eroded by the BIS (Lee *et al*., 2002, 2004b) with minor reworking of erratics derived from earlier incursions of the SIS into the North Sea (Hoare and Connell, 2005; Lee *et al*., 2006). Whilst some argue that these tills are still of Scandinavian origin (i.e. Gibbard *et al*., 2008), ice flow trajectories for the SIS required to incorporate such a geographical range of lithologies from southern Norway, central Scotland and northern and eastern England are glaciologically-implausible (Lee *et al*., 2008b). It also overlooks extensive evidence for the configuration of the Norwegian sector of the SIS during repeated Pleistocene expansions into the North Sea (Sejrup *et al*., 2000).

The removal of the SIS from northern East Anglia raises considerable questions regarding the configuration of the SIS and BIS during the Middle Pleistocene as it is unclear how far west the SIS extended. For instance, several conceptual models require the SIS to be in close proximity to the British land mass to deflect the BIS through the Wash Basin (i.e. Perrin *et al.*, 1979; Fish and Whiteman, 2001) (Fig. 4). Equally, the provenance of other possible Scandinavian deposits, including those at Warren House Till in County Durham (Davies *et al.*, 2010), has been discredited, whilst others (e.g. the Basement Till along the Holderness East Yorkshire coast) require verification.

Chronology of the Middle Pleistocene Terrestrial Glacial Record

Whilst the Middle Pleistocene glacial succession presented earlier represents a standalone relative arrangement of the geological units, application of chronology to this succession has courted major controversy with conflicts existing between different types of chronological evidence (see Clark *et al.*, 2004; Hamblin *et al.*, 2005; Hoare *et al.*, 2009; Preece and Parfitt, 2008; Preece *et al.*, 2009 and Rose, 2009 for overviews; Figs. 4 and 5.

The chronological cornerstone of the Middle Pleistocene terrestrial glacial record is the Anglian Glaciation (MIS 12) (Mitchell *et al.*, 1973; Bowen *et al.*, 1986; Bowen, 1999). Deposits of this age include the Lowestoft Formation of East Anglia and the Bozeat and Thrussington tills of the Wolston Formation in the English Midlands. The age of these tills are constrained by interglacial organic deposits that underlie and overlie them and attributed to the 'Cromerian Complex' and Hoxnian, respectively (West, 1956, 1980; Turner, 1970; Rose, 1989a; Preece *et al.*, 2007; Preece and Parfitt, 2008). Further evidence is the lithostratigraphical relationship of Anglian till to terraces of the River Thames (Gibbard, 1977; Bridgland, 1994); and the post- Anglian Thames terrace chronology based upon temporal patterns of river terrace aggradation and incision, FAD and LAD mammal and molluscan biostratigraphy, and amino-acid racemisation (AAR) (Bowen *et al.*, 1989; Bridgland, 1994; Bridgland and Schreve, 2004). Together, this body of evidence for dating the Anglian Glaciation to MIS 12 must be seen as substantive. However, it needs to be recalled that the original correlation was based upon pollen assemblage biostratigraphy (see Rose, 1989a), and this method has limited chronostratigraphical sensitivity (Tzedakis *et al.*, 2001; Rose, 2009). Further, both MIS 11 and MIS 9 absolute age determinations have been made for organic sediments containing pollen assemblages attributed to the Hoxnian (Bowen *et al.*, 1989; Rowe *et al.*, 1997, 1999; Grün and Schwarz, 2000; Geyh and Müller, 2005; Preece *et al.*, 2007). A systematic dating study of the glaciofluvial deposits in the area using OSL (Pawley *et al.*, 2008) gave a mean age for all the deposits listed above to around MIS 12. It is important to note that this study did not examine material ascribed to MIS 16.

The timing of the deposition of the Happisburgh Formation glacial sediments in northern East Anglia is controversial. Conventional models, based largely upon pollen biostratigraphy, imply that the Happisburgh Formation is of Anglian age (Perrin *et al.*, 1979; West, 1980; Bowen *et al.*, 1986; Bowen, 1999; Gibbard *et al.*, 2008). However, a growing body of evidence demonstrates the existence of a significant time gap and temperate climate(s) between the deposition of the Happisburgh and Lowestoft formations. Evidence includes (a) sedimentological evidence for intervening high sea-level stands at Pakefield (Lee *et al.*, 2006) and Norwich (Read *et al.*, 2007; see Gibbard *et al.*, 2008 and Lee *et al.*, 2008a,b for a debate of this evidence); (b) temperate soil separating till units of the Happisburgh and Lowestoft formations in central East Anglia (Rose, 2009); (c) a further intervening soil that also contains a human artefact (Wymer, 1985). This evidence precludes the Happisburgh Formation from being the product of the same glacial event that deposited the Lowestoft Till, and instead, points to an earlier glacial episode possibly equivalent to MIS 16 (Lee *et al.*, 2004b; Hamblin *et al.*, 2005; Rose, 2009). The rationale for this age is based upon the input of Happisburgh Formation glacial lithologies into the third terrace aggradation of the Bytham River at Leet Hill (Rose *et al.*, 1999b, 2000; Lee, 2001; Lee *et al.*, 2004b). The Bytham River catchment was subsequently overridden and destroyed during the Anglian Glaciation (Rose, 1994). However, between the third terrace and the youngest (first) terrace aggradation that immediately preceded the arrival of Anglian ice within the Bytham catchment (Rose, 1989b), several episodes of terrace aggradation and incision may be delineated. Application of a climate-forced model for river terrace development, where each aggradation/incision cycle represents a ca. 100 ka time-span (c.f. Bridgland, 2000), enables the various stages of aggradation and incision to be counted back from the Anglian placing the 'Happisburgh Glaciation' within MIS 16 (Lee *et al.*, 2004b).

Several recent publications disagree with this evidence and argue for the 'Happisburgh Glaciation' to be still part of the Anglian (MIS 12). Preece and Parfitt (2008), for example, suggest that the glacial input into the Bytham River at Leet Hill generated a 'complex response' within the terrace sequence. Rose (2009) refutes this claim, demonstrating that the 'complex response' occurred later during the deposition of overlying glacial outwash. In a new interpretation of the Bytham terrace sequence, Westaway (2009) presents a terrace model comprising just three terrace ag- gradations, with the Happisburgh Formation glacial input occurring during the lowest (first/early Anglian) terrace ag- gradation (cf. Lee *et al*., 2004b). However, the validity of this terrace model is questionable because individual aggradations are largely unconstrained by palaeosol evidence that is necessary to demonstrate that the projected terrace surfaces correspond to recognisable land surfaces (cf. Lewis, 1993; Lee *et al*., 2004a). In a different study, Preece *et al*. (2009) examines the biostratigraphical and aminostratigraphical record from a temperate deposit of the Cromer Forest-bed Formation, the Sidestrand *Unio* Bed, at Sidestrand in northern East Anglia. Critically, the deposit underlies the Happisburgh Formation which would suggest, if the glacial deposits are MIS 16, that its youngest age would be MIS 17. However, the deposit contains the microtine rodent *Arvicola t. Cantiana* (Preece and Parfitt, 2000) which is widely believed to have evolved from *Mimomys savini* and is believed to have first appeared across Europe during MIS 15 (Banham *et al*., 2001; Preece *et al*., 2009). Amino acid data from fresh- water shells also reveal racemisation rates that are more consistent with younger 'Cromerian Complex' deposits - probably equivalent to either MIS 13 or 15 (Preece *et al*., 2009). Interestingly, although Preece *et al*. (2009) argue that this evidence disproves the concept of an MIS 16 glaciation, it does not disprove a pre-Anglian age for the Happisburgh Formation. Further, as the LAD biostratigraphy is empirically de- rived, the lithostratigraphic interpretation could invalidate the use of this method at this period of time in Britain.

The ages of stratigraphically higher deposits (Oadby Fm, Sheringham Cliffs Fm, Briton's Lane Fm) within the glacial succession are also contentious and highlight further contradictions between different types of chronological evidence (Rose, 2009). Whilst conventional interpretations of their ages imply an Anglian (MIS 12) age (Perrin *et al*., 1979; Bowen *et al*., 1986; Banham *et al*., 2001), other interpretations suggest that they may relate additionally, to further glaciations during MIS 10 and 6 (Rose in Clark *et al*., 2004; Hamblin *et al*., 2005; Rose, 2009). In the Nar Valley, organic deposits dated to MIS 9 by U-Series (Rowe *et al*., 1997) and AAR (Scourse *et al*., 1999) geo- chronology form part of a continuum with the Oadby Till suggesting that the till is of MIS 10 age (Ventris, 1996; Scourse *et al*., 1999; Hamblin *et al*., 2005). Elsewhere, an MIS 10 age for the Oadby Till is also suggested by the relationship between the till and the terrace aggradations within the Upper Thames (Sumbler, 1995, 2001), and the lower number of terrace aggradations within the river catchments of the Midlands compared to those of the Thames below the Goring Gap (Keen, 1999). Additionally, organic material and a temperate palaeosol have been found in the sequence between a chalk-free till (probably the Anglian- age Bozeat Till) from the chalky Oadby Till in the East Midlands (Rose, 2009).

It has been suggested that the equivalent to the Oadby Till in northern East Anglia is the Sheringham Cliffs Formation, and that this may also equate to MIS 10 (Clark *et al*., 2004; Hamblin *et al*., 2005; Rose, 2009). Overlying the Sheringham Cliffs Formation in northern East Anglia is the Briton's Lane Formation. It has been argued by Rose in Clark *et al*. (2004), Hamblin *et al*. (2005) and Rose (2009) that the Briton's Lane Formation may correlate with a MIS 6 glaciation for several reasons. First, that the apparent freshness of the Cromer Ridge push moraine and Glaven Valley ice-marginal landforms is akin to the MIS 6 land- forms of the Netherlands and north Germany and quite un- like heavily degraded MIS 12 landforms, or any other landforms beyond the MIS 2 ice limit in Britain. Second, an inferred correlation with MIS 6 deposits at Tottenhill (i.e. Gibbard *et al*., 1991b, 1992, 2009; Lewis and Rose, 1991), and pre-Ipswichian tills in East Yorkshire (Basement Till) and County Durham (Warren House Till) that contain similar reported elevations of Scandinavian lithologies.

The concept of MIS 10 and 6 glaciations in northern East Anglia has been disputed by several different lines of evidence that instead, suggest that the Sheringham Cliffs and Briton's Lane formations belong to the Anglian Glaciation. First, that the apparent freshness of the Cromer Ridge and other ice-marginal landforms could be a function of their sedimentology and later modification by periglacial processes (Banham *et al*., 2001; Gale and Hoare, 2007). Second, that the push moraine was formed during the Anglian based upon: (a) biostratigraphical and aminostratigraphical age constraint of a Hoxnian-age (MIS 11) kettle-hole infill (Hart and Peglar, 1990; Preece *et al*., 2009); (b) examination of the polyphase deformation signature within the upper parts of the glaciogenic sequence within the moraine complex that suggest deposition and subsequent deformation within a single glaciation (Lee and Phillips, 2008; Phil- lips *et al*., 2008); (c) outwash sands and gravels that lie on top of the Cromer Ridge that are dated by OSL to MIS 12 (Pawley *et al*., 2008).

LEE, J R, ROSE, J, HAMBLIN, R J, MOORLOCK, B S, RIDING, J B, PHILLIPS, E, BARENDREGT, R W, AND CANDY, I. 2011. The Glacial History of the British Isles during the Early and Middle Pleistocene: Implications for the long-term development of the British Ice Sheet. 59-74 in *Quaternary Glaciations–Extent and Chronology, A Closer look. Developments in Quaternary Science*. EHLERS, J, GIBBARD, P L, AND HUGHES, P D (editors). 15. (Amsterdam: Elsevier.)

DISCUSSION

Stratigraphical and Correlation Problems

The evidence for the Early and Middle Pleistocene glacial history of the British Isles has been presented within previous sections. It is evident that ice has been active in Britain for 2.6 million years, and that the scale and frequency of glaciation has evolved progressively in response to global-scale climatic trends. It is equally evident that major problems of correlation and chronology still exist as they do elsewhere within Europe (i.e. Ehlers and Gibbard, 2004, 2007). This is largely due to a lack of join-up between the onshore and offshore records, the often limited precision and resolution of dating methods beyond the Late Pleistocene, and the availability of suitable materials for dating (see Rose, 2009).

Glaciations in Britain

Despite the limitations highlighted above, and acknowledging that there are major issues of chronological and strati- graphical debate that require resolving, it is possible to gain a broad overall understanding of how glaciation has evolved in Britain during the Early and Middle Pleistocene and this is outlined in the following sections (Fig. 6).

Dropstones within sediments on the Hebrides Shelf pro- vide the first evidence for the inception of the Scottish sec- tor of the BIS at the beginning of the Pleistocene (c. 2.6 Ma) (Stoker *et al.*, 1994). The first evidence for ice within Wales occurs tentatively at c. 1.8 Ma (MIS 68), with erratic input into the oldest Sudbury Formation river terrace of the Kesgrave Thames (Whiteman and Rose, 1992). It may tentatively be correlated with the 'Baventian' cold stage where subarctic conditions prevailed in East Anglia and the North Sea region (West *et al.*, 1980; Gibbard *et al.*, 1991a). Several further mountain-scale glaciations occurred at various times in Wales during the Early Pleistocene (White- man and Rose, 1992; Rose *et al.*, 2010)).

Lowland glaciation associated with Scottish ice appears to have occurred at c. 1.1 Ma (MIS 34) with deposition of till (Sejrup *et al.*, 1987) and outwash (Ekman, 1999) within the North Sea (Fig. 6). Several further expansions of Scottish into lowland and coastal areas of the North Sea occurred during the Jaramillo Subchron (c. 1.07–0.99 Ma), and during cold stages within the post-B/M 'Cro- merian Complex' (c. MIS 18). Icebergs calving from these glacier incursions into the North Sea possibly floated south- wards before becoming grounded in the present area of East Anglia shedding the erratics found within the Wroxham Crag (Larkin *et al.*, 2011). The first lowland expansion of Welsh ice may relate to the beheading and truncation of the Thames catchment during the 'Cromerian Complex' at c. 0.8 Ma (MIS 20); with possible lowland glaciation of the Cotswold Hills which deposited a diamicton in that region and an increased influx of far-travelled material into the Ardleigh aggradation of the River Thames during MIS 18 (Whiteman and Rose, 1992).

Terrestrial evidence for the first lowland glaciation to reach eastern England may correspond with the Happisburgh Glaciation of northern East Anglia (Fig. 6). It is considered by Lee *et al.* (2004a) to correlate with MIS 16, although others still consider it to be of Anglian (MIS 12) age (Banham *et al.*, 2001; Preece *et al.*, 2009). The most extensive glaciation to affect the British Isles was the Anglian Glaciation of the late Middle Pleistocene (MIS 12). Evidence for this consists of tills, outwash deposits and widespread glacial erosion surfaces throughout both the terrestrial and offshore records (Perrin *et al.*, 1979; Cameron *et al.*, 1992; Fish and Whiteman, 2001; Hamblin *et al.*, 2005). This glaciation also represents the first 'shelf-edge' expansion of the BIS along the northwest European margin (Stoker *et al.*, 1994). The history and extent of the BIS during other late Middle Pleistocene cold stages is vague and open to several different interpretations from the same evidence. Current debate surrounds attempts at trying to establish a re- liable chronology for glacial deposits within this part of the stratigraphical record, and whether there are just two Middle Pleistocene glaciations during MIS 12 and 6 four separate glacier expansions during MIS 16, 12, 10 and 6.

Regional and Glaciological Context

Published evidence cited within this review demonstrates a long Quaternary record of glaciation within Britain. The initiation of glaciation within Britain coincides generally with the onset of Northern Hemisphere Glaciation between 3.6 and 2.4 Ma (Mundelsee and Raymo, 2005). Inception of several of the high-latitude polar ice sheets, including the Greenland and Barents Sea ice sheets (Jansen et al., 2000; Knies *et al.*, 2009), occurs slightly earlier during the Late Pliocene. However, major expansions of ice volume within these ice sheets, and the neighbouring Laurentide Ice Sheet, occur at the beginning of the Quaternary (Flesche Kleiven *et al*., 2002), and these appear to be coeval with the inception of mid-latitude ice sheets in Europe such as the SIS (Jansen *et al*., 2000; Sejrup *et al*., 2005) and of course the BIS.

Within Britain, this review also demonstrates that the scale of glaciation progressively stepped-up during the Early and Middle Pleistocene via a series of steps: (Step 1) glacier inception at c. 2.6 Ma and restricted mountain-scale glaciation during the Early Pleistocene; (Step 2) the initiation of lowland glaciation and first incursion of ice into the North Sea during the late Early Pleistocene (c. MIS 34); (Step 3) the first shelf-edge glaciation during the Anglian MIS 12. Interestingly, these 'steps' are broadly synchronous with major increases in the scale of glaciation identified in Scandinavia, and similarities between the two areas are discussed further by Lee *et al*. (2010). It appears that the principal trigger driving steps '2' and '3' may well have been the MPT and the progressive amplification of the 100 ka 'eccentricity' global climate signal that occurred between 1.2 and 0.7 Ma (Clark *et al*., 2006). For example, the first expansion of British ice into the North Sea Basin occurs c. 0.1 Ma after the beginning of this transition (1.2 Ma). However, the first extensive expansion of the BIS during MIS 12 demonstrates a lag of c. 0.35 Ma from the end of the MPT. It suggests that while Northern Hemisphere climate may have been modulated by 100 ka forcing, it took a further 0.35 Ma for this forcing to drive the build-up of ice volume within the BIS to sufficient levels to induce its first shelf-edge/continental-scale glaciation.

Within the cited records, it is also possible that there are regional differences between different ice accumulation areas in Britain although it is not clear whether this is real or an artefact of availability of evidence. For example, evidence suggests that the first mountain glaciations in Scotland may have occurred c. 0.8 Ma earlier than in Wales, and that the first significant lowland expansion of ice from Scotland occurred c. 0.3 Ma earlier than in Wales. These differences may involve their respective ability to build-up and retain ice volume over short and long periods of time relative to either the different uplift histories of the two areas, or significant regional differences in elevation/ precipitation/relative position to the polar front. Equally, differences in the timing of the first lowland expansion may reflect differences in the nature of the subglacial bed material and topography that partly control the lateral expansion of ice.

CONCLUSIONS

Britain has a long glacial history with evidence indicating a number of restricted and lowland glaciations during the Early and Middle Pleistocene prior to the Anglian Glaciation. The first evidence for glaciation relates to IRD layers on the Hebrides Shelf tentatively dated to 2.6 Ma.

Whilst the offshore record in Britain provides several lines of evidence for different episodes of glaciation during the Early and Middle Pleistocene, the chronology of these episodes should be viewed with caution as they are largely based on inferred correlations with the terrestrial record, and pollen assemblage biostratigraphy which has limited chronostratigraphical value.

Offshore evidence from the North Sea suggests that the first lowland expansion of Scottish ice occurred during the late Early Pleistocene at c. 1.1 Ma. The onset of lowland glaciations within southern Britain started during the 'Cromerian Complex'. Evidence for these events is linked to the possible beheading of the proto-Thames (MIS 20) and erratic input into the Ardleigh Terrace (possibly MIS 18).

The Anglian Glaciation (c. 0.43 Ma; MIS 12) marks the biggest Quaternary expansion of the BIS and had a marked effect on the landscape of Britain. It radically altered drainage and relief, and initiated the formation of the Straits of Dover which led Britain to be isolated from mainland Europe during various high sea-level stands during the Middle and Late Pleistocene.

The chronology of Middle Pleistocene expansions of the BIS is still contentious, with conflicts existing between different types of evidence, and in some cases, different interpretations of the same evidence.

Despite problems surrounding the precise chronology of expansions of the BIS, it is still possible to demonstrate that the long-term behavior of glaciation in Britain shows strong links to orbital forcing.

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REFERENCES

Allen, P., Cheshire, D.A., Whiteman, C.A., 1991. The tills of southern East Anglia. In: Ehlers, J., Gibbard, P.L., Rose, J. (Eds.), Glacial Deposits in Great Britain and Ireland. Balkema, Rotterdam, pp. 255–278.

Balson, P.S., Jeffrey, D.H., 1991. The glacial sequence of the southern North Sea. In: Ehlers, J., Gibbard, P.L., Rose, J. (Eds.), Glacial De- posits of Great Britain and Ireland. Balkema, Rotterdam, pp. 245–254.

Banham, P.H., 1968. A preliminary note on the Pleistocene stratigraphy of north-east Norfolk. Proc. Geologists' Assoc. 79, 469–474.

Banham, P.H., Gibbard, P.L., Lunkka, J.P., Parfitt, S.A., Preece, R.C., Turner, C., 2001. A critical assessment of 'A New Glacial Stratigraphy for Eastern England. Quatern. Newsl. 93, 251–258.

Barron, A.J.M., Morigi, A.N., Reeves, H.J., 2006. Geology of the Welling- borough District—a brief explanation of the geological map. In: Sheet Explanation of the British Geological Survey. British Geological Sur- vey, Nottingham, 34 pp. Wellingborough (England and Wales).

Bateman, M.D., Catt, J.A., 1996. An absolute chronology for the raised beach and associated deposits at Sewerby, East Yorkshire, England. J. Quatern. Sci. 11, 389–395.

Bowen, D.Q. (Ed.), 1999. A Revised Correlation of Quaternary Deposits in the British Isles. Geological Society of London, Bath Special Report No. 23.

Bowen, D.Q., Rose, J., McCabe, A.M., Sutherland, D.G., 1986. Quaternary Glaciations in England, Ireland, Scotland, and Wales. Quatern. Sci. Rev. 5, 299–340.

Bowen, D.Q., Hughes, S., Sykes, G.A., Miller, G.H., 1989. Land-sea correlations in the Pleistocene based on isoleucine epimerization in non-marine molluscs. Nature 340, 49–51.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D., *et al*., 2007. The northern sector of the last British Ice Sheet: maximum extent and demise. Earth Sci. Rev. 88, 207–226.

Bridgland, D.R., 1994. Quaternary of the Thames. Geological Conservation Review Series. Joint Nature Conservation Committee Chapman and Hall, London, pp. 441.

Bridgland, D.R., 2000. River terrace systems in north-west Europe: an archive of environmental change, uplift and early human occupation. Quatern. Sci. Rev. 19, 1293–1303.

Bridgland, D.R., Schreve, D.C., 2004. Quaternary lithostratigraphy and mammalian biostratigraphy of the Lower Thames terrace system, south-east England. Quaternaire 15, 29–40.

Busschers, F.S., Kasse, C., van Balen, R.T., Vandenberghe, J., Cohen, K.M., Weerts, H.J.T., *et al*., 2008. Late Pleistocene evolution of the Rhine- Meuse system in the southern North Sea Basin: imprints of climate change, sea-level oscillation and glacio-isostacy. Quatern. Sci. Rev. 26, 3216–3248.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffrey, D.H., Lott, J.K., Bulat, J., *et al*., 1992. The Geology of the Southern North Sea. HMSO, London United Kingdom Offshore Regional Report, HMSO for the British Geological Survey.

Carney, J.N., Ambrose, K., 2007. Geology of the Leicester district—a brief explanation of the geological map. In: Sheet Explanation of the British Geological Survey. British Geological Survey, Nottingham Leicester (England and Wales).

Carr, S.J., 2004. The North Sea Basin. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations—Extent and Chronology, Part I: Europe. Elsevier Publishers, Amsterdam, pp. 261–270.

Catt, J.A., 2007. The Pleistocene glaciations of eastern Yorkshire: a review. Proc. Yorks. Geol. Soc. 56, 177–207.

Catt, J.A., Penny, L.F., 1966. The Pleistocene deposits of Holderness, East Yorkshire. Proc. Yorks. Geol. Soc. 35, 275–420.

Clark, C.D., Gibbard, P.L., Rose, J., 2004. Pleistocene glacial limits in England, Scotland and Wales. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations—Extent and Chronology, Part I: Europe. Amsterdam, Elsevier, pp. 47–82.

Clark, P.U., Archer, D., Pollard, D., Blum, J.D., Rial, J.A., Brovkin, V., *et al*., 2006. The Middle Pleistocene transition: characteristics, mech- anisms, and implications for long-term changes in atmospheric CO_2. Quatern. Sci. Rev. 25, 3150–3184.

Davies, B.J., Roberts, D.H., Bridgland, D.R., Ó Cofaigh, C., Riding, J.B., Demarchi, B., Penkman, K.E.H., Pawley, S.M., 2010. Timing and de- positional environments of a Middle Pleistocene glaciation of north-east England: New evidence from Warren House Gill, County Durham. Quatern. Sci. Rev. in Press.

Ehlers, J., Gibbard, P.L., 1991. Anglian glacial deposits in Britain and the adjoining offshore regions. In: Ehlers, J., Gibbard, P.L., Rose, J. (Eds.), Glacial Deposits of Great Britain and Ireland. Balkema, Rotterdam, pp. 17–24.

Ehlers, J., Gibbard, P.L. (Eds.), 2004. Quaternary Glaciations—Extent and Chronology, Part I: Europe. Elsevier, Amsterdam, pp. 47–82.

Ehlers, J., Gibbard, P.L., 2007. The extent and chronology of Cenozoic Glaciation. Quatern. Int. 164–165, 6–20.

Ehlers, J., Gibbard, P.L., Whiteman, C.A., 1987. Recent investigations of the Marly Drift of northwest Norfolk, England. In: van der Meer, J.J.M. (Ed.), Tills and Glaciotectonics. Balkema, Rotterdam, pp. 39–54.

Ehlers, J., Gibbard, P.L., Whiteman, C.A., 1991. The glacial deposits of northwest Norfolk. In: Ehlers, J., Gibbard, P.L., Rose, J. (Eds.), Glacial Deposits of Great Britain and Ireland. Balkema, Rotterdam, pp. 223–232.

Ekman, S.R., 1999. Early Pleistocene pollen biostratigraphy in the central North Sea. Rev. Palaeobot. Palynol. 105, 171–182.

Fish, P.R., Whiteman, C.A., 2001. Chalk micropalaeontology and the provenancing of Middle Pleistocene Lowestoft formation till in eastern England. Earth Surf. Process. Land. 26, 953–970.

Flesche Kleiven, H., Jansen, E., Fronval, T., Smith, T.M., 2002. Intensification of Northern Hemisphere glaciations in the circum Atlantic region (3.5–2.4 Ma) - ice-rafted detritus evidence. Palaeogeo. Palaeoclimatol. Palaeoecol. 184, 213–223.

Funnell, B.M., 1995. Global sea-level and the (pen-) insularity of late Cenozoic Britain. In: Preece, R.C. (Ed.), Island Britain: A Quaternary Perspective, Geological Society Special Publication No 96, pp. 3–13. Gale, S.J., Hoare, P.G., 2007. The age and origin of the Blakeney Esker of north Norfolk: implications for the glaciology of the southern North Sea Basin. In: Hambrey, M.J., Christoffersen, P., Glasser, N.F., Hubbard, B.P. (Eds.), Glacial Sedimentary Processes and Products, International Association of Sedimentologists Special Publication, 39 203–234.

Gatliff, R.W., Richards, P.C., Smith, K., Graham, C.C., McCormac, M., Smith, N.J.P., *et al*., 1994. The Geology of the Central North Sea. HMSO, London United Kingdom Offshore Regional Report, British Geological Survey.

Geyh, M.A., Müller, H., 2005. Numerical 230Th/U dating and a palynological review of the Holsteinian/Hoxnian Interglacial. Quatern. Sci. Rev. 24, 1861–1872.

Gibbard, P.L., 1977. Pleistocene history of the Vale of St Albans. Philos.Trans. R. Soc. Lond. B280, 445–483.

Gibbard, P.L., 1995. The formation of the Strait of Dover. In: Preece, R.C. (Ed.), Island Britain: A Quaternary Perspective, Geological Society, London, Special Publication, 96 15–26.

Gibbard, P.L., West, R.G., Zagwijn, W.H., Balson, P.S., Burger, A.W., Funnell, B.M., *et al*., 1991a. Early and early Middle Pleistocene corre- lations in the Southern North Sea Basin. Quatern. Sci. Rev. 10, 23–52. Gibbard, P.L., West, R.G., Andrew, R., Pettit, M., 1991b. Tottenhill, Nor- folk (TF 636115). In: Lewis, S.G., Whiteman, C.A., Bridgland, D.R. (Eds.), Central East Anglia and the Fen Basin—Field Guide. Quaternary Research Association, London, pp. 131–144.

Gibbard, P.L., West, R.G., Andrew, R., Pettit, M., 1992. The margin of a Middle Pleistocene ice advance at Tottenhill, Norfolk, England. Geol. Mag. 129, 59–76.

Gibbard, P.L., Moscariello, A., Bailey, H.W., Boreham, S., Kock, C., Lord, A.R., *et al*., 2008. Comment: Middle Pleistocene sedimentation at Pakefield, Suffolk, England. J. Quatern. Sci. 23, 85–92.

Gibbard, P.L., Pasanen, A.H., West, R.G., Lunkka, J.P., Boreham, S., Cohen, K., *et al*., 2009. Late Middle Pleistocene glaciation in East An- glia, England. Boreas 38, 504–528.

Gray, J.M., 1997. The origin of the Blakeney Esker, Norfolk. Proc. Geologists' Assoc. 108, 177–182.

Green, C.P., McGregor, D.F.M., 1990. Pleistocene gravels of the north Norfolk coast. Proc. Geologists' Assoc. 101, 197–202.

Grün, R., Schwarz, H.P., 2000. Revised open system U-series/ESR age calculations for teeth from Stratum C at the Hoxnian Interglacial type locality, England. Quatern. Sci. Rev. 19, 1151–1154.

Hamblin, R.J.O., Moorlock, B.S.P., Rose, J., 2000. A New Glacial Stratigraphy for Eastern England. Quatern. Newsl. 92, 35–43.

Hamblin, R.J.O., Moorlock, B.S.P., Rose, J., Lee, J.R., Riding, J.B., Booth, S.J., *et al.*, 2005. Revised Pre-Devensian glacial stratigraphy in Norfolk, England, based on mapping and till provenance. Geol. Mijnbouw 84, 77–85.

Hart, J.K., Peglar, S.M., 1990. Further evidence for the timing of the Middle Pleistocene glaciation in Britain. Proc. Geologists' Assoc. 101, 187–196.

Head, M.J., Gibbard, P.L. (Eds.), 2005a. Early-Middle Pleistocene Transitions—The Land-Ocean Evidence, In: Geological Society, London, Special Publication, 247, 326 pp.

Head, M.J., Gibbard, P.L., 2005b. Early-Middle Pleistocene transition: an overview and recommendation for the defining boundary. In: Head, M. J., Gibbard, P.L. (Eds.), Early-Middle Pleistocene Transitions—The Land-Ocean Evidence, Geological Society, London, Special Publication vol. 247. 1–18.

Hey, R.W., 1980. Equivalent of the Westland green gravels in Essex and East Anglia. Proc. Geologists' Assoc. 91, 279–290.

Hey, R.W., Brenchley, P.J., 1977. Volcanic pebbles from the Pleistocene gravels in Norfolk and Essex. Geol. Mag. 114, 219–225.

Hibbert, F.D., Austin, W.E.N., Leng, M.J., Gatliff, R.W., 2009. British Ice Sheet dynamics inferred from North Atlantic ice-rafted debris records spanning the last 175,000 years. J. Quatern. Sci. 25, 461–482.

Hibbert, F.D., Austin, W.E.N., Leng, M.J., Gatliff, R.W., 2010. British Ice Sheet dynamics inferred from North Atlantic ice-rafted debris records spanning the last 175,000 years. J. Quatern. Sci. 25, 461–482.

Hoare, P.G., Gale, S.J., Robinson, R.A.J., Connell, E.R., Larkin, N.R., 2009. Marine Isotope Stage 7–6 transition age for the beach sediments at Morston, north Norfolk, UK: implications for Pleistocene chronol- ogy, stratigraphy and tectonics. J. Quatern. Sci. 24, 311–316.

Holmes, R., 1997. Quaternary stratigraphy: the offshore record. In: Gordon, J.E. (Ed.), Reflections on the Ice Age in Scotland: An Update on Quaternary Studies. The Scottish Association of Geography Teachers and Scottish Natural Heritage, Glasgow, pp. 72–94.

Holmes, R., Bulat, J., Hamilton, I., Long, D., 2003. Morphology of an ice- sheet limit and constructional glacially-fed slope front, Færoe-Shet- land Channel. In: Mienart, J., Weaver, P. (Eds.), European Margin Sediment Dynamics: Side-Scan Sonar and Seismic Images. Springer-Verlag, Berlin, pp. 149–151.

Jansen, E., Fronval, T., Rack, F., Channell, J.E.T., 2000. Pliocene-Pleistcene ice rafting history and cyclicity in the Nordic Seas during the last 3.5 Myr. Paleoceanography 15, 709–721.

Keen, D.H., 1999. The chronology of Middle Pleistocene ('Wolstonian') events in the English Midlands. In: Andrews, P.J., P.H., Banham (Eds.), Late Cenozoic Environments and Hominid Evolution—A Tribute to Bill Bishop. Geological Society of London Special Publication, London, pp. 159–168.

Knies, J., Matthiessen, J., Vogt, C., Laberg, J.S., Hjelstuen, B.O., Smelror, M., *et al.*, 2009. The Plio-Pleistocene glaciation of the Ba- rents Sea-Svalbard region: a new model based on revised chronostratigraphy. Quatern. Sci. Rev. 28, 812–829.

Laban, C., 1995. The Pleistocene glaciations in the Dutch sector of the North Sea. A synthesis of sedimentary and seismic data. Ph.D. thesis, University of Amsterdam.

Larkin, N.R., Lee, J.R., Connell, E.R., 2011. Possible ice-rafted erratics in late Early to early Middle Pleistocene shallow marine and coastal de- posits in northeast Norfolk, UK. Proce. Geologists' Assoc. in press.

Lee, J.R., 2001. Genesis and palaeogeographical significance of the Corton Diamicton (basal member of the North Sea Drift Formation), East An- glia, UK. Proc. Geologists' Assoc. 112, 29–43.

Lee, J.R., 2009. Patterns of preglacial sedimentation and glaciotectonic de- formation within early Middle Pleistocene sediments at Sidestrand, north Norfolk, UK. Proc. Geologists' Assoc. 120, 34–48.

Lee, J.R., Phillips, E., 2008. Progressive soft sediment deformation within a subglacial shear zone—a hybrid mosaic-pervasive deformation model for Middle Pleistocene glaciotectonised sediments from Eastern England. Quatern. Sci. Rev. 27, 1350–1362.

Lee, J.R., Rose, J., Riding, J.B., Hamblin, R.J.O., Moorlock, B.S.P., 2002. Testing the case for a Middle Pleistocene Scandinavian glaciation in Eastern England: evidence for a Scottish ice source for tills within the Corton Formation of East Anglia, UK. Boreas 31, 345–355.

Lee, J.R., Rose, J., Hamblin, R.J.O., Moorlock, B.S.P., 2004a. Dating the earliest lowland glaciation of eastern England: the pre-Anglian early Middle Pleistocene Happisburgh Glaciation. Quatern. Sci. Rev. 23, 1551–1566.

Lee, J.R., Booth, S.J., Hamblin, R.J.O., Jarrow, A.M., Kessler, H., Moorlock, B.S.P., *et al*., 2004b. A new stratigraphy for the glacial de- posits around Lowestoft, Great Yarmouth, North Walsham and Cromer, East Anglia, UK. Bull. Geol. Soc. Norfolk 53, 3–60.

Lee, J.R., Moorlock, B.S.P., Rose, J., Hamblin, R.J.O., Pawley, S.M., Riding, J.B., *et al*., 2005. A reply to the paper by Hoare and Connell. "The first appearance of Scandinavian indicators in East Anglia's glacial record" Bull. Geol. Soc. Norfolk 55, 43–62.

Lee, J.R., Rose, J., Candy, I., Barendregt, R.W., 2006. Sea-level changes, river activity, soil development and glaciation around the western mar- gins of the southern North Sea Basin during the Early and early Middle Pleistocene: evidence from Pakefield, Suffolk, UK. J. Quatern. Sci. 21, 155–179.

Lee, J.R., Pawley, S.M., Rose, J., Moorlock, B.S.P., Riding, J.B., Hamblin, R.J.O., *et al*., 2008a. Pre-Devensian lithostratigraphy of shal- low marine, fluvial and glacial sediments in northern East Anglia. In: Candy, I., Lee, J.R., Harrison, A.M. (Eds.), The Quaternary of North- ern East Anglia Field Guide. Quaternary Research Association, Lon- don, pp. 42–59.

Lee, J.R., Rose, J., Candy, I., Barendregt, R.W., Moorlock, B.S.P., Riding, J.B., *et al*., 2008b. Reply: Middle Pleistocene sedimentation at Pakefield, Suffolk, UK. J. Quatern. Sci. 23, 93–98.

Lee, J.R., Busschers, F., Sejrup, H.P., 2010. Pre-Weichselian Quaternary glaciations of the British Isles, The Netherlands, Norway and adjacent marine areas south of 68^{o}N: implications for long-term ice sheet development in northern Europe. Quatern. Sci. Rev. in press.

Lewis, S.G., 1993. The status of the Wolstonian Glaciation in the English Midlands and East Anglia. Unpublished Ph.D. thesis, University of London.

Lewis, S.G., Rose, J., 1991. Tottenhill, Norfolk (TF 639 120). In: Lewis, S. G., Whiteman, C.A., Bridgland, D.R. (Eds.), Central East Anglia and the Fen Basin, Field Guide. Quaternary Research Association, Lon- don, pp. 145–148.

Long, D., Laban, C., Streif, H., Cameron, T.D.J., Schüttenhelm, R.T.E., 1988. The sedimentary record of climatic variation in the southern North Sea. Philos. Trans. R. Soc. Lond. B318, 523–537.

Lunkka, J.P., 1994. Sedimentation and lithostratigraphy of the North Sea Drift and Lowestoft Till Formations in the coastal cliffs of northeast Norfolk, England. J. Quatern. Sci. 9, 209–233.

McGregor, D.F.M., Green, C.P., 1978. Gravels of the River Thames as a guide to Pleistocene catchment changes. Boreas 7, 197–203.

Merritt, J.W., Auton, C.A., Connell, E.R., Hall, A.M., Peacock, J.D., Aitken, J.F., *et al*., 2003. Cainozoic Geology and Landscape Evolution of North-East Scotland: Memoir for the Drift Editions of 1:50,000 Geological Sheets 66E Banchory, 67 Stonehaven, 76E Inverurie, 77 Aberdeen, 86E Turriff, 87W Ellon, 87E Peterhead, 95 Elgin, 96W Portsoy, 96E Banff and 97 Fraserburgh. Memoir of the Geological Sur- vey of Great Britain (Scotland) HMSO, London.

Mitchell, G.F., Penny, L.F., Shotton, F.W., West, R.G., 1973. A Correlation of Quaternary Deposits in the British Isles. Geological Society of London, London Special Report no. 4.

Moorlock, B.S.P., Booth, S.J., Fish, P., Hamblin, R.J.O., Kessler, H., Riding, J., *et al*., 2000. Briton's Lane Gravel pit, Beeston Regis (TG 168 415). In: Lewis, S.G., Whiteman, C.A., Preece, R.C. (Eds.), The Quaternary of Norfolk and Suffolk: Field Guide. Quaternary Re- search Association, London, pp. 115–117.

Moorlock, B.S.P., Hamblin, R.J.O., Rose, J., Lee, J.R., 2001. The occurrence of rhomb-porphyry within diamictons in north-east Norfolk. Quatern. Newsl. 95, 49–50.

Mundelsee, M., Raymo, M.E., 2005. Slow dynamics of the Northern Hemi- sphere Glaciation. Paleoceanography 20, PA4200.

Pawley, S.M., 2006. Quaternary glaciations of north and west Norfolk. Unpublished Ph.D. thesis, Royal Holloway, University of London.

Pawley, S.M., Rose, J., Lee, J.R., Hamblin, R.J.O., Moorlock, B.S.P., 2004. Middle Pleistocene stratigraphy of Weybourne, north-east Norfolk, England. Proc. Geologists' Assoc. 115, 22–42.

Pawley, S.M., Bailey, R.J.J., Rose, J., Moorlock, B.S.P., Hamblin, R.J.O., Booth, S.J., *et al*., 2008. Age limits on Middle Pleistocene glacial sediments from OSL dating, North Norfolk, UK. Quatern. Sci. Rev. 27, 1363–1377.

Perrin, R.M.S., Rose, J., Davies, H., 1979. The distribution, variation and origins of pre-Devensian tills in eastern England. Philos. Trans. R. Soc. Lond. B287, 535–570.

Phillips, E., Lee, J.R., Burke, H.K., 2008. Progressive proglacial to subglacial deformation and syntectonic sedimentation at the margins of the Mid-Pleistocene British Ice Sheet: evidence from north Norfolk, UK. Quatern. Sci. Rev. 27, 1848–1871.

Pointon, K.W., 1978. The Pleistocene succession at Corton, Suffolk. Bull.Geol. Soc. Norfolk 30, 55–76.

Praeg, D., 2003. Seismic imaging of mid-Pleistocene tunnel valleys in the North Sea Basin—high resolution from low frequencies. J. Appl. Geo- phys. 53, 273–298.

Preece, R.C., Parfitt, S.A., 2000. The Cromer Forest-bed formation: new thoughts on an old problem. In: Lewis, S.G., Whiteman, C.A., Preece, R.C. (Eds.), The Quaternary of Norfolk and Suffolk, Field Guide. Quaternary Research Association, London, pp. 1–27.

Preece, R.C., Parfitt, S.A., 2008. The Cromer Forest-bed formation: some recent developments relating to early human occupation and lowland glaciation. In: Candy, I., Lee, J.R., Harrison, A.M. (Eds.), The Quaternary of Northern East Anglia, Field Guide. Quaternary Research As- sociation, London, pp. 60–83.

Preece, R.C., Parfitt, S.A., Bridgland, D.R., Lewis, S.G., Rowe, P.J., Atkinson, T.C., *et al*., 2007. Terrestrial environments during MIS 11: evidence from the Palaeolithic site at West Stow, Suffolk, UK. Quatern. Sci. Rev. 26, 1236–1300.

Preece, R.C., Parfitt, S.A., Coope, G.R., Penkman, K.E.H., Ponel, P., Whittaker, J.E., 2009. Biostratigraphic and aminostratigraphic constraints on the age of the Middle Pleistocene glacial succession in north Norfolk. J. Quatern. Sci. 24, 557–580.

Read, A., Godwin, M., Mills, C.A., Juby, C., Lee, J.R., Palmer, A.P., *et al*., 2007. Evidence for Middle Pleistocene temperate-climate high sea- level and lowland-scale glaciation, Chapel Hill, Norwich, UK. Proc. Geologists' Assoc. 118, 143–156.

Reid, C., 1882. The Geology of the Country Around Cromer. Memoirs of the Geological Survey of England and Wales.

Rice, R.J., 1968. The Quaternary deposits of central Leicestershire. Philos.Trans. R. Soc. Lond. A262, 459–509.

Rose, J., 1987. Status of the Wolstonian Glaciation in the British Quater- nary. Quatern. Newsl. 53, 1–9.

Rose, J., 1989a. Stadial type sections in the British Quaternary. In: Rose, J., Schlüchter, C. (Eds.), Quaternary Type Sections: Imagination or Reality?. Balkema, Rotterdam, pp. 45–67.

Rose, J., 1989b. Castle Bytham. In: Keen, D.H. (Ed.), West Midlands Field Guide. Quaternary Research Association, Cambridge, pp. 117–122.

Rose, J., 1992. High lodge—regional context and geological background. In: Ashton, N.M., Cook, J., Lewis, S.G., Rose, J. (Eds.), High Lodge: Excavations by G. de G. Sieveking, 1962-8 and J. Cook, 1988. British Museum Press, London, pp. 13–24.

Rose, J., 1994. Major river systems of central and southern Britain during the Early and Middle Pleistocene. Terra Nova 6, 435–443.

Rose, J., 2009. Early and Middle Pleistocene landscapes of eastern England. Proc. Geologists' Assoc. 120, 3–33.

Rose, J., Whiteman, C.A., Allen, P., Kemp, R.A., 1999a. The Kesgrave sands and gravels: 'pre-glacial' Quaternary deposits of the River Thames in East Anglia and the Thames Valley. Proc. Geologists' Assoc. 110, 93–116.

Rose, J., Lee, J.A., Candy, I., Lewis, S.G., 1999b. Early and Middle Pleistocene river systems in eastern England: evidence from Leet Hill, southern Norfolk, England. J. Quatern. Sci. 14, 347–360.

Rose, J., Moorlock, B.S.P., Hamblin, R.J.O., 2000. Lithostratigraphy and palaeoenvironments of the pre-Anglian sands and gravels of East Anglia. In: Lewis, S.G., Whiteman, C.A., Preece, R.C. (Eds.), The Quaternary of Norfolk and Suffolk: Field Guide. Quaternary Research Association, London, pp. 35–45.

Rose, J., Moorlock, B.S.P., Hamblin, R.J.O., 2001. Pre-Anglian fluvial and coastal deposits in Eastern England: lithostratigraphy and Palaeoenvironments. Quatern. Int. 79, 5–22.

Rose, J., Carney, J.N., Silva, B.N., Booth, S.J., 2010. A striated, far travelled clast of rhyolitic tuff from Thames river deposits at Ardleigh, Essex, England: evidence for early Middle Pleistocene glaciation in the Thames catchment. Neth. J. Geosci. 89, 137–146.

Rowe, P.J., Richards, D.A., Atkinson, T.C., Bottrell, S.H., Cliff, R.A., 1997. Geochemistry and radiometric dating of a Middle Pleistocene peat. Geochim. Et Cosmochim. Acta 61, 4201–4211.

Rowe, P.J., Atkinson, T.C., Turner, C., 1999. U-series dating of Hoxnian interglacial deposits at Marks Tey, Essex, England. J. Quatern. Sci. 14, 693–702.

Scourse, J.D., Austin, W.E.N., Sejrup, H.P., Ansari, M.H., 1999. Foraminiferal isoleucine epimerization determinations from the Nar Valley Clay, Norfolk, UK: implications for quaternary correlations in the southern North Sea basin. Geol. Mag. 136, 543–560.

Sejrup, H.P., Aarseth, K.L., Ellingsen, K.L., Reither, E., Jansen, E., Li:vlie, R., *et al.*, 1987. Quaternary stratigraphy of the Fladen area, central North Sea: a multidisciplinary study. J. Quatern. Sci. 2, 33–58. Sejrup, H.P., Larsen, E., Landvik, J., King, E.L., Haflidason, H., Nesje, A., 2000. Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the northern North Sea region. Quatern. Sci.

Rev. 19, 667–685.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason, H., Kuijpers, A., Nygård, A., *et al.*, 2005. Pleistocene glacial history of the NW European continental margin. Mar. Petrol. Geol. 22, 1111–1129.

Shotton, F.W., 1953. The Pleistocene deposits of the area around Coventry, Rugby and Leamington and their bearing upon topographic develop- ment of the Midlands. Philos. Trans. R. Soc. Lond. 237B, 209–260.

Shotton, F.W., 1983. The Wolstonian Stage of the British Pleistocene in and around its type area of the English Midlands. Quatern. Sci. Rev. 2, 261–280.

Soloman, J.D., 1935. The Westleton Series of East Anglia: its ages, distribution and relations. Q. J. Geol. Soc. Lond. 91, 16–238.

Stoker, M.S., 1995. The influence of glacigenic sedimentation on slope- apron development on the continental margin off Northwest Britain. In: Scrutton, R.A., Stoker, M.S., Schimmield, G.B., Tudhope, A.W. (Eds.), The Tectonics, Sedimentation and Palaeooceanography of the North Atlantic Region. Geological Society Special Publications, London, pp. 159–177.

Stoker, M.S., Bent, A., 1985. Middle Pleistocene glacial and glaciomarine sedimentation in the west central North Sea. Boreas 14, 325–332.

Stoker, M.S., Hitchen, K., Graham, C.C., 1993. United Kingdom offshore regional report: the geology of the Hebrides and west Shetland shelves and adjacent deep-water areas. HMSO for the British Geological Sur- vey, London.

Stoker, M.S., Leslie, A.B., Scott, W.D., Briden, J.C., Hine, N.M., Harland, R., *et al.*, 1994. A record of late Cenozoic stratigraphy, sedimentation and climate change from the Hebrides Shelf, NE Atlantic Ocean. J. Geol. Soc. Lond. 151, 235–249.

Straw, A., 1983. Pre-Devensian glaciation of Lincolnshire (Eastern England) and adjacent areas. Quatern. Sci. Rev. 2, 239–260.

Sumbler, M.G., 1995. The terraces of the rivers Thame and Thames and their bearing on the chronology of glaciation in central and eastern England. Proc. Geologists' Assoc. 106, 93–106.

Sumbler, M.G., 2001. The Moreton Drift: a further clue to glacial chronology in central England. Proc. Geologists' Assoc. 112, 13–27.

Trechmann, C.T., 1916. The Scandinavian Drift of the Durham coast and the general glaciology of southeast Durham. Q. J. Geol. Soc. Lond. 71, 53–82.

Turner, C., 1970. Middle Pleistocene deposits at Marks Tey, Essex. Philos. Trans. R. Soc. Lond. B247, 373–437.

Tzedakis, P.C., Andrieu, V., de Beaulieu, J.-L., Birks, H.J.B., Crowhurst, S., Follieri, M., *et al.*, 2001. Establishing a terrestrial chronological framework as a basis for biostratigraphical comparisons. Quatern. Sci. Rev. 20, 1583–1592.

Ventris, P.A., 1996. Hoxnian interglacial freshwater and marine deposits in northwest Norfolk, England and their implications for sea-level reconstruction. Quatern. Sci. Rev. 15, 437–450.

West, R.G., 1956. The Quaternary deposits at Hoxne, Suffolk. Philos.

Trans. R. Soc. Lond. B239, 265–356.

West, R.G., 1980. The Pre-Glacial Pleistocene of the Norfolk and Suffolk Coasts. Cambridge University Press, Cambridge.

West, R.G., Donner, J.J., 1956. The glaciations of East Anglia and the East Midlands: a differentiation based on stone orientation measurements of the tills. Q. J. Geol. Soc. Lond. 112, 146–184.

West, R.G., Funnell, B.M., Norton, P.E.P., 1980. An Early Pleistocene cold marine episode in the North Sea: pollen and faunal assemblages at Covehithe, Suffolk, England. Boreas 9, 1–10.

Westaway, R., 2009. Quaternary vertical crustal motion and drainage evolution in East Anglia and adjoining parts of southern England: chronology of the Ingham River terrace deposits. Boreas 10, 261–284.

Westaway, R., Maddy, D., Bridgland, D., 2002. Flow in the lower continental crust as a mechanism for the Quaternary uplift of south-east En- gland: constraints from the Thames record. Quatern. Sci. Rev. 21, 59–603.

Whiteman, C.A., 1992. The palaeogeography and correlation of pre-Anglian Glaciation terraces of the River Thames in Essex and the London Basin. Proc. Geologists' Assoc. 103, 37–56.

Whiteman, C.A., Rose, J., 1992. Thames river sediments of the British Early and Middle Pleistocene. Quatern. Sci. Rev. 11, 363–375.

Wymer, J.J., 1985. Palaeolithic Sites in East Anglia. Geobooks, Norwich. Zagwijn, W.H., 1989. The Netherlands during the Tertiary and the Quaternary: a case history of Coastal Lowland evolution. Geol. Mijnbouw 68, 107–120.

Zagwijn, W.H., 1996. The Cromerian Complex Stage of the Netherlands and correlation with other areas in Europe. In: Turner, C. (Ed.), The Early Middle Pleistocene in Europe. Balkema, Rotterdam, pp. 145–172.

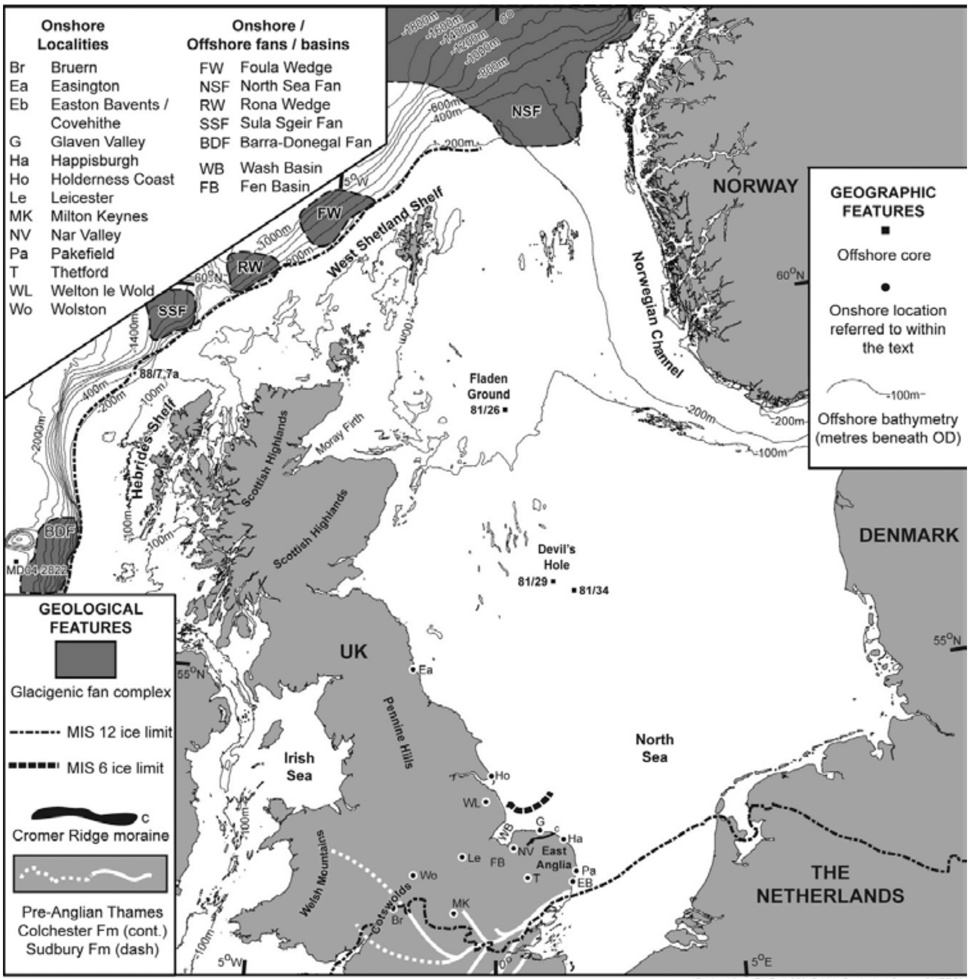

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FIGURE. 1 Map of the British Isles, North Sea Basin and northwest European margin showing the location of sites and features referred to within the text. The MIS 12 and 6 ice limits are shown after Bowen et al. (1986) and Ehlers and Gibbard (2004).

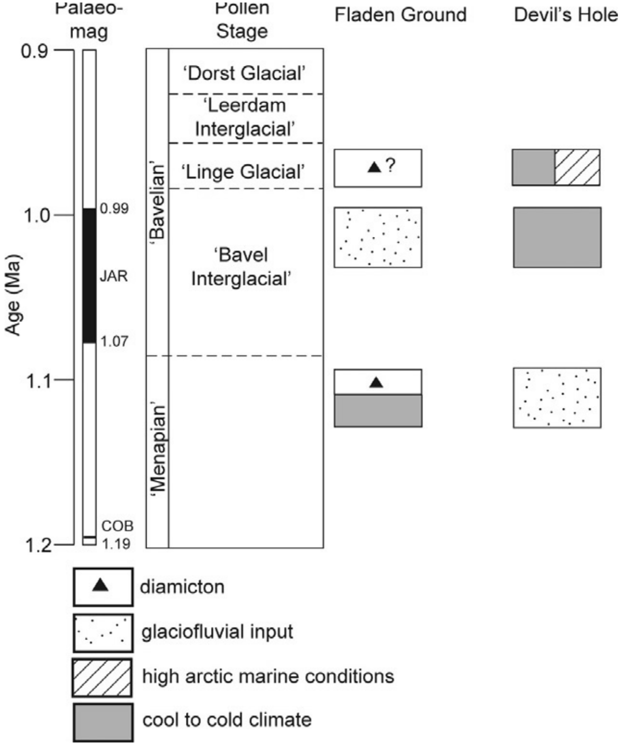

FIGURE. 2 Evidence for late Early Pleistocene glaciation in the Fladen Ground and Devil's Hole areas of the North Sea. Adapted from Sejrup et al. (1987) and Ekman (1999). Palaeomagnetism is from Funnell (1995).

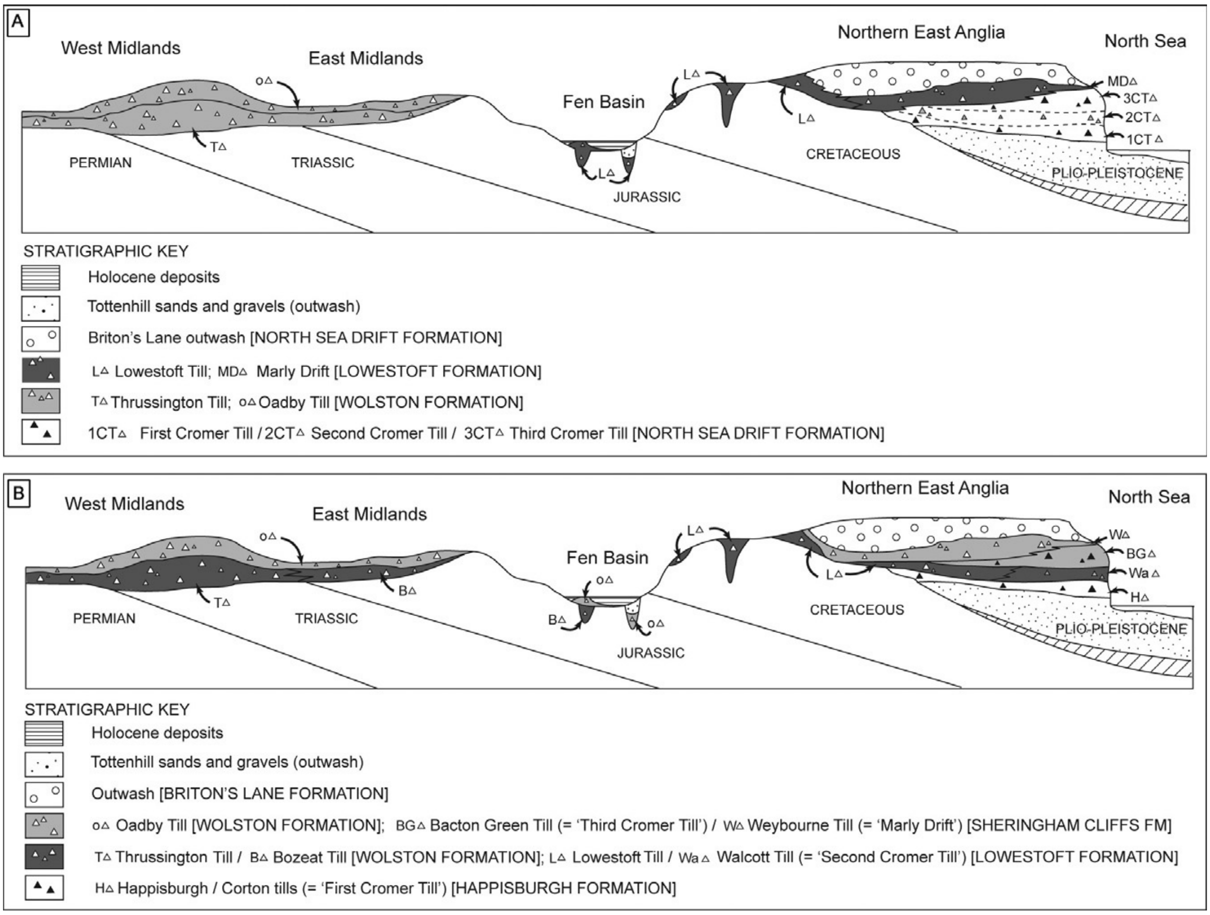

FIGURE. 3 Schematic cross-section across the Midlands and East Anglia showing the distribution, geometry and stratigraphy of major till units. (A) The 'conventional' interpretation of the glacial succession showing the interdigitation of the Lowestoft and 'North Sea Drift' in northern East Anglia after Bowen et al. (1986), Ehlers and Gibbard (1991) and Bowen (1999). (B) The 'new' interpretation of the glacial succession based on extensive geological mapping, borehole evidence and lithological analyses—after Lee et al. (2004a), Hamblin et al. (2005), Rose (2009).

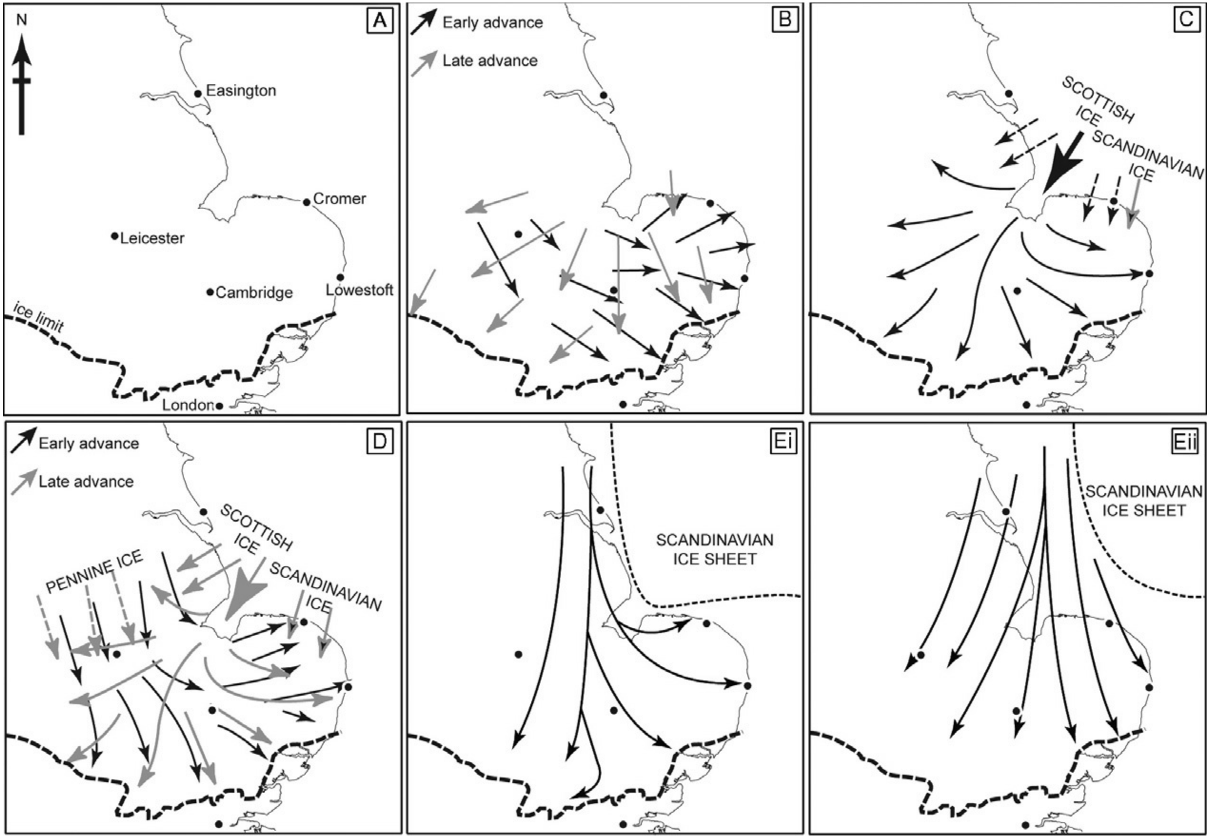

FIGURE. 4 Models for the Middle Pleistocene glaciation in the Midlands and Eastern England. (A) Location map. (B) Ice flow model of West and Donner (1956): this model recognises an initial ‘Anglian’ advance that deposits the Jurassic-rich Lowestoft Till and a later ‘Gipping/Wolstonian’ advance that deposits the chalky Gipping Till. (C) Ice flow model of Perrin et al. (1979): recognises a single sheet of chalky till including the Calcethorpe Till of Lincolnshire, and a single Lowestoft Till including Jurassic-rich and Chalk-rich facies. (D) Ice flow model of Rose (1992): the ‘conventional’ model for the Anglian glaciation that recognises an earlier ice advance from the west depositing the Triassic-rich (Thrussington Till) and Jurassic-rich (Lowestoft Till), followed by a later advance and the deposition of the Oadby Till and chalky tills of East Anglia. (E) Ice flow model of Fish and Whiteman (2001): this model recognises two separate ice advances within chalk-bearing tills including an earlier (i) and later (ii) advances.

LEE, J R, ROSE, J, HAMBLIN, R J, MOORLOCK, B S, RIDING, J B, PHILLIPS, E, BARENDREGT, R W, AND CANDY, I. 2011. The Glacial History of the British Isles during the Early and Middle Pleistocene: Implications for the long-term development of the British Ice Sheet. 59-74 in *Quaternary Glaciations–Extent and Chronology, A Closer look. Developments in Quaternary Science*. EHLERS, J, GIBBARD, P L, AND HUGHES, P D (editors). 15. (Amsterdam: Elsevier.)

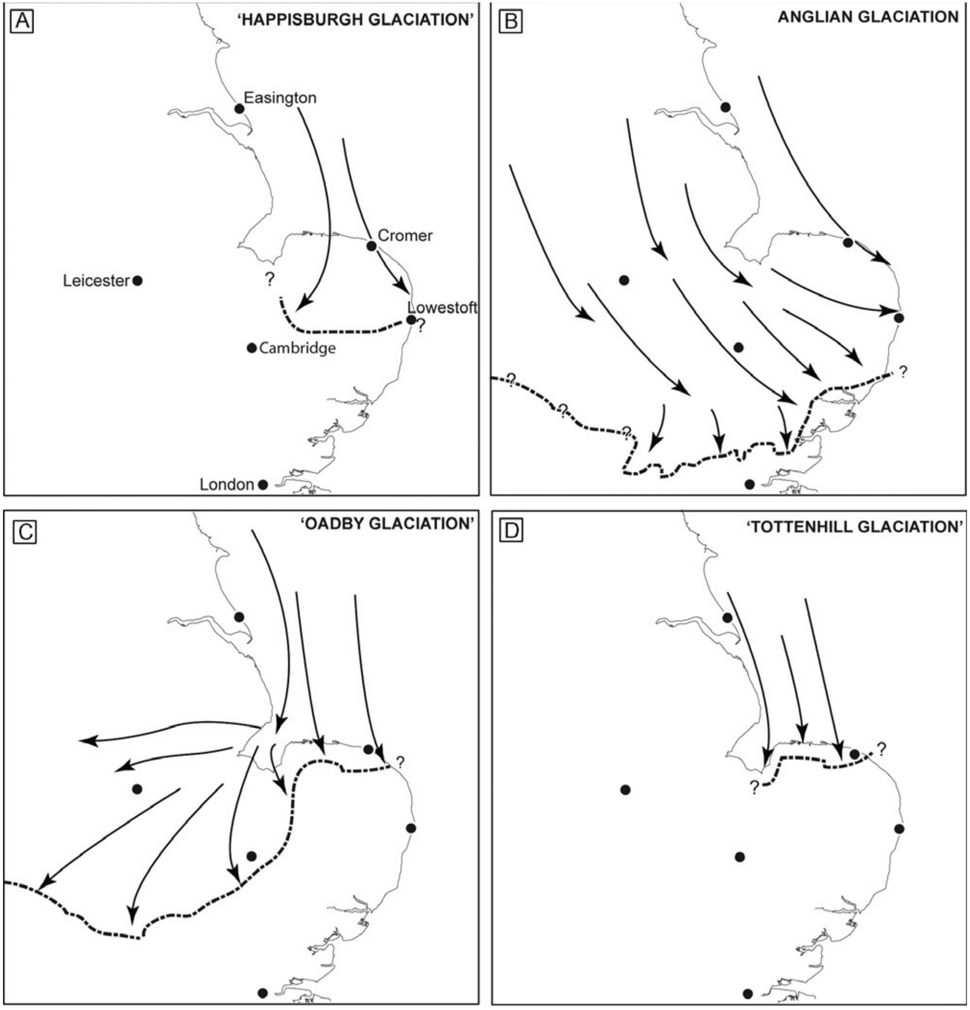

FIGURE. 5 Ice flow models based on the four-stage glaciation model after Clark et al. (2004), Hamblin et al. (2005) and Rose (2009). (A) Happisburgh Glaciation. (B) Anglian Glaciation. (C) Oadby Glaciation. (D) Tottenhill Glaciation. Note that the ice flow paths and ice limits are reconstructed on the basis of the distribution of tills and their lithological and provenance properties.

LEE, J R, ROSE, J, HAMBLIN, R J, MOORLOCK, B S, RIDING, J B, PHILLIPS, E, BARENDREGT, R W, AND CANDY, I. 2011. The Glacial History of the British Isles during the Early and Middle Pleistocene: Implications for the long-term development of the British Ice Sheet. 59-74 in *Quaternary Glaciations–Extent and Chronology, A Closer look. Developments in Quaternary Science*. EHLERS, J, GIBBARD, P L, AND HUGHES, P D (editors). 15. (Amsterdam: Elsevier.)

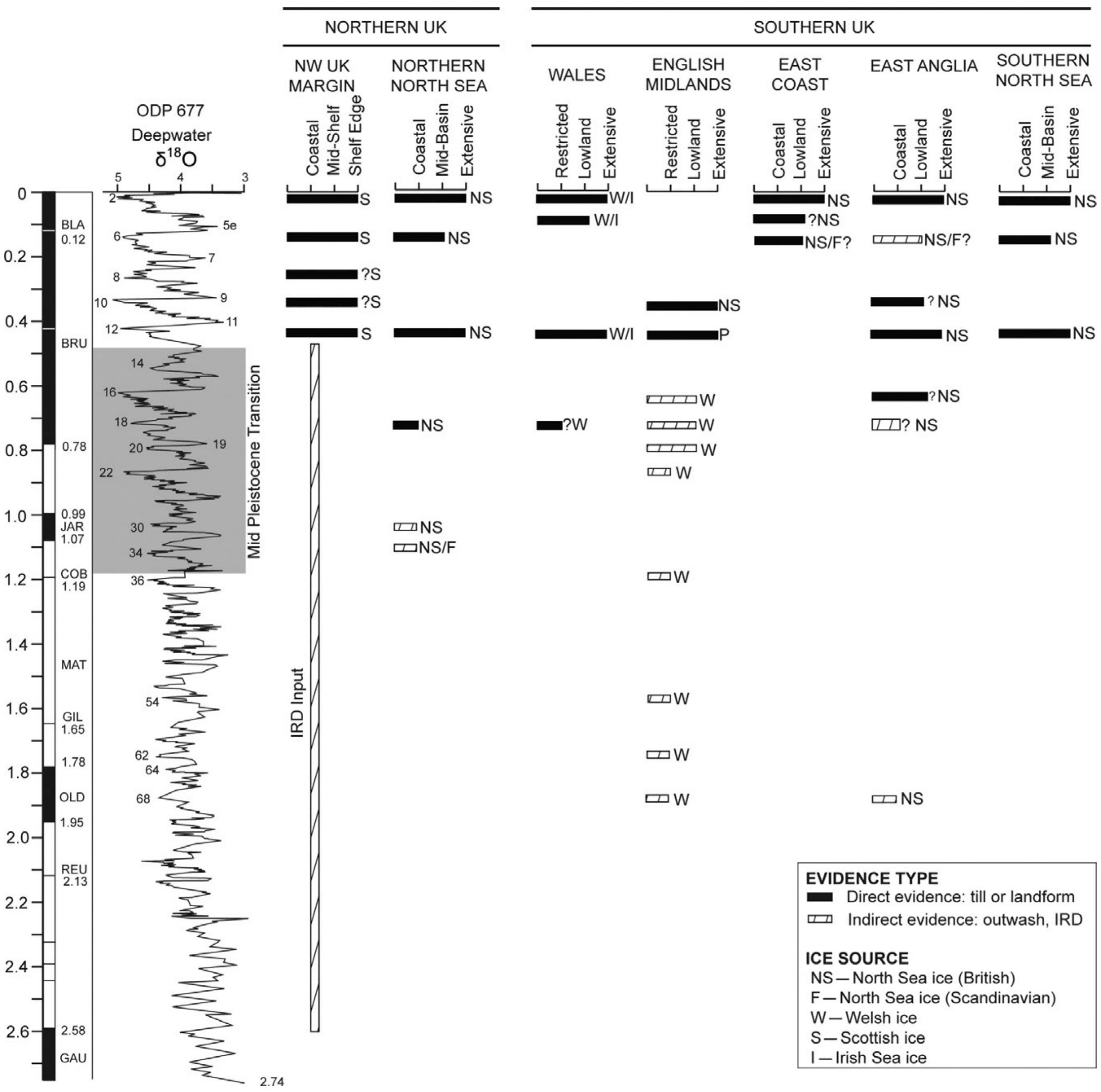

FIGURE. 6 Quaternary glacial history of the British Isles with evidence for the scale and sources of glaciations inferred from different onshore and offshore areas. Based upon data and evidence from Bowen et al. (1986), Whiteman and Rose (1992), Stoker et al. (1994), Sejrup et al. (2000), Westaway et al. (2002), Carr (2004), Clark et al. (2004), Hamblin et al. (2005), Catt (2007) and Hibbert et al. (2010).