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Palaeomagnetic correlation and dating of Plio/Pleistocene sediments at the southern margins of the North Sea Basin

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ABSTRACT: A series of discontinuous sediment sequences, of Plio/Pleistocene age, occur onshore around the southern North Sea margins, notably in the East Anglian region of Britain. Intensive lithological and palaeontological analyses of these sediments have shown that they record both major and minor oscillations in climate, sea level and environmental conditions. However, significant uncertainties exist regarding the absolute and relative chronostratigraphies of many of these sequences, hindering understanding of the relative impacts of climatic, eustatic and tectonic changes on the palaeogeographic development of the southern North Sea basin. Here, a number of key East Anglian Plio/Pleistocene sites are subjected to robust palaeomagnetic and mineralogical examination, in order to determine those sediments which display reliable, syn-depositional magnetic polarities, which are thus of use in ascribing a palaeomagnetically determined age from comparison with the Geomagnetic Polarity Timescale (GPTS). Based on a range of palaeomagnetic and complementary mineralogical methods, reliable palaeomagnetic directions were obtained from eight sites, with reversed polarities displayed by sediments from three sites. These polarity determinations can be used to infer absolute ages and test published, between-site correlations. Copyright © 2005 John Wiley & Sons, Ltd.

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KEYWORDS: palaeomagnetism; British Pleistocene sediments.

Introduction

Laterally variable and vertically discontinuous series of sediments of Plio/Pleistocene age occur onshore in East Anglia, Great Britain, on the southern margins of the North Sea basin. Intensive lithological and biological analyses of these sediments have shown that they record both major and minor oscillations in climate, sea level and environmental conditions. However, no site contains a continuous sedimentary record for this time period. Stages in the Plio/Pleistocene have thus been defined for this area on the basis of biostratigraphy at a number of 'type sites'. Subsequently, correlation of sedimentary units between sites has been attempted on biostratigraphic, lithostratigraphic and stratigraphic grounds. However, uncertainties and controversies continue to exist regarding the number of climate stages represented within the British Quaternary sequences, and their correlation with the marine oxygen isotope record—such debate currently centres, for example, on the Cromerian Complex of the British Pleistocene record (e.g. Preece and Parfitt, 2000; Hamblin *et al.*, 2000; Banham *et al.*, 2001).

For many of these sequences, magnetostratigraphy provides the only possible means of an absolute geochronology. When rocks and sediments are formed, they may acquire a record of the Earth's magnetic field. By measuring their remanent magnetisations, it is often possible to deduce the direction of the geomagnetic field at the time the rock or sediment was formed. This information is of interest in the study of the Plio/Pleistocene because (a) the geomagnetic field vector varies with time, most significantly by changing polarity, and (b) a sequence of polarity reversals has occurred during the last 2.5 million years, for which absolute ages have been determined (Hilgen, 1991).

Use of palaeomagnetism for purposes of correlation and dating may, however, be limited by the availability of 'suitable' sediments. Measurement of the magnetic polarity of a sediment should be accompanied by additional magnetic and mineralogical analyses in order to determine the timing and reliability of the acquired magnetic signal. Efficient remanence acquisition at, or close to, the time of sediment deposition is favoured by the presence of sub-micrometre, strongly magnetic ferrimagnets (such as magnetite), and a low-energy depositional environment. Subsequent preservation of the (post-)depositional

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natural remanence (PDRM) is favoured by lack of physical disturbance and minimal diagenetic alteration of, or addition to, the magnetic minerals. As will be discussed, these conditions are met with rather rarely in the context of the Plio/Pleistocene East Anglian sedimentary sequences.

One of the most common ways of establishing palaeomagnetic reliability is to demonstrate repeatability in duplicate sediment sequences. However, the uncertainties in the correlation of the East Anglian sediments are one of the main reasons for undertaking palaeomagnetic analysis. In addition, the sedimentary units found in East Anglia are vertically discontinuous and some have high rates of sedimentation. For example, Funnell and Pearson (1989) found Holocene sedimentation rates on the northern barrier coast of East Anglia to be $\sim 1\,\mathrm{m\,ka^{-1}}$. If sedimentation rates were of similar magnitude for similar sedimentary systems in the Late Pliocene/Early and Middle Pleistocene, then palaeomagnetic data from a few metres of such sediment would represent 'spot readings' of the geomagnetic field at the time of remanence acquisition. Such sequences are unlikely therefore to contain a geomagnetic polarity transition, which may take 10 ka to occur (e.g. Tric *et al.*, 1991), let alone a sequence of reversals. There is thus little chance of locating sequences of reversals which can be matched between localities in this region. A possibility matrix (Fig. 1) summarises the possible origins and polarities of remanence in Plio/Pleistocene sediments. With only two polarity possibilities (reversed or normal), it is clear that similar polarity directions are no guarantee of either syn-depositional remanence acquisition or synchronous deposition. This caveat is significant, given that most previous studies of the polarity of sediments from Plio/Pleistocene sediments in East Anglia have yielded normal polarities (Table 1). These studies have, however, tended to rely on the measurement of remanent magnetisation directions, accompanied only by some limited demagnetisation analysis.

Here we report new palaeomagnetic data for a number of the East Anglian Plio/Pleistocene sites, and assess their reliability by:

1 coupling measurements of the remanent magnetisation of freshly sampled sediments with comprehensive demagnetisation experiments, in order to isolate the various components of magnetisation; and
2 investigating the mechanisms by which these components of magnetisation were acquired, using demagnetisation data, mineral magnetic measurements and analysis of magnetic extractions to identify the carriers of magnetic remanence.

The details of the palaeomagnetic and mineralogical investigations are discussed in Hallam and Maher (in press). Here, we summarise the palaeomagnetic polarity data obtained, and use the Geomagnetic Polarity Timescale (GPTS) to date those sediments where both accuracy and syn-depositional timing of remanence acquisition can be inferred.

The pre-Anglian/Elsterian geology of East Anglia

The Plio/Pleistocene geological record of East Anglia is represented by a series of unconsolidated sediments, lying upon 'bedrock' of Cretaceous chalk and Tertiary sands and clays. (A brief overview follows here but detailed summaries of the region's late Tertiary/Quaternary geology are given by, for example, Zalasiewicz and Gibbard (1988), Funnell (1996) and Gibbard *et al.* (1998).) Figure 2 shows the locations of the main pre-Anglian/Elsterian, Plio/Pleistocene sedimentary bodies of East Anglia, and the sites sampled in this investigation. The stratigraphic succession comprises shallow marine, fluvial and extensive glacial facies. Spatially, the sediments can be divided into two main groups. Sediments deposited at the western margin of the contemporary southern North Sea are mostly marine and intertidal in origin, deposited under marine, brackish and episodically freshwater conditions, and are vertically and laterally discontinuous. The oldest unit is the Red Crag Formation, overlain, in sequence, by the Crag (Norwich and Wroxham) and the Cromer Forest Bed Formations (Fig. 3). Molluscan evidence from the coastal outcrops of the Cromer Forest Bed Formation in Norfolk and Suffolk suggests at least three separate interglacial stages are represented by these deposits, with the type Cromerian correlated to marine isotope stage (MIS) 15 (Preece and Parfitt, 2000). Hamblin *et al.* (2000) and Lee *et al.* (2004) contest this correlation, inferring

Time of remanence acquisition → Measured Polarity ↓	Syn-depositional	Some time after deposition
Normal	Acquisition in normal Chron, remanence preserved	Original remanence deleted, subsequent remanence acquisition during normal Chron
Reversed	Acquisition in reversed Chron, remanence preserved	Original remanence deleted, subsequent remanence acquisition during reversed Chron

Figure 1 Possibility matrix for the origin and polarity of remanent magnetisation in Pleistocene sediments

Table 1 Palaeomagnetic polarity determinations from pre-Anglian Pleistocene sediments

Locality	Stage	Reference	Number of samples	Polarity: N = Normal R = Reversed
Mundesley	Upper Cromerian	5	6	N
Sugworth	Cromerian	1	27	N
	Cromerian	1	15	N
West Runton	Cromerian	3	20	N
Little Oakley	Cromerian	4	35	N
Westbury-sub-Mendip	mid-Pleistocene	1	5	N?
Nettlebed	pre-Cromerian	1	4	N?
Caistor St Edmund	Kesgrave Sands and Gravels	3	20	N
Ardleigh	Kesgrave Sands and Gravels	8		N
West Runton	Pastonian	5	6	N
Chillesford	Pastonian	1	13	N
Aldeburgh	Pastonian	1	15	N
Easton Bavents	Baventian	1	28	N
	Baventian	1	25	N
	Baventian	2	105	N
	Baventian	5	10	N
Covehithe	Baventian	3	12	N
Cove Bottom	Baventian	1	10	N
	Baventian	1	20	N
	Baventian	2	47	N
Chillesford	Baventian	2	3	N
Sidestrand	Baventian	5	12	N
Ludham L2	Thurnian	1	20	N?
Ludham L1	Ludhamian	1	6	N
Aldeburgh–Sizewell	Ludhamian	7	3	R
Stradbrooke	early Ludhamian	5, 6	1	N
	pre-Ludhamian	5, 6	14	N
Aldeburgh–Sizewell	pre-Ludhamian	7	48	N

References: 1 Thompson (1991); 2 Zalasiewicz *et al.* (1991); 3 Ramshaw (1992); 4 Austin (1990); 5 van Montfrans (1971a,b); 6 Beck *et al.* (1972); 7 Zalasiewicz *et al.* (1988); 8 Bridgland and Gibbard (1990).

(on lithostratigraphic/modelling grounds) an MIS 16 age for overlying (Happisburgh) glacial deposits and thus a significantly older age and MIS stage (19) for the Cromer Forest Bed Formation. Critically, the Brunhes/Matuyama (normal/reversed) boundary occurred within this isotope stage (Tauxe *et al.*, 1996). Hence, the Cromer Forest Bed Formation would be expected to record reversed magnetic polarity, unless it was deposited during or after *late*-MIS 19. Variably superimposed on these coastal formations are pre-Anglian fluvial sediments of the Ingham Formation (Rose *et al.*, 2001). In contrast, the southern and eastern parts of the region are characterised by the presence of gravel trains, deposited by a pre-Anglian ancestor of the River Thames (e.g. Rose *et al.*, 1976; Whiteman, 1992; Bridgland, 1994). This fluvial Formation, the Kesgrave Sands and Gravels (Bowen, 1999), has been subdivided into the Sudbury and Colchester Formations (Fig. 3), and is distinguished from overlying fluvioglacial gravels of Anglian/Elsterian age by their clast lithology. The Kesgraves comprise large proportions of rounded flints, together with increasingly far-travelled lithologies, particularly including quartz and quartzites (from the English Midlands region) and acid igneous rocks (from North Wales). These 'proto-Thames' gravel trains occur as a sequence of terraces, upon which distinctive palaeosols (the Valley Farm Soil) are developed to varying degrees (e.g. Rose *et al.*, 1976; Kemp, 1987). On the upper gravels, the soil shows repeated cycles of temperate and cold climate evolution (Kemp, 1985, 1987), whereas on the lowest gravels (e.g. at Wivenhoe) the soil shows evidence of development in a single temperate stage or is absent (for example at St. Osyth). Establishing relations between the Kesgrave Formation and the Crag basin sequences has proved problematic, as the Kesgraves are mostly non-fossiliferous. However, inter-stratified organic sediments at Little Oakley in Essex have yielded *Mimomys savini* (water voles with rooted teeth), indicating an early/mid Cromerian Complex age (Preece and Parfitt, 2000). Other organic sediments in the lower Kesgrave gravels of Essex (at Ardleigh and Wivenhoe) have been attributed to separate pre-Anglian/Elsterian interglacial stages (e.g. Bridgland, 1988, 1994; Gibbard, 1999; Preece and Parfitt, 2000). As the Kesgrave Formation is overlain by Anglian/Elsterian sediments over much of East Anglia, it is assumed to lie within the pre-Pastonian *a*/late Tiglian to Anglian/Elsterian interval (Gibbard *et al.*, 1991). Whiteman and Rose (1992) proposed that their 'Kesgrave Group' represents a substantial part of the Pleistocene, with the Sudbury Formation (occurring on the upper terraces of the Kesgraves) deposited in the interval from the pre-Pastonian *a* until the end of the Early Pleistocene, and the Colchester Formation (lower terraces) during the pre-Anglian/Elsterian Middle Pleistocene.

Figure 3 also identifies the Plio/Pleistocene stratigraphy of the Netherlands, which represents one of the most complete sequences available from presently terrestrial (marine and freshwater) sediments. This sequence has been fitted within the absolutely dated framework of palaeomagnetic reversals (van Montfrans, 1971a,b; Zagwijn, 1985) and, although incomplete, has been correlated with the oxygen isotope record of environmental change (de Jong, 1988; Fig. 3).

Given the importance of the Netherlands' sedimentary succession, and its proximity to East Anglia, correlations between the two parts of the same sedimentary basin have been sought, both to establish the British chronostratigraphy and in order to deconvolve the effects of changes in climate, environment and isostasy on this region. Based on pollen evidence, faunal data and some palaeomagnetic constraints, Gibbard *et al.* (1991) suggested that a significant hiatus must occur between the Pastonian (or later part of the Beestonian) and Cromerian

Figure 2 East Anglia, showing the limits of the coastal embayment containing crag deposits and of the gravel aggradations of the Kesgrave Sands and Gravels Formation, together with the localities sampled for this investigation. After Bristow (1983) and Whiteman (1992)

Stages, associated with the growth of the Great-European Delta (the Eridanos delta of Overeem *et al.* (2002)) which, together with a fall in sea level, excluded the sea from the southern North Sea basin (Funnell, 1996). Gibbard *et al.* (1991) suggested that the Kesgrave Formation represents this missing time interval. Whiteman and Rose (1992) proposed that the Colchester Formation was deposited during the Cromerian Complex as defined within the Dutch stratigraphy, with the Sudbury Formation deposited during the interval between the Tiglian substage C4c and the end of the Bavel Complex (Bavelian Stage).

The earliest 'Pleistocene' sediments in East Anglia are of pre-Ludhamian age (Beck *et al.*, 1972). In the Netherlands sedimentary succession, most workers accept the traditional lower limit for the Pleistocene as the base of the Praetiglian Stage (Gibbard *et al.*, 1991). Pre-Ludhamian sediments from East Anglia have been correlated with the Praetiglian or Reuverian C Stage, on the basis of pollen and magnetic polarity (Zalasiewicz *et al.*, 1988), which is consistent with the base of the Pleistocene lying below the pre-Ludhamian Stage. However, the international definition of the base of the Pleistocene (Aguirre and Pasini, 1985) is just below the top of the Olduvai Sub-chron (Hilgen, 1991). With an age of 1.81 Ma BP in Hilgen's (1991) timescale, this would place it at the Tiglian/Eburonian boundary, or within the Tiglian C5-6 sub-stage of the Netherlands succession (Zagwijn, 1985; Funnell, 1995). The Tiglian C5 sub-stage has been correlated with the Pastonian Stage of the East Anglian succession (Gibbard *et al.*, 1991). Thus, the regional definition of the base of the Pleistocene considerably pre-dates the Italian boundary stratotype. If the internationally accepted base of the Pleistocene were applied to northwest Europe, all sediments below the Tiglian C5-6/Pastonian Stages would be of Pliocene age (e.g. Funnell, 1995). This controversy is beyond the scope of this work. Here, the regional definition of the base of the Pleistocene is used, i.e. the base of the pre-Ludhamian/Praetiglian Stages. Under this definition, the sediments investigated here are of Pleistocene age. (Similarly, the intention of The International Commission on Stratigraphy to eliminate the Quaternary as a formal chronostratigraphic unit in the new Geological Time Scale will not be considered here.)

Palaeomagnetic polarity results from the Pleistocene sediments of the North Sea basin

Southeast England

The palaeomagnetic polarity of a number of East Anglian (and other southern British) sites was investigated initially (Table 1) by van Montfrans (1971a,b) and subsequently summarised by Thompson (1991). It is notable that stable reversed polarities have been obtained only twice in this region, by Zalasiewicz *et al.* (1988), from specimens of Ludhamian/Tiglian age, and Hallam and Maher (1994) from greigite-bearing sediments of Pastonian/late Tiglian age. All the remaining polarity determinations from terrestrial British Pleistocene sediments have been

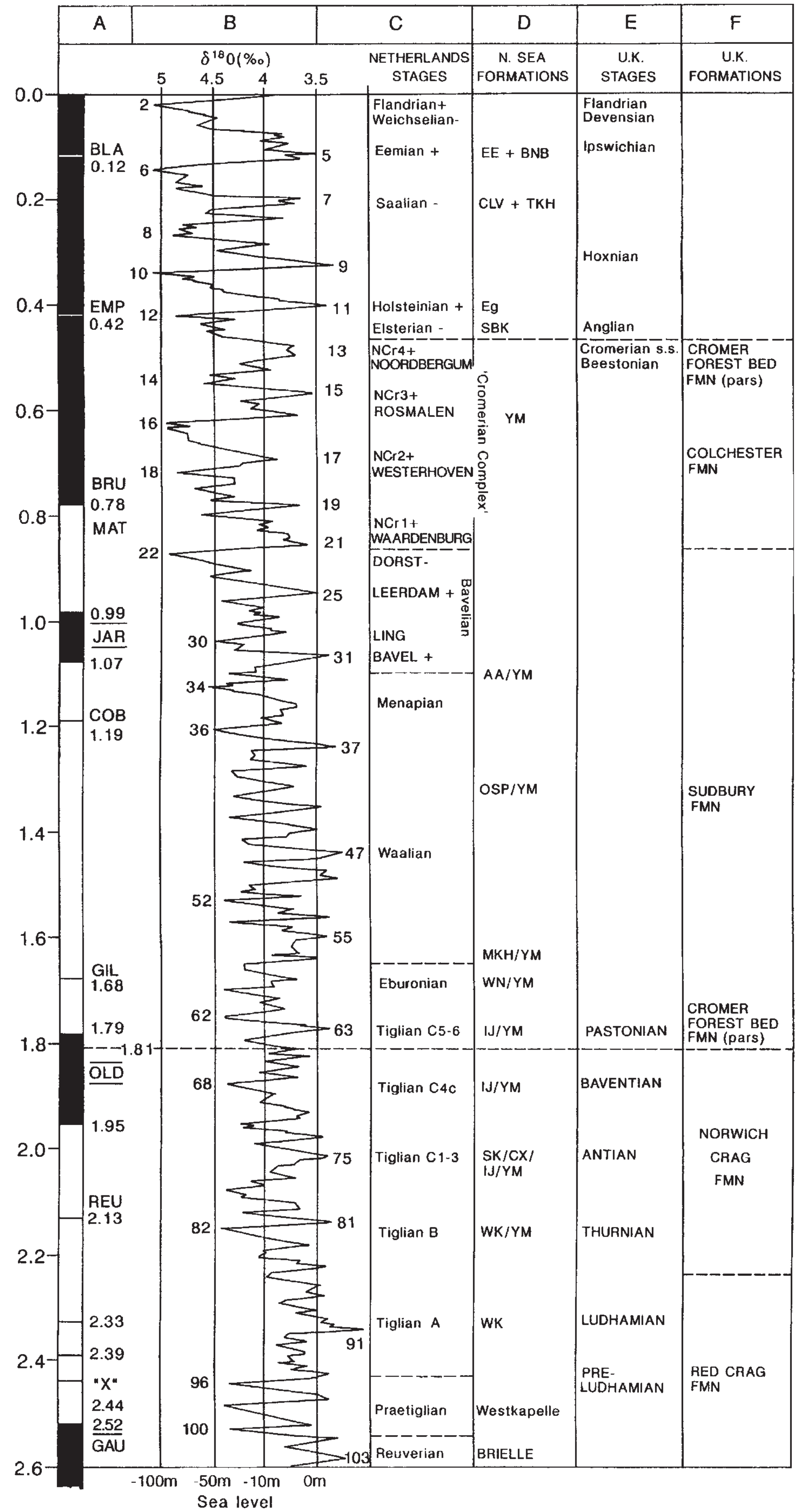

Figure 3 A Plio/Pleistocene stratigraphy for sediments from the North Sea basin (Funnell, 1995)

of normal polarity. This lack of reversals, in comparison with the Pleistocene sediments of the Netherlands, was one of the reasons Zagwijn (1975) proposed that large stratigraphic hiatuses occur in the East Anglian Pleistocene succession.

Northwest Europe

van Montfrans (1971a,b) investigated samples of known lithological age from sites in the Netherlands, Belgium and Germany. To exclude spurious remanent magnetisations from the data, he applied various rejection criteria, based on scatter of natural remanent magnetisation (NRM) directions and alternating field (AF) demagnetisation to 20 millitesla (mT). The most recent samples of reversed polarity were from sediment of Cromerian Complex Glacial 'A' age. This was van Montfrans' preferred location for the Brunhes/Matuyama polarity transition. Normal polarities, representing the Jaramillo Sub-chron, were found in exposures initially ascribed a Waalian 'C' age, but later revealed to be part of a post-Menapian Bavelian Complex (Zagwijn and de Jong, 1984). New information on the GPTS led Zagwijn (1985) to extend further correlations based on van Montfrans' data. Normal polarities in sediments of Tiglian age were assigned to the Olduvai Sub-chron and the Réunion and 'X' events (Fig. 3). Reversed and normal polarities associated with the Praetiglian/Reuverian biostratigraphic boundary led to location of the Matuyama/Gauss transition in the Reuverian Stage. van Montfrans' work had important implications for the chronological framework for regional stratigraphy. First, the base of the Pleistocene, as defined in northwest Europe, was earlier than previously thought (at around 2.3 Ma BP); second, the duration of the Cromerian Complex was at least 0.4 Ma.

The North Sea

A number of studies have investigated the palaeomagnetic polarity of late-Cenozoic sediments from boreholes in the North Sea. Stoker *et al.* (1983) recognised the Brunhes/Matuyama transition and attributed short reversed polarity intervals in the Brunhes to the Blake and Laschamp geomagnetic events on the basis of palaeontological evidence. Normal polarities below the Brunhes/Matuyama transition were tentatively assigned to the Jaramillo Sub-chron. Skinner and Gregory (1983) attributed two reversed polarity zones to the Blake Event. Biostratigraphy indicated that these coincided with a climatic amelioration, correlated with the Eemian Stage. Normal and reversed polarities, interpreted as representing the Brunhes/Matuyama transition, in sediment with an early Pleistocene fauna indicative of climate amelioration, were correlated with the Cromerian Complex. Cameron *et al.* (1984) interpreted normal polarity intervals in the predominantly reversed Westkappelle Ground Formation as representing the Réunion and 'X' Events.

Thompson *et al.* (1992) investigated the magnetic polarity of a number of boreholes in the southern North Sea. Upper Pliocene sediments of both polarities were interpreted as representing the Kaena–Gauss and Gauss–Matuyama transitions, and were assigned to the Reuverian Stage. Early Pleistocene normal polarities were attributed to the Olduvai Sub-chron and an upward normal to reversed transition of (probably) Eburonian age was attributed to the top of the Olduvai. The Brunhes/Matuyama transition was not recorded, but Elsterian and later normal polarities were ascribed to the Brunhes Chron. Reversed polarity of Eemian 'E3' age was correlated with the Blake Event, although similar results from Holocene sediments were considered to be spurious.

Methods

Sampling

Samples were taken from a number of exposures of the marine/intertidal beds laid down at the margins of the Early Pleistocene North Sea, and of the fluvial Kesgrave Formation (Table 2). In addition, an exposure of the Gerrards Cross gravel Member, located in the Middle Thames region, was sampled. Fine-grained, undeformed sediments were sampled where possible, to maximise the possibility of obtaining a syn-depositional remanence record. However, such sediment is rare in the Kesgrave Formation; although over thirty sites were visited, most contained no 'suitable' material. Before sampling, the surface of the exposed sediment (at quarry sites or coastal cliffs) was cleaned to expose unweathered material. A vertical surface was dug out with a spade and made smooth by scraping away material with a mason's trowel. The dip of the face was checked with a compass-clinometer. Samples were taken from where there was little or no disturbance of the sedimentary fabric, although laminated sediments showing some dip but otherwise undisturbed were sampled. Samples were taken by pushing plastic cubes ($19 \times 19 \times 19$ mm internal dimensions) into the sediment, either manually or using a trowel or spade as a lever (*not* a hammer). At least two samples were taken from each level so that the reproducibility of results could be tested.

Before the cubes were removed from the sediment, the up direction was permanently marked, the sample numbered and the number, push direction and any bedding dip and strike recorded. Compass directions were corrected to be relative to true north prior to specimen measurement. A sketch was made of the sample positions and the sediment type and structures. Usually, a photograph of the sample cubes in position was taken, to confirm their way up. Finally, the sample cubes were cut out of the sediment, and transported in an airtight box to inhibit dehydration. On arrival at the palaeomagnetic laboratory, sample cubes were cleaned and the air-escape hole sealed with sticky tape. Specimens were stored in airtight boxes in a cold store (4 °C) to inhibit dehydration and possible oxidation of magnetic minerals.

Hailwood (personal communication) investigated soft-sediment sampling errors. A systematic deflection was observed in the magnetic declination of several tens of degrees towards the sample-cube push direction. This error was most important for mechanically weak sediments and attributed to disturbance of the internal structure of the sediment. The vertical component was, however, found to be reliable.

Measurement

The NRM of most samples was measured using a GM400 Cryogenic Magnetometer (Cryogenic Consultants Ltd, London), which is magnetically shielded, very sensitive (mean background noise level of 5.9×10^{-11} Am^2) and suitable for rapid measurements of samples with a weak magnetic movement. Different components of the NRM may be acquired at different times in a sediment's history and/or by different mechanisms, and may be carried by different populations of

Table 2 Sampled sites (GB = Great Blakenham)

Site/unit	No. samples
GB–Creeting Sands	33
GB–College Farm Silty Clay	38
Thorpe St Andrew	13
South Cove Brickworks	76
Thorington	22
Caistor Pit	59
Sheringham unit e	12
Sheringham unit g	58
Stebbing	8
GB–Baylham Common Gravels	8
Drakes Farm	5
Bradwell	6
Springfield	37
Ardleigh inorganic clay (upper gravels)	6
Ardleigh organic silts	20
Ormesby Borehole	62

magnetic grains. Stepwise demagnetisation is thus used to isolate the stable, characteristic (ChRM) components of the NRM which are then taken to represent the primary remanence direction. Two types of demagnetisation were used here: AF demagnetisation and thermal demagnetisation. The equipment used for AF demagnetisation was a Highmoor Alternating Field Demagnetiser (Highmoor Electronics Ltd), with a maximum H_{AF} of 90 mT, operating at 250 Hz. To ensure no bias to the alternating field, the laboratory magnetic field was nulled using three orthogonal Helmholtz coils, supplemented by partial mu-metal shielding. The field was measured using a MAG-03MC Tri-axial Fluxgate Magnetometer (Bartington Instruments Ltd, Oxford).

Stepwise thermal demagnetisation involves heating specimens to progressively higher temperatures in zero field, with measurement of the remaining NRM after each heating step. Pilot samples from each site were subjected to stepwise thermal demagnetisation at 50 °C intervals, up to the maximum temperature at which NRMs were stable. The equipment used for thermal demagnetisation was an MMTD1 Thermal Demagnetiser (Magnetic Measurements Ltd). After each demagnetisation step, the low field susceptibility of each specimen was measured, using an MS2 Magnetic Susceptibility Meter (Bartington Instruments Ltd, Oxford), to monitor for any chemical changes which might affect the specimen's bulk magnetic properties. Thermal demagnetisation was halted when large increases in susceptibility (indicating formation through the heating process of new magnetic minerals) were accompanied by directional changes and/or increases in remanence intensity. Demagnetisation of a specimen's NRM gives information on how well the process of NRM acquisition has recorded the magnetic field and the stability of the grains carrying the NRM. To gain better understanding of the mode of acquisition of the NRM, and, critically, the timing of that acquisition, two additional sets of analytical methods were used to identify the magnetic carriers: (a) mineral magnetic measurements (magnetic susceptibility, isothermal remanent magnetisation, and anhysteretic remanent magnetisation); and (b) direct petrographic analysis of magnetic extracts (X-ray diffraction, microscopy and elemental analysis). Detailed discussion of these data, and the types and reliability of the minerals carrying the NRM in the East Anglian sediments, is given in Hallam and Maher (in press).

Results

Dating and correlations

All the investigated sites are listed in Table 2. Those for which reliable polarity determinations have been obtained are summarised stratigraphically in Table 3 and Fig. 4. Data have been judged unreliable where the remanence has been found to be unstable (mainly due to the presence of viscous magnetic components, carrying a normal magnetic overprint of any possible original ChRM). Conversely, data have only been judged robust upon identification of the likely timing and mechanism of acquisition of a stable remanence signal (Hallam and Maher, in press). The reliable results can be compared with Fig. 3, which summarises previous correlations between the Pleistocene stages of the Netherlands and those of the UK, together

Table 3 Sites for which reliable polarity determinations have been obtained

Site/Unit	Age/Member	Polarity
Ardleigh	Ardleigh Upper Gravel (Colchester Farm)	Normal
Ardleigh	Ardleigh Interglacial Bed (Colchester Farm)	Normal
Bradwell	Moreton Gravel (Sudbury Farm)	Normal
Drakes Farm	Moreton Gravel (Sudbury Farm)	Normal
Sheringham unit *g*	Pastonian	Reversed
Sheringham unit *e*	Pastonian	Normal
Ormesby Borehole	pre-Pastonian *a* or Pastonian	Normal
Ormesby Borehole	pre-Pastonian *a*	Reversed
Thorington	Late Baventian/pre-Pastonian *a*	Normal
South Cove Brickworks	Baventian	Normal
College Farm Silty Clay	Antian	Reversed
Ormesby Borehole	pre-Ludhamian (Thurnian?)	Reversed
″ ″		'Short' normal
″ ″		Long period of reversed
″ ″		Normal

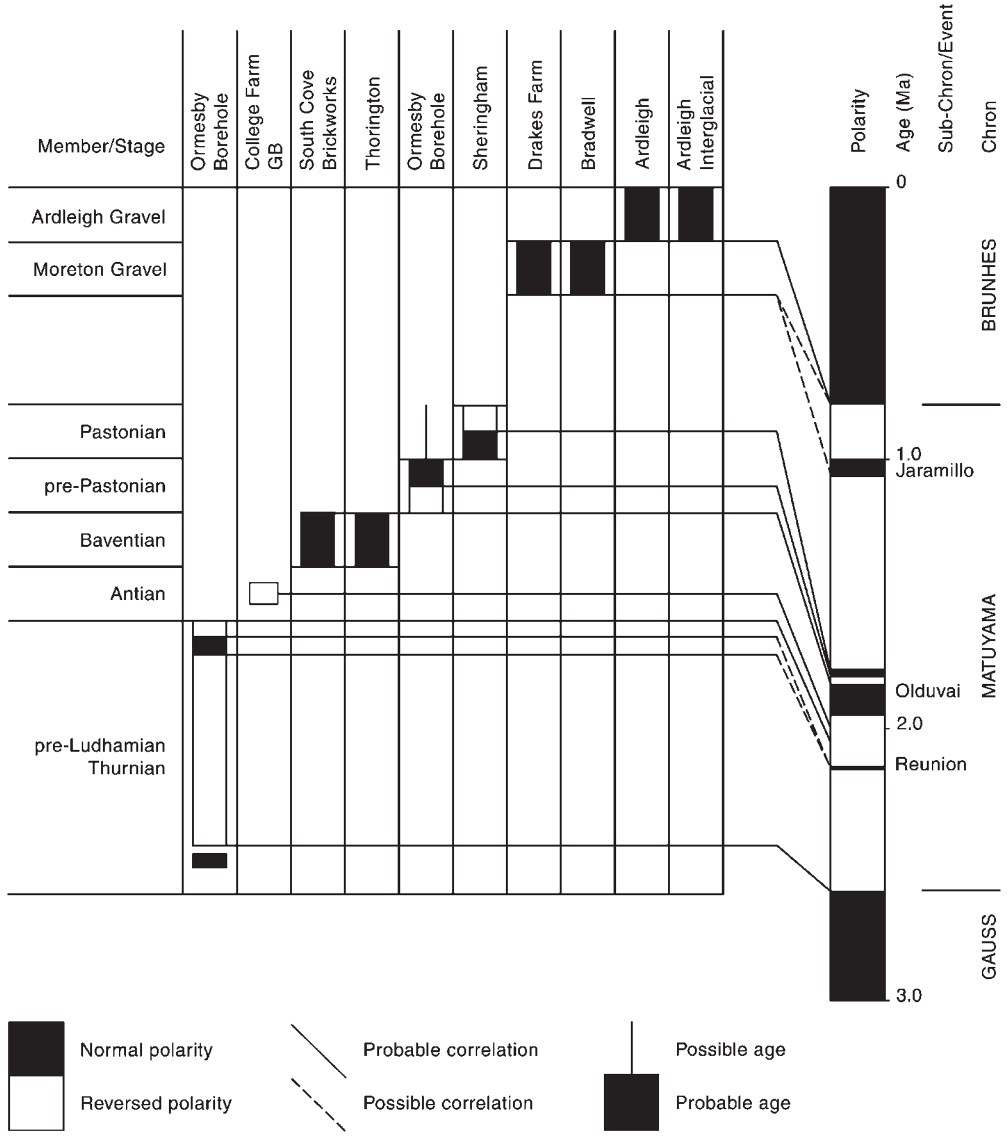

Figure 4 Palaeomagnetically constrained stratigraphy for eight East Anglian sites

with palaeomagnetic determinations from the Netherlands succession, and Table 1, which summarises previous polarity determinations from the UK. Correlations based upon polarity determinations attributed to sediment bodies is dependent upon the reliability of biostratigraphic ages. Thus, if the biostratigraphic age changes, the correlations must be revised.

Discussion

Here only those sites and sediments which have provided reliable palaeomagnetic directions will be discussed, from oldest to youngest through the East Anglian Quaternary succession.

Crag deposits

The lower part of the Ormesby borehole record provides an apparently continuous sedimentary sequence. Ascribed a pre-Ludhamian/Thurnian age (Harland *et al.*, 1991, Funnell, personal communication), the long reversed interval probably represents part of the lower Matuyama Chron. The normal polarity interval which precedes the long reversed interval (and is separated from it by mixed polarities) may thus correspond to the upper part of the Gauss Chron. Alternatively, this basal normal interval could represent part of the 'X' or other event in the lower Matuyama. Similarly, it is possible that the 'short' normal polarity interval, which occurs towards the top of the long period of reversed polarity, may represent the Réunion Event. The normal polarities are represented by approximately 0.8 metres of sediment. A problem here is that the sedimentation rate is unknown; if it was of the order of 1 m ka^{-1}, then this thickness of sediment would correspond to 800 years (and thus record a very short geomagnetic event, not identified in the GPTS). Conversely, a sedimentation rate of 8 cm ka^{-1} would yield an interval of 10 ka, the duration attributed by Hilgen (1991) to the Réunion Event.

The predominantly reversed polarities of the Ormesby borehole are consistent with biostratigraphic correlations between the pre-Ludhamian and the Praetiglian Stage, and between the Thurnian and the early Tiglian Stage of the Netherlands succession (Fig. 3). However, according to Thompson (1991), Ludhamian and Thurnian samples from the Ludham borehole yielded normal polarities. Palaeomagnetic investigations by van Montfrans (1971a,b) indicated normal polarities from sediments attributed to the lowermost Ludhamian and greater part of the pre-Ludhamian in the Stradbroke borehole

(Beck *et al.*, 1972). Thus, the reversed polarity intervals identified here represent new data, the reliability of which has been tested more comprehensively than in any previous study. The new and previous data may be congruent, if the normal polarities from the pre-Ludhamian (van Montfrans, 1971a,b) correspond to either of the short normal polarity intervals recorded by the Ormesby borehole. Zalasiewicz *et al.* (1988) also found normal polarities in sediment of pre-Ludhamian age, but a single reversed polarity horizon in sediment of Ludhamian age. If the Ormesby record represented the whole of the pre-Ludhamian–Thurnian interval (which was not suggested by Harland *et al.*, 1991), the pre-Ludhamian normal polarities reported by Zalasiewicz *et al.* (1988) might correspond to the short normal polarity interval at the base of the Ormesby borehole, and their reversed polarities from the Ludhamian might correspond to part of the long reversed interval in the Ormesby borehole.

The College Farm Silty Clay, a localised bowl of fine sediment (up to ~ 3 m thick) which caps the Chillesford Sand Member of the Crag in the Great Blakenham area, neatly illustrates the characteristic problems associated with palaeomagnetic analysis of the East Anglian Pleistocene sediments. Palaeomagnetic samples originally obtained from this unit (Gibbard *et al.*, 1996) were stored (in a cold store) for a period of several months prior to analysis. Subsequent measurements indicated they were of normal polarity, with a mixed magnetic mineralogy of a ferrimagnetic mineral (presumed from the magnetic data to be magnetite) and high-coercivity goethite. These palaeomagnetic data were in conflict with the biostratigraphical correlation—abundant remains of the water fern, *Azolla tegeliensis* indicated correlation with the Tiglian C3 stage of the Netherlands' succession (Gibbard *et al.*, 1996). However, new samples were obtained at a later date and measured both 'fresh' and post-storage. All the fresh samples displayed normal NRMs, but upon AF demagnetisation at fields of 20 mT and higher, a large normal overprint was removed, and, in several cases, a reversed magnetic component revealed. Monitoring of magnetic changes upon storage showed that the original magnetic assemblage present in these sediments was unstable under oxidative conditions. Decreases through time in magnetic susceptibility, saturation remanence (SIRM), low-field acquisition of remanence and SIRM/susceptibility ratios, and increases in the high-field acquisition of remanence indicated the initial presence of ferrimagnetic iron sulphides (greigite), with alteration upon storage to iron oxyhydroxides, including goethite. The normal NRMs of these sediments thus appear to represent a later overprint, and the characteristic remanence, a CRM, is actually of reversed polarity. This indicates that these sediments were deposited during the Matuyama Chron, in agreement with a Tiglian C3 correlation.

Normal polarities from Baventian sediments at South Cove Brickworks are in agreement with all previous polarity determinations from similar sediment. However, the origin of the remanence has also been identified here as a CRM, again acquired by *in situ* formation of the magnetic iron sulphide, greigite (see Hallam and Maher, in press). The nature of this CRM accounts for those characteristics of the remanence behaviour previously thought to cast doubt on the origin of the NRM signal (Zalasiewicz *et al.*, 1991). The normal polarity directions at South Cove are also consistent with results from the Baventian sediments at Thorington. In relation to the GPTS, this suggests that these sediments were laid down during the Olduvai normal polarity Sub-chron, and corroborates correlations between the Baventian Stage and the Tiglian C4c sub-stage of the Netherlands.

Pre-Pastonian *a* sediment from the Ormesby borehole is of reliable reversed polarity. The overlying sediment, of normal polarity, has also been ascribed (on biostratigraphic grounds) a pre-Pastonian *a* or Pastonian age (Harland *et al.*, 1991). At Sheringham, sediments attributed to the Pastonian (West, 1980) have reliable normal, followed by reversed, polarity (Hallam and Maher, 1994). The Pastonian Stage has been correlated with the Tiglian C5-6 Stage of the Netherlands (Gibbard *et al.*, 1991). These data would thus place the Baventian/Pastonian boundary at or close to the top of the Olduvai Sub-chron and its boundary with the upper Matuyama. However, this Upper Olduvai/Matuyama transition may be complex (Tric *et al.*, 1991; Zijderveld *et al.*, 1991; Hilgen, 1991). Marine marl sequences in Italy contain evidence for a short (~30 ka) reversed Sub-chron following the major part of the Olduvai Sub-chron but, in turn, preceding a short (~15 ka) return to normal polarity. Zijderveld *et al.* (1991) interpreted the short reversed polarity interval as a Sub-chron within the Olduvai Sub-chron. In detail, then, it is possible that the reversed polarities of the pre-Pastonian *a*—(lower) Pastonian sediment of the Ormesby borehole might correspond to the short (~30 ka) reversed polarity Sub-chron (Marine Isotope Stage 64), and that of the (upper) Pastonian sediments at Sheringham to the early part of the Upper Matuyama Chron, i.e. MIS 63 and younger. The intervening ~15 kyr interval of normal polarity, if recorded in its entirety by ~2 metres of the Ormesby sediments, indicates a sedimentation rate of 13 cm ka^{-1}. These correlations with the GPTS are consistent with correlations between the pre-Pastonian *a*–Pastonian Stages with the Tiglian C4c to C6 substages of the Netherlands succession, located towards the top of the Olduvai Sub-chron (Fig. 5 in Gibbard *et al.*, 1991).

An alternative explanation is that these reversed-normal, normal-reversed polarity determinations might represent a record of the later, Jaramillo Sub-chron, within the Matuyama Chron. Such correlations would be inconsistent with those of Gibbard *et al.* (1991). Another possibility is that the normal polarities from Sheringham, and/or from the Ormesby borehole, might correspond to short-lived normal polarity events within the post-Olduvai part of the Matuyama Chron, such as the Gilsa Sub-chron. Such correlations also imply contradictions with the biostratigraphic relations of Gibbard *et al.* (1991). Given the biostratigraphic evidence available, correlation of the Ormesby/Sheringham pre-Pastonian *a*—Pastonian Stage polarity determinations with the Upper Olduvai Sub-chron/Matuyama transition seems probable.

Kesgrave Formation

The terrace stratigraphy of the Kesgrave Formation enables some evaluation of the respective ages both of Cromerian Complex and older sites on an altimetric basis. Whiteman and Rose (1992) suggested that the Sudbury Formation, i.e. the older, higher-level Kesgrave Gravels, represents the period of time between the pre-Pastonian *a* Stage and the end of the Early Pleistocene, including the substantial post-Pastonian/Beestonian hiatus in the British biostratigraphic record (Gibbard *et al.*, 1991). The reliable, normal polarity results from the Moreton Member, the lowest gravel aggradation of the Sudbury Formation, at Drakes Farm and at Bradwell might thus have been acquired during the Jaramillo Sub-chron. This would imply a correlation of the Moreton Member with sediments of the Bavelian Stage (Zagwijn and de Jong, 1984). Alternatively, the normal polarities might have been acquired in the early Brunhes Chron, which would imply that the Kesgrave Formation was deposited during a much shorter time than suggested by Whiteman and Rose (1992). The Ardleigh Member, attributed to the younger, lower-level Colchester Formation, has been correlated (Whiteman and Rose, 1992; Gibbard, 1999) with the Cromerian Complex of the Netherlands. Reliable, normal polarity determinations from two beds within the Ardleigh Member (the upper gravel and the organic unit between the upper and lower gravels) are consistent with an early Brunhes age (i.e. late MIS 19 or younger). These results are consistent with normal polarity results from the Crag basin Cromerian sediments at the type site, West Runton (Ramshaw, 1992) and Cromerian sediments at Sugworth (cited in Thompson, 1991). They also match the normal polarities from the Kesgrave Formation at Caistor St Edmund (Ramshaw, 1992) and Little Oakley (Austin, 1990). Faunal evidence from the interglacial sediments of Little Oakley indicates it represents an interglacial younger than the West Runton type Cromerian, whilst Ardleigh is thought to represent another and possibly older interglacial (Preece and Parfitt, 2000). As always, caution must be exercised in interpreting apparent consistency between normal polarity results—unreliable results from Pleistocene sediments in East Anglia are characteristically of normal polarity, due to overprinting of primary NRMs during the present normal Chron. Normal polarity determinations need to be treated with scepticism unless there is firm, complementary evidence (as here) for their palaeomagnetic reliability. Nevertheless, the new and published palaeomagnetic data suggest that each of these Cromerian interglacial stages occurred during the Brunhes, and thus postdate mid-MIS 19.

Conclusions

1 Reliable palaeomagnetic directions have been obtained from eight Plio/Pleistocene sites in the East Anglian region. Data were judged reliable only when the stability, timing and process of remanence acquisition could be identified.
2 The reliable palaeomagnetic polarity determinations can be used, in combination with biostratigraphic data, in comparison with the GPTS, to ascribe correlations and absolute ages.
3 Reliable reversed polarities have been obtained from the lower sediments of the Ormesby borehole (pre-Ludhamian/Thurnian), from the College Farm Silty Clay at Great Blakenham (Antian) and from intertidal sediments at Sheringham (Pastonian).
4. The Kesgrave Formation presents difficulties in palaeomagnetic dating, due to the scarcity of fine-grained sediments within these gravel bodies. However, reliable normal polarity determinations from the Moreton Member indicate either a Jaramillo or Brunhes age for these higher-level Kesgrave sediments. Reliable normal polarity determinations from the lower-level Ardleigh Member, suggests a Brunhes age for these Cromerian Complex sediments.
5. Normal polarity magnetisations have also been reported for the type Cromerian sediments at West Runton, and at Sugworth in Oxfordshire, and for some other lower-level Kesgrave sites, including Caistor St Edmund and Little Oakley. These data suggest that the sediments representing at least three separate Cromerian interglacial stages were all deposited within the Brunhes normal Chron, and must therefore postdate mid-MIS 19.

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