Published in Proceedings of the Geologists' Association (2011)

Possible ice-rafted erratics in late Early to early Middle Pleistocene shallow marine and coastal deposits in northeast Norfolk, UK.

Nigel R. Larkin[a*], Jonathan R. Lee[b] & E. Rodger Connell[c]

[a] The Natural History Department, Norfolk Museums and Archaeology Service, Shirehall, Market Avenue, Norwich, Norfolk NR1 3JQ, UK nrlarkin@easynet.co.uk

[b] British Geological Survey, Keyworth, Nottingham NG12 5GG, UK jrlee@bgs.ac.uk

[c] Geography and Environment, School of Geosciences, University of Aberdeen, St Mary's, Elphinstone Road, Aberdeen, AB24 3UF UK rodger_connell@yahoo.co.uk

*Corresponding author: email nrlarkin@easynet.co.uk telephone 07973 869613

Abstract
Erratic clasts with a mass of up to 15 kg are described from preglacial shallow marine deposits (Wroxham Crag Formation) in northeast Norfolk. Detailed examination of their petrology has enabled them to be provenanced to northern Britain and southern Norway. Their clustered occurrence in coastal sediments in Norfolk is believed to be the product of ice-rafting from glacier incursions into the North Sea from eastern Scotland and southern Norway, and their subsequent grounding and melting within coastal areas of what is now north Norfolk. The precise timing of these restricted glaciations is difficult to determine. However, the relationship of the erratics to the biostratigraphic record and the first major expansion of ice into the North Sea suggest these events occurred during at least one glaciation between the late Early Pleistocene and early Middle Pleistocene (c. 1.1–0.6 Ma). In contrast to the late Middle (Anglian) and Late Pleistocene (Last Glacial Maximum) glaciations, where the North Sea was largely devoid of extensive marine conditions, the presence of far-travelled ice-rafted materials implies that earlier cold stage sea-levels were considerably higher.

Keywords: late Early Pleistocene, early Middle Pleistocene, glaciation, erratic, ice-rafted, shallow marine, Wroxham Crag.

1. Introduction

Much of our current understanding of the history of glaciation adjacent to the North Sea Basin is based on the distribution of glacial phenomena associated with large-scale ice sheet advances and retreats. Evidence of former glaciations in this region can be found on land and within the North Sea Basin and includes tills, erosional and constructional landforms and widespread glacial erosion surfaces (Bowen *et al.*, 1986; Cameron *et al.*, 1992; Sejrup *et al.*, 1987; Bowen, 1999; 2000; Clark *et al.*, 2004). Whilst this evidence allows a relatively detailed reconstruction of glaciation spanning the past 480,000 years (Anglian to Devensian stages) (Perrin *et al.*, 1979; Bowen *et al.*, 1986; Carr, 2004; Clark *et al.*, 2004; Rose, 2009), the extent, scale and timing of glaciation prior to the Anglian (Marine Isotope Stage (MIS) 12) is relatively unknown. Despite this, it is apparent from well documented evidence from the northwest European margin and the Nordic Seas that several ice sheets adjacent to the North Atlantic, including the British-Irish Ice Sheet (BIIS) and Scandinavian Ice Sheet (SIS), had been active long before the Anglian (Heinrich and Baumann, 1994; Stoker *et al*., 1994; Jansen et al., 2000; Sejrup *et al*., 2000, 2004; Lee *et al*., 2010; Thierens *et al*., 2011).

Evidence from the Norwegian Channel, North Sea Trough Mouth Fan and the Northern North Sea demonstrates the existence of the Norwegian Channel Ice Stream draining the western sector of the SIS through the North Sea during the late Early Pleistocene (Fedje Glaciation / 1.1 Ma / MIS 34; Sejrup *et al*., 1987, 2000). Evidence for similar expansions of the BIIS around the North Sea is more limited and it is unclear whether this is an artefact of non-glaciation, interpretation of the geological record, or limited preservation of evidence. It has been suggested that the pre-Anglian BIIS was spatially restricted, and at its greatest extent probably did not advance beyond coastal areas adjacent to their highland source areas (Lee *et al*., 2010). In all probability, direct evidence for these early glaciations is likely to have been removed by spatially more extensive Middle and Late Pleistocene glaciations. However, discrete evidence for these glaciations in the form of far-travelled erratics and iceberg scours may still be preserved in distal locations (e.g. Zandstra, 1971; Whiteman and Rose, 1992; Ekman, 1999; Graham, 2007; Kuhlmann and Wong, 2008; Toucanne *et al*, 2009). Such evidence may provide a longer-term perspective on the spatial and temporal evolution of the BIIS and its response to regional-scale geographic and climatic drivers. In turn, they may permit a comparison of the history of the BIIS with other northwest European ice sheets (e.g. SIS), with long-term climate change in the North Atlantic region and with global-scale climate-forcing mechanisms (Lee *et al*., 2010; Thierens *et al*., 2010).

Here we report the presence of erratic clasts (from cobble sized to 15 kg) in pre-Anglian ('pre-glacial') shallow marine and coastal deposits of the Wroxham Crag Formation (WCF) in northeast Norfolk that are from ultimate bedrock sources in northern Britain and southern Norway. The clasts are described and provenanced and possible mechanisms for their emplacement are evaluated. Finally their stratigraphic context within the Pleistocene climatic and sea-level history of Britain and northern Europe is outlined.

2. Regional geological context and site locations

2.1. Regional geological context

'Pre-glacial' Pleistocene deposits in East Anglia include shallow marine and coastal deposits (part of the Crag Group that were deposited along the western margins of the North Sea Basin) together with extensive fluvial sequences laid down by a number of major river systems that drained eastwards into the North Sea (Funnell, 1995; Gibbard, 1995; Rose *et al*., 2001).

Crag Group deposits of Early and Middle Pleistocene age are sub-divided into an older Norwich Crag Formation (NCF: c. 2.6−1.8 Ma) and a younger Wroxham Crag Formation (WCF: c. 1.8−0.48 Ma) (Table 1) (Rose *et al*., 2001). Sub-divisions are based upon relative ages determined by biostratigraphy and palaeomagnetism, and by lithological character and spatial proximity to fluvial sediments with which they interdigitate (Rose *et al*., 2001, 2002; Maher and Hallam, 2005; Lee *et al*., 2006, 2008; Lee, 2009; Rose, 2009). The fluvial deposits are represented by the Kesgrave Group, Ingham and Cromer Forest-bed formations deposited by the Thames, Bytham and 'northern' river systems respectively that drained across central England and East Anglia into the North Sea (Green and McGregor, 1990; Rose *et al*., 2001, 2002; Lee *et al*., 2006; Lee, 2009; Rose, 2009). The complex geometry displayed by these marine, coastal and fluvial deposits reflects the sensitivity and highly dynamic characteristics of the East Anglian region in response to fluctuations in sea level and high rates of subsidence (Funnell, 1995; Allen and Keen, 2000; Rose *et al*., 2001, 2002; Lee *et al*., 2006; Rose, 2009).

The Crag and related fluvial deposits in East Anglia form one of the longest, albeit discontinuous, temporal sediment archives within the Quaternary of the British Isles and has been correlated with sediments in the North Sea Basin and continental Europe (Gibbard *et al*., 1991; Kuhlmann *et al*., 2006). Collectively they provide a valuable insight into environmental change and landscape response within the North Sea region during the Early to early Middle Pleistocene. To date, most research on the Crag Group deposits has centred upon reconstructing depositional environments, defining their wider litho- and biostratigraphic context, and determining the links between marine, coastal and terrestrial processes (West, 1980; Rose *et al*., 1996, 2001, 2002; Briant *et al*., 1999; Allen and Keen, 2000; Pawley *et al*., 2004; Lee *et al*., 2006; Lee, 2009).

The Early to early Middle Pleistocene Crag deposits reflect the progressive deterioration of regional (and global) climate that in turn drove numerous fluctuations in sea level within the North Sea Basin and highly dynamic terrestrial processes (Rose *et al*., 1985, 2001; Kemp *et al*., 1993; Candy *et al*., 2006; Lee *et al*., 2006; Rose, 2009). Evidence for cold climates during the deposition of these units includes cold marine faunas (West, 1980; West *et al*., 1980), and intra-formational ice-wedge casts formed during low sea-level stands (Gardener and West, 1975; Fish *et al*., 1998; Briant *et al*., 1999; Whiteman, 2002; Lee *et al*., 2003, 2006; Candy *et al*., 2011). Numerous studies have also reported traces of pebbles from north Wales and northern Britain determined by clast-lithological counts of Kesgrave Thames fluvial deposits (Whiteman and Rose, 1992) and WCF coastal deposits (Hey, 1976, 1982; Green and McGregor, 1990; Rose *et al*., 1996, 2001; Briant *et al*., 1999; Lee *et al*., 2006). Whilst the precise genetic and stratigraphic contexts of these erratics remain uncertain, due principally to their small size and propensity for recycling, several authors have suggested that they may originally relate to earlier glaciations within highland areas of Britain (Whiteman and Rose, 1992; Lee *et al*., 2006). A glacial origin has also been argued for the occurrence of alkali amphibole and titanite ('sphene') heavy mineral grains found within the Easton Bavents Clay (NCF) (Solomon in Funnell and West, 1962). However, Berger (in Gibbard *et al*., 1991) argued against a glacial origin for these grains, demonstrating both heavy minerals to be present throughout the Crag Group.

The earliest direct evidence for glaciation within the Pleistocene of East Anglia relates to the tills and outwash deposits of the Happisburgh Formation; these overlie, and in turn are partly overlain locally by the WCF (Lee *et al*., 2006; Read *et al*., 2007). Previously, it was thought that glacial deposits now attributed to the Happisburgh Formation, belonged to the North Sea Drift and were deposited during the Anglian Glaciation of MIS 12 (Bowen *et al*., 1986; Ehlers and Gibbard, 1991; Bowen, 1999). Currently, the age of the Happisburgh Formation is the subject of much debate (Clark *et al*., 2004) with opinions divided as to whether this glaciation is indeed Anglian (Preece and Parfitt, 2008; Preece *et al*., 2009; Westaway, 2009), or whether it relates to an earlier glaciation possibly equivalent to MIS 16 (Lee *et al*., 2004; Hamblin *et al*., 2005; Rose, 2009).

2.2 Site locations

The WCF is readily accessible at West Runton and Sidestrand in northeast Norfolk (Figure 1). At West Runton, far-travelled clasts were collected from outcrops located east of the slipway (National Grid Reference (NGR): TG 1872 4318). At Sidestrand, far-travelled clasts were collected 400 m northeast of Sidestrand church (NGR: TG 2613 4005). The stratigraphical context of the sample sites is referred to below. Further exotic erratics were also recovered from WCF sediments beneath Wood Hill at West Runton (NGR: TG 1947 4304) and at East Runton (NGR: TG 2044 4274) although the stratigraphic context in both of these cases is poorly constrained at present and the sites are the subject of further investigation by the authors.

3. Methods

In situ erratic clasts were collected from cliff-face and foreshore exposures of the WCF at West Runton and Sidestrand between 2004 and 2010. At both sites the cliff base is occasionally obscured by modern beach and fallen material, and unrestricted access is constrained to short periods following those storms that clear slipped debris and lower the foreshore sufficiently. The precise stratigraphic context was noted. The erratics were examined using a high-powered binocular microscope and thin sections under a standard petrological microscope. Specimens were compared with reference collections held by the British Geological Survey to determine their provenance. Specimens are now held in the geology collections of the British Geological Survey and Norwich Castle Museum.

4. Site stratigraphy and erratic lithologies

4.1 West Runton

Much of the 'pre-glacial' sequence to the east of Woman Hythe Gap at West Runton has been described by West (1980), and confirmed by the work reported here (Figure 2). The base of the sections observed by the authors corresponds to West's (1980) 'Bed E' – interpreted here as a distinctive tempestite WCF facies. It is composed of a c.0.5 m thick brecciated clay containing occasional thin seams of ferruginous gravel and detrital shell material. Overlying 'Bed E' is a variable assemblage of WCF coastal and estuarine sands, laminated silts and clays, and gravel ('Beds F−I' of West, 1980). These include well-sorted and well-rounded beach gravels ('Bed I' of West, 1980) which are cut through by an ice-wedge cast that penetrates down to 'Bed F' (Figure 3). An examination of possible lateral equivalents of these deposits (the 'lower sands and gravels') by Rose *et al*. (2008) identified evidence for several hiatuses within the sequence and the development of both temperate and arctic soil structures. Younger deposits include the West Runton Freshwater Bed (West, 1980), that fills a channel incised into the WCF and an overlying sequence of marine sands and gravels (WCF) (Davies *et al*., 2000). The WCF is truncated at this study site by highly deformed Bacton Green Till (Sheringham Cliffs Formation) that marks the 'beginning' locally of the glacial succession. Earlier tills (i.e. the Happisburgh and Walcott tills) have been removed by glaciotectonic thrusting (Phillips *et al*., 2008) but crop out *in situ* at nearby sections both to the west and east.

Two clusters of far-travelled erratics, each composed of six specimens, were collected from 'Bed I' of the WCF. The clasts range between 0.06 and 0.23 m in *a*-axis length, and between 0.2 and 4.0 kg in mass. Six of the clasts were sandstones and angular quartzites with limited provenance value. The remaining six clasts were sufficiently distinctive to provide a meaningful provenance (Table 2). Lithologies identified were: Old Red Sandstone, greywacke (x3), quartz dolerite and chlorite schist. None of the clasts that could be provenanced was striated, although all were of sub-angular to sub-rounded form, with rounded edges.

4.2 Sidestrand

Lee's (2009) subdivision of the 'pre-glacial' sequence at Sidestrand (Figure 4) is followed here (see also Reid, 1882; West, 1980). Within this scheme, three major lithofacies associations may be recognised. The base of the succession consists of faintly stratified sand and gravel ('Units A and B') that records the migration of offshore sand and gravel bars within the outer parts of a river estuary. This is overlain by 'Unit C' the Sidestrand *Unio* Bed (*sensu stricto)* of the Cromer Forest-bed Formation (Lee, 2009; Preece *et al*., 2009), a stiff bluish-grey clay of fluvial origin, rich in *Unio* shells, that occupies a number of shallow channels cut into the underlying lithofacies. The uppermost part of the 'pre-glacial' succession is up to 4.0 m thick ('Units D–L'). It forms a transgressive sequence representing the transition from lagoonal to estuarine conditions. These deposits are unconformably overlain by glacial sediments, including glaciotectonites ('Units K and M') and till facies ('Unit N') of the Happisburgh Formation.

A cluster of far-travelled erratics was recovered from detached sections of 'Unit A–B' (Lee, 2009); they range in *a*-axis length from 0.16 to 0.35 m, and mass 0.05–15.0 kg. Twenty-two far-travelled clasts were collected, of which eighteen were sufficiently distinctive to provide a provenance (Table 3). These clasts comprised quartz dolerite, diorite (felsic), chlorite schist, pyroxene-rich gabbro, greywacke, dark grey coarse grained meta-quartzite, amphibolite (Figure 5), biotite alkali-feldspar granite, rhomb porphyry (Figure 6) and quartz mica schist. Clasts were typically of sub-angular or sub-rounded form but all exhibited rounded edges; none exhibited striations.

5. Discussion

5.1 Provenance of the erratics

A significant number of the far-travelled clasts from the WCF at West Runton and Sidestrand possess distinctive characteristics that enable their geographic and geological provenance to be determined (Figure 1). The majority of the metamorphic erratics are low- to medium-grade greenschist facies most likely derived from the Dalradian meta-pelites of central Scotland. These include the grey meta-quartzite, the chlorite schist and the garnet mica schist. The amphibolite erratic is a meta-basite produced by higher pressures/temperatures than those associated with the greenschist erratics. It is thought to have been derived from the Highland Border Complex located to the north of the Highland Border Fault in east-central Scotland. Of the igneous erratics, the quartz dolerite is typical of the Palaeogene basic intrusions of northern Britain such as the Whin Sill of Northumberland or certain central Scottish outcrops. The biotite-alkali feldspar granite erratic might have been derived from central Scotland, although sources in southern and western Norway cannot be eliminated. Rhomb porphyry is a distinctive igneous lithology and is derived from the Permian lavas of the Oslo Graben in Oslofjord, Norway. The red sandstone is of Old Red Sandstone facies, whilst the Old Red Sandstone fault breccia was most probably derived from an outcrop of Devonian strata in either the Scottish Midland Valley or eastern Scotland; the Southern Uplands are thought to have been the source of the greywacke clasts.

5.2 Mechanism of erratic derivation and emplacement

The WCF erratics at West Runton and Sidestrand are located at least 500 km from their ultimate source areas. Their occurrence in 'pre-glacial' marine deposits in northeast Norfolk might be accounted for by one of two possibilities.

Hypothesis one is that these far-travelled clasts are reworked from pre-existing glacial sediments in the North Sea Basin by shallow marine and coastal processes. However, it is difficult to reconcile this mechanism with the highly concentrated spatial and stratigraphic clast distribution, the sub-angular form of some, and their not inconsiderable masses. Prolonged marine and coastal recycling would attenuate the concentration and mechanical abrasion would be expected to produce more rounded clasts. Furthermore, the palaeogeography of the 'pre-glacial' coastline of eastern England was interrupted by major river estuaries (Rose *et al.*, 2001) (Figure 1), making long distance longshore-drift implausible.

Hypothesis two is that the far-travelled clasts were deposited by melt-out from (possibly grounded) icebergs in estuarine (Sidestrand) and beach (West Runton) environments with minimal local reworking. It is predicated on parts of the BIIS and SIS in northern Britain and southern Norway having floating ice margins within the northern and eastern North Sea Basin, upstream of which ice was actively eroding and entraining bedrock lithologies. This hypothesis is supported by both the clustered spatial and stratigraphic concentration of the erratics, and their frequently comparatively 'fresh' form. An ice-wedge cast penetrating the host deposit at West Runton indicates that the subsequent climate was sufficiently cold to support the development of permafrost after deposition of the erratic-bearing sediments.

5.3 Chronology

The precise date of emplacement of the ice-rafted 'erratics' in the WCF at West Runton and Sidestrand is difficult to determine and it is not certain that the 'erratics' at the two sites correspond to the same cold stage event. They could be the product of two separate glaciations. West (1980) regarded the host deposits of the erratics, now part of the WCF, as belonging to the 'Beestonian' cold stage, immediately preceding the early Middle Pleistocene 'Cromerian' interglacial. More recently, the 'Cromerian Complex' has been shown to consist of five temperate stages with intervening colder episodes that span the late Early to early Middle Pleistocene (MIS 21–13; c. 0.9–0.48 Ma). However at present, only four Brunhes Chron interglacial events have been tentatively recognised in Britain (Preece and Parfitt, 2000, 2008; Preece, 2001; Stuart and Lister, 2001; Preece *et al.*, 2009). It is thus unclear as to whether the so-called 'Beestonian' represents one or more cold stages of the 'Cromerian Complex' or an earlier cold event.

However, given the established Quaternary stratigraphic record in East Anglia, it is possible to establish broadly defined maximum and minimum age constraints for the iceberg-rafting event(s). Their minimum age is indicated by overlying organic deposits belonging to the Cromer Forest-bed Formation (Preece and Parfitt, 2000, 2008). The ice-rafted erratics occur beneath the *Unio* Bed at Sidestrand which, based on faunal and amino-acid evidence, is believed to correspond to one of the younger interglacial stages of the 'Cromerian Complex' (Preece and Parfitt, 2000, 2008; Preece, 2001; Preece *et al.*, 2009). At West Runton, the WCF ice-rafted erratics underlie the normally magnetised West Runton Freshwater Bed which contains a fauna that suggests it relates to an older Brunhes 'Cromerian Complex' interglacial stage (Preece and Parfitt, 2000; Preece, 2001; Stuart and Lister, 2001). The maximum age of the WCF erratics is more difficult to establish. Graham (2007) and Kuhlmann and Wong (2008), using 3D seismic data, reported iceberg scours from the British and Dutch sectors of the North Sea respectively and estimated the features to be around 1.8 Ma in age. This age coincides loosely with the onset of deposition of the WCF in East Anglia (Rose *et al.*, 2001) and sub-polar conditions in the southern North Sea (West *et al.*, 1980). A more realistic age for the erratics within the WCF is that they are unlikely to be older than the late Early Pleistocene (c. 1.1 Ma), as this time interval corresponds to the earliest known large-scale expansion of the BIIS and SIS into the North Sea region (Ekman, 1999; Sejrup *et al.*, 2000; Graham, 2007; Lee *et al.*, 2010). This places the WCF erratics at Sidestrand and West Runton within the late Early Pleistocene to early Middle Pleistocene interval (c. 1.1–0.6 Ma), a period that embraces the 'Menapian' (MIS 34) to late 'Cromerian Complex' (MIS 16) cold stages.

5.4 Palaeoclimatic context

The period between 1.1 and 0.6 Ma coincides with the Middle Pleistocene Transition (MPT) and the progressive change from a climatic signal dominated by the 41 ka obliquity cycle to one in which the 100 ka eccentricity cycle is most marked. Offshore evidence indicates an intensification of glacial activity associated with the BIIS and SIS from 1.1 Ma (Lee *et al.*, 2010). Within the North Atlantic region and specifically the Nordic Seas, the onset of the MPT is recorded by a sharp intensification of glacial and interglacial conditions (Jansen *et al.*, 1988, 2000; Heinrich and Baumann, 1994; Helmke *et al.*, 2003; Knies *et al.*, 2009). Lithological evidence from Ocean Drilling Program cores 643 and 644 from the eastern Norwegian Sea indicate from 1.1 Ma more southern expansions of pack-ice, coupled with greater northern drift of icebergs derived from the North Sea region and erosion of Chalk bedrock within the Baltic (Heinrich and Baumann, 1994; Jansen *et al.*, 1988, 2000). 1.1 Ma also corresponds to the first shelf-edge expansion of the SIS during the Fedje Glaciation (Sejrup *et al.*, 2000) and the first known expansion of the BIS into the coastal margins of the North Sea (Ekman, 1999; Graham, 2007). Working on cores 81/26, 81/29 and 81/34 from the Fladen Ground and Devil's Hole areas of the North Sea, Ekman (1999) also identified several additional phases of glacial input into the North Sea loosely constrained to between 1.1 and 0.9 Ma.

Several pre-Anglian incursions of Scottish ice into the central North Sea have been recognised, although their ages remain tentative and largely inferred. Firstly, Graham (2007) records a series of iceberg plough marks within the central North Sea tentatively dated at c.1.8 Ma. Secondly, a diamicton of possible Scottish origin within the Aberdeen Ground Formation (AGF) occurs above the Jaramillo Subchron and has been tentatively dated to the

'Bavelian Complex' (c. 0.9–0.8 Ma) (Sejrup *et al*., 1987). Thirdly, higher within the AGF in the area of the Firth Approaches and Moray Firth, a sequence of glaciomarine deposits containing ice-rafted dropstones directly overlies the Brunhes-Matuyama palaeomagnetic reversal (c. 0.78 Ma, MIS 19) (Stoker and Bent, 1985), and are coeval with iceberg plough marks recognised further offshore within 3D seismic data (Graham, 2007). Holmes (2003) and Graham (2007) speculate that these glaciomarine deposits could therefore be as old as MIS 18. Finally, cut into the top of the AGF are a series of subglacial channels and 'tunnel valleys' that appear to be polyphase in origin. These tunnel valleys are partially infilled by sediments assigned to the 'Cromerian Complex' by Holmes (1997). However, Stoker *et al*. (1985) considered the valleys to be Anglian age, with the upper interglacial sediment-fill assigned to the Hoxnian.

Associated with the western sector of the BIIS on the Irish Continental Margin, Thierens *et al*. (2011) report several separate events that delivered ice-rafted detritus onto the Irish Continental Margin during the 'Cromerian Complex'.

At Dimlington, East Yorkshire (Figure 1A), shelly marine clays that contain possible ice-rafted erratics of Scottish and Scandinavian origin are preserved as glaciotectonic rafts within the Basement Till (?MIS 6) and are referred to as the Bridlington Crag (Catt, 2007). Similar material from Bridlington contains shells, but with a much more restricted clast assemblage. Shells from the Bridlington exposure have provided amino acid ratios suggestive of an Early Pleistocene or early Middle Pleistocene age (Lewis, 1999; D.Q. Bowen pers. comm., 2009). Whilst it is not yet certain that all the material described as Bridlington Crag is of a single age, the Holderness evidence also suggests that ice-rafting of clasts was occurring in the Early–early Middle Pleistocene of the North Sea Basin.

5.5 Palaeogeography and relative sea-level

Deposition of ice-rafted erratics within the WCF at West Runton and Sidestrand derived from northern British and southern Norwegian sources implies the existence of an extensive body of water – either marine or glaciolacustrine, within the southern North Sea Basin. The existence of an extensive glaciolacustrine basin dammed to the south by land would imply the confluence of the BIIS and the SIS within the northern North Sea. Whilst there is evidence for both ice sheets extending into the northern North Sea around 1.1 Ma (Ekman, 1999), whether the ice sheets were confluent is unclear. Additionally, the erratics cannot be chronologically constrained to this event, and the extent and chronology of North Sea glaciations between 1.1 and 0.6 Ma is uncertain. The simplest explanation is that ice-rafting occurred under marine conditions within the North Sea Basin, and this enables three inferences to be made. First, that during these early glaciation(s) the maximum extent of ice sheets into the North Sea Basin was partly controlled by marine conditions and that iceberg calving occurred along a floating ice margin. Secondly, that relative sea-level within the North Sea was sufficiently high to enable the southward and westward drift of icebergs into the western margins of the southern North Sea. Thirdly, the location of the sites adjacent to the pivot zone separating regions of uplift (to the west) and subsidence (to the east), indicates that the present elevation of the sites (c.2-4 m O.D.) broadly represents the elevation at which the erratics were deposited.

Whilst the presence of a calving ice margin in the deeper northern North Sea is perhaps not unexpected, the drift of icebergs so far southwards and westwards into the southern North Sea during glacial low sea-levels stands is surprising. The southern North Sea basin during the Early and early Middle Pleistocene was occupied by an extensive northwards prograding delta complex fed by rivers that drained central Europe, the Fennoscandian Shield and Britain (Cameron *et al*., 1992; Funnell, 1995; Gibbard, 1995). Examination of the delta clinoform using seismic data suggests that water depths at the distal (northern) end of the delta may have been up to 40−60 m during high sea-level stands. However, the presence of a relatively high glacial sea-level in the southern North Sea during the deposition of the ice-rafted erratics is intriguing as this region would arguably be one of the most sensitive areas of the North Sea Basin to global sea-level change. Evidence from a number of sites in East Anglia demonstrates that during the 'Cromerian Complex' sea-level around the margins of the southern North Sea fluctuated markedly with several oscillations ranging between coastal and terrestrial conditions (Allen and Keen, 2000; Lee *et al*., 2006). Furthermore, during the Anglian (MIS 12) and Last Glacial Maximum (MIS 2) glaciations much of the North Sea Basin, and especially the southern North Sea, was largely devoid of marine conditions (Cameron *et al*., 1992; Carr, 2004). This suggests, tentatively, that sea-level falls during late Early to early Middle Pleistocene glacial stages were smaller than those in late Middle Pleistocene and Late Pleistocene glacial stages. Evidence for similar sea-level trends has been found elsewhere from offshore data. Indeed, whilst interglacial sea-levels have remained largely similar, glacial sea-levels prior to c. 1.0−0.9 Ma were some 20 to 30 m higher than those that followed this time interval (Kitamura and Kawagoe, 2006; Sosdian and Rosenthal, 2009). This temporal threshold reflects a marked intensification in the scale of later Northern Hemisphere glaciations, and the increased ability of ice sheets to lock-up water as ice (Sosdian and Rosenthal, 2009).

6. Conclusions

- Concentrations of erratics within WCF coastal deposits at Sidestrand and West Runton in northern East Anglia are considered the product of melt-out from (possibly grounded) icebergs.

- The provenance of the erratics implies that these icebergs were derived from glaciers that were eroding bedrock in the Southern Uplands, Midland Valley and southern Grampian Highlands of Scotland, and Oslofjord in southern Norway.

- The age of these erratic-bearing beds can be broadly constrained to a period from the late Early Pleistocene to early Middle Pleistocene interval (c. 1.1–0.6 Ma, a time period that spans the 'Menapian' (MIS 34)) to late 'Cromerian Complex' (MIS 16) stages.

- These erratics demonstrate both the existence of restricted glaciations in Scotland and Norway, and their periodic expansion into the North Sea Basin prior to the maximum extent of the ice sheets during the Anglian Glaciation (MIS 12) of the Middle Pleistocene.

- This research supports the work of Sejrup *et al*. (1987) and Ekman (1999) that argues that both the BIIS and SIS were active in the North Sea Basin on at least one occasion well before the Anglian stage of the Middle Pleistocene.

- The deposition of the erratic-bearing beds during these early glaciations appears to coincide with higher glacial sea-levels than occurred during the late Middle and Late Pleistocene.

Acknowledgements

The authors wish to thank Don Aldiss, Peter Batson, Steve Booth, Peter Hoare, Graham Lott, Tony Morigi, Simon Parfitt, Emrys Phillips, Peter Riches, Jim Rose, David Stephenson, Martyn Stoker, Mike Styles, Mieke Thierens and Chris Thomas for their discussions regarding the provenance and significance of the erratics. The constructive comments of two reviewers are also gratefully acknowledged, plus Silvia Bello is thanked for her help with the figures. David Bowen and John Catt are thanked for discussions and for providing information on the Bridlington Crag. JRL publishes with the permission of the Executive Director of the British Geological Survey (NERC). This is a contribution to the Ancient Human Occupation of Britain and its European Context (AHOB 3) project funded by the Leverhulme Trust.

References

Allen P., Keen D.H. 2000. Uppermost Norwich Crag and lower part of the Cromer Forest-bed Formations. In: Lewis, S.G., Whiteman, C.A., Preece, R.C. (Eds.), The Quaternary of Norfolk and Suffolk. Field Guide. Quaternary Research Association, London, pp. 29-34.

Bowen D.Q. (Ed.) 1999. A revised correlation of Quaternary deposits in the British Isles. Special Report no.23, Geological Society of London.

Bowen DQ, Rose J, McCabe AM, Sutherland DG. 1986. Quaternary Glaciations in England, Ireland, Scotland, and Wales. Quaternary Science Reviews 5, 299-340.

Briant, R.M., Rose, J., Branch, N.P., Lee, J.A. 1999. 'Pre-glacial' Quaternary sediments from Trimingham, north Norfolk, England. Bulletin of the Geological Society of Norfolk 49, 15-47.

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

Candy, I., Rose, J., Lee, J.R. 2006. A seasonally 'dry' interglacial climate in Eastern England during the early Middle Pleistocene: Palaeopedological and stable isotopic evidence from Pakefield, UK. Boreas 35, 255-265.

Candy, I., Silva, B.N., Lee, J,R. 2011. Climates of the early Middle Pleistocene in Britain: Environments of the earliest humans in northern Europe. In: Ashton, N.M., Lewis, S.G., Stringer, C.B. (eds.). Ancient Human Occupation of Britain (AHOB), Development in Quaternary Science, 14, 23-38.

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, 261-270.

Catt, J.A. 2007. The Pleistocene glaciations of eastern Yorkshire: a review. Proceedings of the Yorkshire Geological Society 56, 177 – 207.

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. Elsevier Publishers, Amsterdam, 47-82.

Davies, S.M., Rose, J., Branch, N.P., Candy, I., 2000. West Runton (TG 188 432 & TG 185 432). Pre-glacial freshwater muds and coastal sands and gravels. In: Lewis, S.G., Whiteman, C.A., Preece, R.C. (Eds.), The Quaternary of Norfolk and Suffolk, Field Guide, Quaternary Research Association, London, 61–65.

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, 17-24, Balkema, Rotterdam, 223-232.

Ekman, S.R. 1999. Early Pleistocene pollen biostratigraphy in the central North Sea. Review of Palaeobotany and Palynology 105, 171-182.

Fish, P.R., Carr, S.J., Rose, J., Hamblin, R.J.O., Eissmann, L. 1998. A periglacial composite-wedge cast from the Trimingham area, north Norfolk, England. Bulletin of the Geological Society of Norfolk 46, 11-16.

Funnell, B.M., West, R.G. 1962. The Early Pleistocene of Easton Bavents, Suffolk. Quarterly Journal of the Geological Society of London 470, 125-141.

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.

Gardner, K., West, R.G. 1975. Fossil ice-wedge polygons at Corton, Suffolk. Bulletin of the Geological Society of Norfolk 27, 47-53.

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, pp. 15–26.

Gibbard, P.L., West, R.G., Zagwijn, W.H., Balson, P.S., Burger, A.W., Funnell, B.M., Jeffery, D.H., de Jong, J., van Kolfschoten, T., Lister, A.M., Meijer, T., Norton, P.E.P., Preece, R.C., Rose, J., Stuart, A.J., Whiteman, C.A., Zalasiewicz, J.A. 1991. Early and early Middle Pleistocene correlations in the Southern North Sea Basin. Quaternary Science Reviews, 10, 23-52.

Graham, A.G.C. 2007. Reconstructing Pleistocene glacial environments in the Central North Sea using 3D seismic and borehole data. Unpublished PhD Thesis, Imperial College, University of London.

Green, C.P., McGregor, D.F.M. 1990. Pleistocene gravels of the north Norfolk coast. Proceedings of the Geologists' Association, 101, 197-202.

Hamblin, R.J.O., Moorlock, B.S.P., Rose, J., Lee, J.R., Riding, J.B., Booth, S.J., Pawley, S.M. 2005. Revised Pre-Devensian glacial stratigraphy in Norfolk, England, based on mapping and till provenance. Geologie en Mijnbouw 84, 77-85.

Helmke, J.P., Henning, A.B., Erlenkeuser, H. 2003. Development of glacial and interglacial conditions in the Nordic seas between 1.5 and 0.35 Ma. Quaternary Science Reviews, 22, 1717-1728.

Henrich, R., Baumann, K.-H., 1994. Evolution of the Norwegian current and the Scandinavian ice sheets during the past 2.6 m.y.: evidence from ODP leg 104 biogenic carbonate and terrigenous records. Paleogeography, Paleoclimatology, Paleoecology 108, 75–94.

Hey, R.W., 1976. Provenance of far-travelled pebbles in the Pre-Anglian Pleistocene of East Anglia. Proceedings of the Geologists' Association, 87. 69-82.

Hey, R.W., 1982. Composition of pre-Anglian gravels in Norfolk. Bulletin of the Geological Society of Norfolk, 32, 51-59.

Holmes R. 1997. Quaternary stratigraphy: the offshore record. In: Gordon JE. (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. 2003. Offshore Stratigraphical Record. 57 – 64 in Merritt, J.W., Auton, C.A., Connell, E.R., Hall, A.M. and Peacock, J.D. Cainozoic geology and landscape evolution of north-east Scotland. Memoir of the British Geological Survey, Sheets 66E, 67, 76E, 77, 86E, 87W, 87E, 95, 96W, 96E and 97 (Scotland).

Jansen, E., Bleil, U., Henrich, R., Kringstad, L., Slettermark, B. 1988. Palaeoenvironmental changes in the Norwegian Sea and the northeast Atlantic during the last 2.8 m.y: deep sea drilling project / ocean Drilling Program sites 610, 642, 643 and 644. Paleoceanography 3, 563-581.

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

Kemp, R.A., Whiteman, C.A., Rose, J. 1993. Palaeoenvironmental and stratigraphic significance of the Valley Farm and Barham Soils in Eastern England. Quaternary Science Reviews 12, 833–848.

Kitamura, A. and Kawagoe, T. 2006. Eustatic sea-level change at the Mid-Pleistocene climate transition: new evidence from the shallow-marine sediment record of Japan Quaternary Science Reviews, 25, 3-4, 323-335.

Knies, J., Matthiessen, J., Vogt, C., Laberg, J.S., Hjelstuen, B.O., Smelror, M., Larsen, E., Andreassen, K., Eidvin, T., Vorren, T.O. 2009. The Plio-Pleistocene glaciation of the Barents Sea-Svalbard region: a new model based on revised chronostratigraphy. Quaternary Science Reviews 28, 812-829.

Kuhlmann, G., Langereis, C.G., Munsterman, D., van Leeuwen, R.-J., Verreuseel, R., Meulenkamp, J.E., Wong, T.E. 2006. Integrated chronostratigraphy of the Pliocene-Pleistocene interval and its relation to the regional stratigraphical stages in the southern North Sea region. Geologie en Mijnbouw 85, 19-35.

Kuhlmann, G., Wong, T.E. 2008. Pliocene palaeoenvironmental evolution as interpreted from 3D-seismic data in the southern North Sea, Dutch offshore sector. Marine and Petroleum Geology 25, 173-189.

Lee, J.R. 2009. Patterns of preglacial sedimentation and glaciotectonic deformation within early Middle Pleistocene sediments at Sidestrand, north Norfolk, UK. Proceedings of the Geologist's Association 120, 34-48.

Lee, J.R., Brown, E.J., Rose, J., Moorlock, B.S.P., Hamblin, R.J.O. 2003. Reply to "Implications of a Middle Pleistocene Ice-Wedge Cast at Trimingham, Norfolk, eastern England". Permafrost and Periglacial Processes 14, 75-77.

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

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

Lee, J.R., Pawley, S.M., Rose, J., Moorlock, B.S.P., Riding, J.B., Hamblin, R.J.O., Candy, I., Barendregt, R.W., Booth, S.J., Harrison, A.M. 2008. Pre-Devensian lithostratigraphy of shallow marine, fluvial and glacial sediments in northern East Anglia. In: Candy, I., Lee, J.R., Harrison, A.M. (Eds.). The Quaternary of Northern East Anglia. Field Guide. Quaternary Research Association, London, 42-59.

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°N: implications for long-term ice sheet development in northern Europe. Quaternary Science Reviews, in press.

Lewis, S.G. 1999. Eastern England. In: Bowen, D.Q. (Ed.) A Revised Correlation of Quaternary Deposits in the British Isles. Geological Society of London, Special Report No. 23, 10 – 27.

Maher, B.A., Hallam, D.F. 2005. Palaeomagnetic correlation and dating of Plio/Pleistocene sediments at the southern margins of the North Sea Basin. Journal of Quaternary Science 20, 67-77.

Parfitt, S.A., Barendregt, R.W., Breda, M., Candy, I., Collins, M.J., Coope, G.R., Durbidge, P., Field, M.H., Lee, J.R., Lister, A.M., Mutch, R., Penkman, K.E.H., Preece, R.C., Rose, J., Stringer, C.B., Symmons, R., Whittaker, J.E.P., Wymer, J.J., Stuart, A.J. 2005. The earliest humans in Northern Europe: artefacts from the Cromer Forest-bed Formation at Pakefield, Suffolk, UK. Nature 438/15, 1008-1012.

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. Proceedings of the Geologists' Association 115, 22-42.

Perrin, R.M.S., Rose, J., Davies, H. 1979. The distribution, variation and origins of pre-Devensian tills in eastern England. Philosophical Transactions of the Royal Society of London 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. Quaternary Science Reviews 27, 1848-1871

Preece, R.C. 2001. Molluscan evidence for differentiation of interglacials within the 'Cromerian Complex'. Quaternary Science Reviews 20, 1643-1656.

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, 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 Association, London, 60-83.

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. Journal of Quaternary Science 24, 557-580.

Read A, Godwin M, Mills CA, Juby C, Lee JR, Palmer AP, Candy I, Rose J. 2007. Evidence for Middle Pleistocene temperate-climate high sea-level and lowland-scale glaciation, Chapel Hill, Norwich, UK. Proceedings of the Geologists' Association 118, 143-156.

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

Rose, J. 2009. Early and Middle Pleistocene landscapes of eastern England. Proceedings of the Geologists' Association 120, 3-33.

Rose, J., Allen, P., Kemp, R.A, Whiteman, C.A., Owen, N. 1985. The Early Anglian Barham Soil of eastern England. In: J. Boardman (Ed.). Soils and Quaternary Landscape Evolution. Wiley, Chichester, 197–230.

Rose, J., Gulamali, N., Moorlock, B.S.P., Hamblin, R.J.O., Jeffrey, D.H., Anderson, E., Lee, J.A., Riding, J.B. 1996. Pre-glacial Quaternary sediments, How Hill near Ludham, Norfolk, England. Bulletin of the Geological Society of Norfolk 45, 3-28.

Rose, J., Moorlock, B.S.P., Hamblin, R.J.O. 2001. Pre-Anglian fluvial and coastal deposits in Eastern England: lithostratigraphy and palaeoenvironments. Quaternary International 79, 5-22.

Rose, J., Candy, I., Moorlock, B.S.P., Wilkins, H., Lee, J.A., Hamblin, R.J.O., Lee, J.R., Riding, J.B., Morigi, A.N. 2002. Early and early Middle Pleistocene river, coastal and neotectonic processes , southeast Norfolk, England. Proceedings of the Geologists's Association 113, 47-67.

Rose, J., Juby, C., Bullen, M., Davies, S.M., Branch, N., Gammage, Z., Candy, I., Palmer, A. 2008. The stratigraphy, palaeoenvironments and duration of the early Middle Pleistocene sediments at West Runton, north Norfolk, England. In: Candy, I., Lee, J.R., Harrison, A.M. (Eds.). The Quaternary of Northern East Anglia. Field Guide. Quaternary Research Association, London, 157–181.

Sejrup, H.P., Aarseth, K.L., Ellingsen, K.L., Reither, E., Jansen, E., Løvlie, R., Bent, A., Brigham-Grette, J., Larsen, E., Stoker, M.S. 1987. Quaternary stratigraphy of the Fladen area, central North Sea: a multidisciplinary study. Journal of Quaternary Science 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. Quaternary Science Reviews 19, 667-685.

Sejrup HP, Hjelstuen BO, Dahlgren KIT, Haflidason H, Kuijpers A, Nygård A, Praeg D, Stoker MS, Vorren TO. 2005. Pleistocene glacial history of the NW European continental margin. Marine and Petroleum Geology 22, 1111-1129.

Sosdian, S, Rosenthal, Y. 2009. Deep-Sea Temperature and Ice Volume Changes across the Pliocene-Pleistocene Climate Transitions. Science 325, 306-310.

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., Long, D., Fyfe, A.J. 1985. The Quaternary succession in the central North Sea. Newsletters on Stratigraphy 14, 119-128.

Stoker, M.S., Leslie, A.B., Scott, W.D., Briden, J.C., Hine, N.M., Harland, R., Wilkinson, I.P., Evans, D., Ardus, A.S. 1994. A record of late Cenozoic stratigraphy, sedimentation and climate change from the Hebrides Shelf, NE Atlantic Ocean. Journal of the Geological Society of London 151**,** 235-249.

Stuart, A.J., Lister, A.M. 2001. The mammalian faunas of Pakefield/Kessingland and Corton, Suffolk, UK: evidence for a new temperate episode in the British early Middle Pleistocene. Quaternary Science Reviews 20, 1677-1692.

Thierens, M., Pirlet, H., Colin, C., Latruwe, K., Vanhaeck, F., Lee, J.R., Stuutf, J.-B., Titschack, J., Huvennei, V.A.I., Dorschel, B., A.J. Wheelera, A.J., Henriet, J.-P. 2011. Ice-rafting from the British-Irish ice sheet since the earliest Pleistocene (2.6 million years ago): implications for long-term mid-latitudinal ice-sheet growth in the North Atlantic region. Quaternary Science Reviews, accepted for publication.

Toucanne, S., Zaragosi, S., Gibbard, P.L., Bourillet, J.F., Cremer M., Eynaud, F., Turon, J.L. & Cortijo, E. 2009. A 1.2 my record of glaciation and fluvial discharge from the West European continental margin. Quaternary Science Reviews 28, 2974–2981.

West, R.G. 1980. The pre-glacial Pleistocene of the Norfolk and Suffolk coasts. Cambridge University Press, Cambridge.

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.

Whiteman, C.A. 2002. Implications of a Middle Pleistocene ice-wedge cast at Trimingham, Norfolk, eastern England. Permafrost and Periglacial Processes, 13, 163-170.

Whiteman, C.A., Rose, J. 1992. Thames river sediments of the British Early and Middle Pleistocene. Quaternary Science Reviews 11, 363-375.

Zandstra, J.G., 1971. Geologisch onderzoek in de stuwwal van de Oostelijke Veluwe bij Hattem en Wapenveld. Mededelingen Rijks Geologische Dienst N.S. 22, 215-260.

Table Captions

Table 1. Early to early Middle Pleistocene stratigraphy of north Norfolk showing alluvial, marine and glacial deposits (modified from Lee, 2009).

Table 2. Large erratics from the WCF at West Runton, north Norfolk. Erratics are held at the British Geological Survey and Norwich Castle Museum.
Table 3. Large erratics from the WCF at Sidestrand, north Norfolk. Erratics are held at the British Geological Survey and Norwich Castle Museum.

Table 1

Lithostratigraphy	Lithology	Palaeoenvironment	Chronostratigraphy
Lowestoft Formation			
Lowestoft Till / Walcott Till Member	Chalky tills	Subglacial	Anglian (MIS 12)
Wroxham Crag Formation			
Pakefield Member	Sands, shelly sand	Coastal	‘Cromerian Complex’
Happisburgh Formation			Happisburgh Glaciation
Corton Till Member	Sandy till	Subglacial / subaqueous	‘Cromerian Complex’
Happisburgh Till Member	Sandy till	Subglacial	MIS 16?
Cromer Forest-bed Formation	Organic, silts, clays and sands	Alluvial	‘Cromerian Complex’
Wroxham Crag Formation			
Mundesley Member How Hill Member Dobbs Plantation Member	Flint-rich gravels with increasing quartzose / northern clast content	Shallow marine, coastal	Early Pleistocene to early Middle Pleistocene (‘Cromerian Complex’)
Norwich Crag Formation	Flint-rich gravels, sands, tidal rhythmites	Shallow marine, coastal	Early Pleistocene

Table 2.

Accession Number	**Description**	**Mass (kg)**	**Provenance**
JRL065	Greywacke	2.7	Southern Uplands, Scotland
JRL061	Quartz dolerite	3.8	Palaeogene basic intrusion, northern England / Scotland
NWHCM : 2005.104.1	Greywacke	4.0	Lower Palaeozoic, Southern Uplands of Scotland
NWHCM : 2006.619	Greywacke	2.1	Lower Palaeozoic, from the Southern Uplands of Scotland
JRL141	Red Sandstone	2.6	Old Red Sandstone, Midland Valley, Scotland
JRL142	Chlorite Schist	1.1	Central Scotland

Table 3.

Accession Number	Description	Mass (kg)	Provenance
JRL143	Biotite alkali-feldspar granite	2.4	Central or Eastern Scotland / Norway?
NWHCM : 2006.263.21	Quartz dolerite	15.0	Palaeogene basic intrusion, northern England / Scotland
NWHCM : 2006.263.22	Quartzite	1.6	Southern Uplands/Central Scotland
NWHCM : 2006.263.23	Greywacke	2.5	Southern Uplands, Scotland
NWHCM : 2008.110	Amphibolite	3.2	Highland Border Complex, Scotland
NWHCM : 2008.285.1	Quartz-mica schist	2.8	Central Scotland
JRL066	Greywacke	1.9	Southern Uplands, Scotland
NWHCM : 2009.276.1	Quartz dolerite	10.5	Palaeogene basic intrusion, northern England / Scotland
NWHCM : 2009.276.2	Pyroxene-rich gabbro	5.9	Grampian Highlands?, Scotland
NWHCM : 2009.276.4	Diorite, felsic	0.5	Grampian Highlands, Aberdeenshire, Scotland
NWHCM : 2009.276.5	Chlorite schist, lower metamorphic grade	0.05	Central Scotland
NWHCM: 2009.276.8	Garnet mica schist	0.4	Central Scotland
SS.06.06.10.1	Rhomb porphyry	0.6	Oslofjord, Norway
SS2	Quartz dolerite	0.5	Palaeogene basic intrusion, northern England / Scotland
SS3	Quartz dolerite	0.5	Palaeogene basic intrusion, northern England / Scotland
SS4	Greywacke	0.4	Southern Uplands, Scotland
SS5	Quartz dolerite	0.4	Palaeogene basic intrusion, northern England / Scotland
SS7	Fault breccia composed of Old Red Sandstone	0.8	Eastern Scotland

Figure Captions

Figure 1. (A) Map showing the regional context of the West Runton and Sidestrand study localities, other localities referred to within the text including offshore boreholes, and the late Early to early Middle Pleistocene palaeogeography (modified from Parfitt et al., 2005). Also indicated on the map is the geographical distribution of the erratic lithologies identified. (B) Map of West Runton showing the location of the WCF (often obscured by beach materials) containing far-travelled clasts (up to 4kg in mass). Samples were collected from two sites - WRa (east of the West Runton slipway; NGR: TG 1872 4318) and WRb (Wood Hill; NGR: TG 1947 4304). Erratics were also collected from a third site ER (located adjacent to East Runton; NGR: TG 2044 4274). However, the stratigraphic context of these erratics is not clearly understood and the results are not included within this study. (C) Location map of

Sidestrand showing the location of the study site, 'X' (NGR: TG 2613 4005), where stratigraphically well-constrained WCF sediments contain far-travelled clasts, up to 15 kg in mass.

Figure 2. Composite stratigraphic log showing the pre-glacial succession at WRa and WRb, situated to the east of the slipway at West Runton, based upon field examinations during the winter of 2007-2008. Units labelled 'E-I' conform to those recognised by West (1980), however, neither 'H' nor the West Runton Freshwater Bed (WRFB) occurred at the two sample sites. The relative position of the WRFB to the erratic-baring beach gravels ('I') is also indicated in italics. Note that along this stretch of cliffs, earlier till units within the regional till succession (i.e. Happisburgh Till and Walcott Till – shown in italics) have been removed by glaciotectonic deformation, and the WCF is overlain uncomfortably by the Bacton Green Till melange. The basal Happisburgh Till occurs in its true stratigraphic position above the WCF further east towards East Runton and west towards Sheringham.

Figure 3. Ice-wedge cast penetrating through beach gravels ('Bed I' of West, 1980) and underlying deposits to the east of Woman Hythe Gap at West Runton. Note that whilst some of this ice-wedge cast has been recently eroded the basal tip of the cast can be traced along the beach platform for several metres demonstrating the feature's three-dimensional form.

Figure 4. Composite stratigraphic log detailing the pre-glacial stratigraphy at Sidestrand and the stratigraphic position of the erratics (after Lee, 2009).

Figure 5. Thin-section photomicrograph of an amphibolite clast (NWHCM : 2008.110) collected from the WCF at Sidestrand in plane polarised light (a) and cross-polarised light (b). The dominant minerals are recrystallised quartz and plagioclase feldspar (1), needle-like amphiboles (2), with minor zoisite (3).

Figure 6. Rhomb porphyry (mass 0.6 Kg, a-axis length 150mm) *in situ* within the WCF at Sidestrand, surrounded by gravels and flint cobbles. Note the head of a geological hammer for scale.

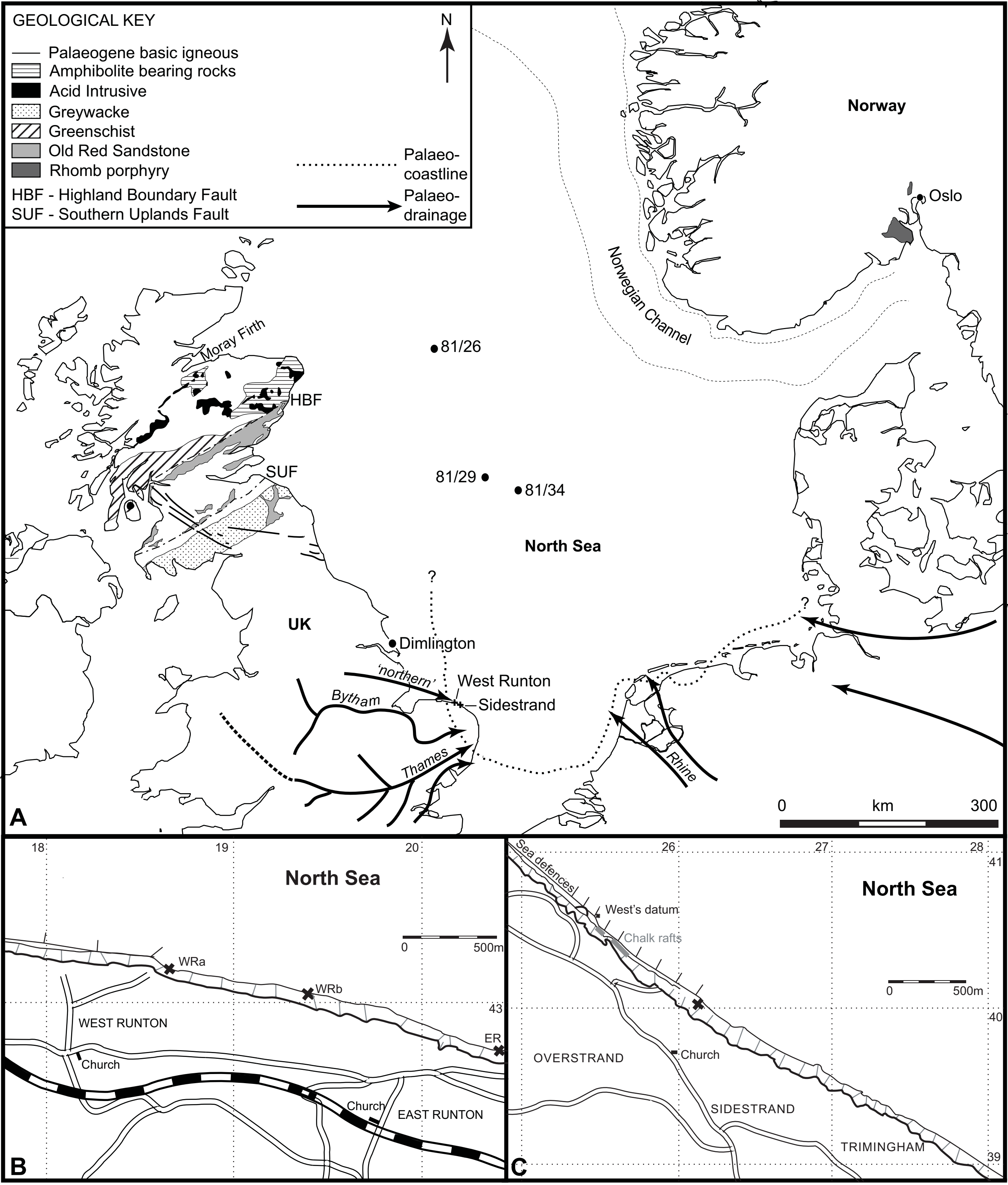
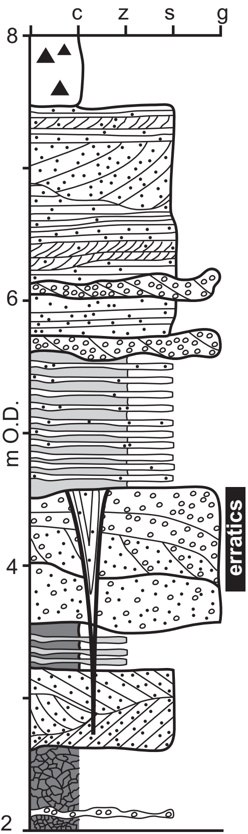
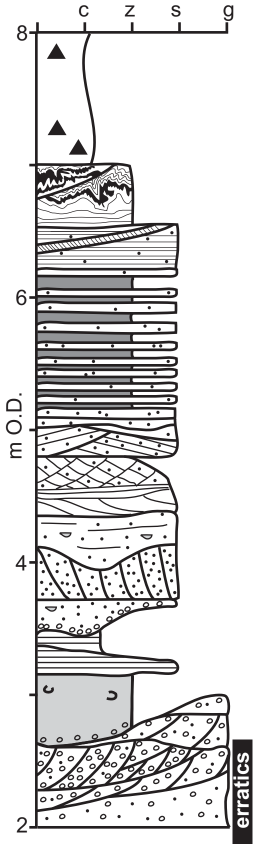

GEOLOGICAL KEY
Palaeogene basic igneous
Amphibolite bearing rocks
Acid Intrusive
Greywacke
Greenschist
Old Red Sandstone
Rhomb porphyry
HBF - Highland Boundary Fault
SUF - Southern Uplands Fault
N
Palaeo-coastline
Palaeo-drainage
Norway
Oslo
Norwegian Channel
Moray Firth
HBF
SUF
81/26
81/29
81/34
North Sea
UK
?
Dimlington
'northern'
West Runton
Bytham
Sidestrand
Thames
Rhine
?
0
km
300
A
18
19
20
North Sea
0
500m
WRa
WRb
43
WEST RUNTON
ER
Church
Church
EAST RUNTON
B
26
27
28
41
Sea defences
West's datum
Chalk rafts
North Sea
0
500m
40
OVERSTRAND
Church
SIDESTRAND
TRIMINGHAM
39
C

FIGURE 1



Unit	Lithofacies	Environment	Lithostratigraphy
	Matrix-supported, highly-consolidated diamicton	Subglacial tectonite	Bacton Green till melange SHERINGHAM CLIFFS FM
	Horizontal, rippled and trough cross-bedded sands, occassional gravel seams and rubified palaeosols.	Semi-emergent tidal sand flat	WROXHAM CRAG FORMATION
	Rhythmically-bedded silts and sands	Tidal flat *Freshwater fluvial**	*West Runton Freshwater Bed* *CROMER FOREST-BED FM**
'I'	Highly spherical flint gravel, faint cross-bedding. Truncated by an ice-wedge cast.	Beach	WROXHAM CRAG FORMATION
'G'	Silt & clay with convolute beds	Tidal flat	
'F'	Trough cross-bedded sand	Tidal flats with sand bars	
'E'	Blue silty-clay containing ferrigunous seams of gravel and intensely brecciated silty-clay fragments	Tidal flats with storm tempestite	

Figure 2



Unit	Lithofacies	Environment	Lithostratigraphy
N	Matrix-supported, highly-consolidated diamicton	Subglacial (till)	Happisburgh Till Member HAPPISBURGH FORMATION
K/M		Subglacial tectonite	
L	Cross-laminated, horizontal-bedded sand	Inner Estuary	WROXHAM CRAG FORMATION
J	Interlayered sand and silt	Tidal Flats	
I	Planar & horizontal cross-bedded sand	Estuary mouth sand bars	
H	Horizontal, rippled sand, HCS	Tidal flat - beneath storm wave base	
G	Longituidinal cross-bedding, lenticular bedding	Tidal Channel	
F	Channels and associated fills		
D/E	Horizontally-bedded sand and silt	Lagoonal	
C	Fine channel fill; Unio shells	Freshwater fluvial	SIDESTRAND *UNIO* BED
A/B	Stratified gravel, rip-up clasts, shell debris	Outer estuary gravel bar	WROXHAM CRAG FORMATION

Figure 4