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Sedimentation, geochemistry and palaeomagnetism of the West Runton Freshwater Bed, Norfolk, England

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A B S T R A C T

The sedimentary succession of the West Runton Freshwater Bed (WRFB) is described and interpreted. The sediments represent a fluvial valley floor accumulation that trends west- to east, subparallel to the modern cliffline. Stabilisation of the stream channels was initially followed by deposition of fine-grained silt in standing water, punctuated by intermittent flood events. Decreased flood intensity resulted in vertical accretion of fine-grained, organic, fossiliferous sediments in carbonate-rich spring water.

Increased organic deposition produced a transition to black detrital sediment. Periodic flooding continued, but flood frequency decreased in response to reduction in accommodation. Local erosion of channel banks and floors also occurred. The sediments were disturbed by water-release structures and bioturbation, the latter resulting from large mammals locally entering the channel and pools, churning the deposits during walking, bathing and so on. River-flow velocity diminished later as forest vegetation stabilised catchment and valley-floor ground surfaces. Stabilisation of the channel led to deposition from low-velocity flowing and standing water. The uppermost part of the succession indicates vertical accretion, sheet-like deposition. The organic silts were deposited in an anoxic environment, and organic sulphur from rotting organic matter allowed formation of early diagenetic sulphides.

Deposition began during the late-glacial (Beestonian Stage) and continued into the first half of a temperate-climate, interglacial event (the Cromerian Stage *s.s.*). The infill comprises an overall fining-upward sequence, the stream adopted a stable meandering pattern. The WRFB stream showed typical chalk-stream behaviour.

The magnetic polarity of the WRFB sediments is normal. The palaeomagnetic data indicates that the sediments are of Brunhes Chron age, and imply that they post-date mid-MIS 19.

1. Introduction

The West Runton Freshwater Bed (WRFB) forms part of the Cromer Forest-bed Formation (CFBF: Funnell and West, 1977; West, 1980; Gibbard and Zalasiewicz, 1988; Gibbard et al., 1991; Lewis, 1999) and is the stratotype of the Middle Pleistocene Cromerian Stage interglacial (*sensu stricto*: West, 1980). This richly fossiliferous unit of organic muds, silts and sands is exposed at beach level in the North Sea coastal cliffs at West Runton, North Norfolk (NGR: TG 201429 to TG 185433; Fig. 1). The constant and rapid cliff retreat has allowed exposure of the WRFB virtually continuously since at least its original description by Reid (1882, 1890) (Fig. 1). Later detailed description by West and Wilson (1966) demonstrated that at this locality the bed overlies estuarine and non-marine, fluvial sediments of Pastonian and Beestonian age respectively. It is overlain by estuarine sands and silts, niveofluvial sands and a substantial glacial diamicton unit, variously referred to as the Cromer Till, Cromer Diamicton or the Contorted Drift (North Sea Drift Formation). The latter is demonstrably of Anglian age (West, 1980; Gibbard and Zalasiewicz, 1988; Gibbard et al., 1991; Ehlers et al., 1991; Lewis, 1999; Pawley et al., 2008), although there has been some dissent from this view (e.g. Clark et al., 2004). Since the end of the nineteenth century the WRFB has been interpreted as representing the infilling of a freshwater (fluvial) channel complex that accumulated during a temperate period (Reid, 1882, 1890; West, 1980). Although this minor stream clearly formed part of the greater North Sea region drainage system, there is no evidence to connect it directly with any major rivers.

Detailed investigation following the initial report of West and Wilson (1966) led to a refined terminology of the sedimentary units

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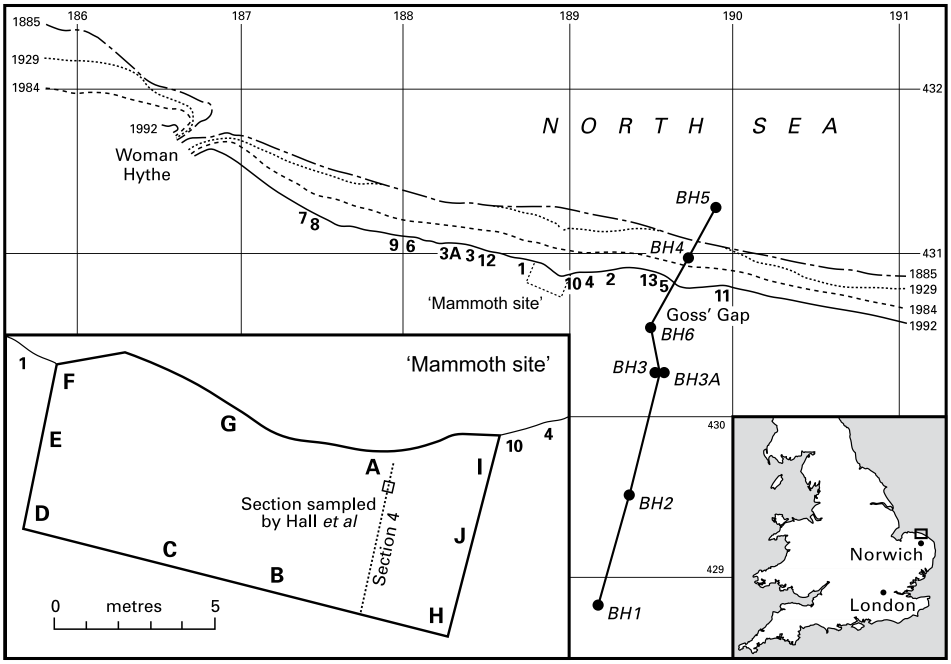

Fig. 1. Location of the West Runton cliff exposures. The logged profiles are indicated by the numbers and the Mammoth site is inset in the lower left-hand corner. Locations of the geological sections described from the Mammoth site are shown. Also shown are the boreholes BH 1-6 put down by Anglia Water and used to construct the section in Fig. 2. The position of the cliffline in 1885, 1929, 1984 and1992 indicates the on-going cliff recession. The divisions shown on the larger map are grid squares at 100 m intervals.

exposed in the West Runton cliff sections. In West and Wilson's (1966) fig. 2, the WRFB is labelled beds f and g. However, in the later, considerably more detailed report by West (1980, p. 17) the WRFB is subdivided into seven subunits labelled a (at the base) to g (at the top). In the current report, the authors assign their own divisional terminology, labelled i–vi, and correlate this with the nomenclature in West (1980) (*cf.* below).

Palaeontological investigations of the WRFB by West and co-workers (West, 1980; summarised in Gibbard and Zalasiewicz, 1988) have indicated that the basal calcareous sediments of the WRFB (beds a–b; West, 1980) yielded a floral assemblage of cold-climate character, referred to the Beestonian Stage. This assemblage, dominated throughout by non-tree pollen with Gramineae (Poaceae – grasses) and Cyperaceae (sedges), can be subdivided into a lower biozone with abundant *Artemisia* (mugwort) and Compositae Liguliflorae (Asteraceae), and an higher biozone, with increasing frequencies of *Betula* (birch) and *Pinus* (pine). Abundant plant macrofossils have also been recovered from both these biozones and indicate a mosaic of local habitats, including species of aquatic, marsh reedswamp, pond margin and dry ground, detailed in West (1980). The floral remains indicate a herb-rich grassland adjacent to a eutrophic pool. Climatic amelioration pre-dating the spread of forest that marks the beginning of the Cromerian temperate Stage (*sensu stricto*) may be recorded by an apparent increase in diversity of the aquatic and fen flora in the upper biozone.

The increase in tree pollen to over 50% of total land taxa marks the beginning of the Cromerian Stage. This is represented by the establishment of *Betula* (birch) and *Pinus* (pine) forest in beds b–d, the shelly sandy muds. The pre-temperate Substage Cr I can be subdivided into an early part with the former two tree taxa dominant, and a later phase in which *Betula* declines, *Pinus* becomes dominant and *Ulmus* (elm), *Picea* (spruce) and *Alnus* (alder) are established. Diversification of the thermophilous tree genera thus begins in Cr I. A rich assemblage of plant macrofossils has been recovered from these sediments and indicates the development of an extensive pool and marginal flora. By the latter part of Cr I areas of open ground or herb vegetation occur on the adjacent drier ground.

Mixed oak forest became fully established in Substage Cr II. It can be subdivided into two parts. In Cr IIa *Quercus* (oak) is substantially represented, with *Pinus* (pine) frequencies falling, *Alnus* (alder) levels rising and *Picea* (spruce) continuously present. Non-tree pollen levels decline, with Gramineae (grasses) remaining the most important element. Overall, this assemblage indicates thermophilous woodland, with the local persistence of open habitats. In Cr IIb the deposition of detritus mud, which forms the bulk of the Upper Freshwater Bed sequence (see below) occurred (West's, 1980; beds f–g). Here *Tilia* (lime) and *Corylus* (hazel) pollen are continuously present, and *Alnus* (alder), *Picea* (spruce) and *Pinus* (pine) remain common. Herbaceous plants continue to remain relatively rare, except for an increase in Chenopodiaceae towards the upper part, which may be associated with colonisation of the sediment surface as the channel became infilled (*cf.* Field and Peglar, submitted for publication). Macroscopic plant remains are abundant in the sediments, the most common taxa being those of fen and reedswamp helophytes and aquatics. Local fen-carr was also present (*cf.* Field and Peglar, submitted for publication).

In Britain, the cyclic pattern of interglacial vegetational development, that typifies all known temperate events, was developed as a means of subdividing, comparing and therefore characterising temperate events by West (1968) and Turner and West (1968). This scheme was based on pollen assemblages, in which temperate (interglacial) sequences are subdivided into four substages as follows: pre-temperate, early temperate, late temperate and post-temperate, abbreviated to I–IV respectively. Comparison with this scheme indicates that the WRFB represents the first half of the interglacial event, i.e. *ca.* 5–6 ka, together with an indeterminate period (potentially a few hundred years) representing the immediately preceding late-glacial time.

Although the sediments were described by West (1980), the excavations for the West Runton Mammoth finds in 1995 provided an important opportunity to re-examine the sediments systematically and provide an interpretation of their environment of deposition and history undertaken in conjunction with the multidisciplinary investigations associated with the excavation programme. This paper presents a detailed description of the sediments, their interpretation and their implications for the palaeontology and geological history of the unit. The descriptions are accompanied by summaries of the sediments' diagenetic history and their palaeomagnetic properties.

2. Depositional sequence

In 1995, when this work was undertaken, the WRFB was exposed for a length of 260 m along the foot of the cliff, above high water mark (*ca*. 3–4 m OD), east of Woman Hythe gap (Fig. 1). It was almost continuously exposed in these cliffs, apart from where it was locally covered intermittently by cliff collapse. Small exposures also occur 40 m west of Woman Hythe at two localities and were logged during this study. A series of boreholes, put down for Anglia Water (and kindly supplied by A.F. Howland Associates), shows the lateral continuity of the bed perpendicular to the current cliffline (Fig. 2). The borehole cross-section indicates that the broad stratigraphy seen in the cliffs extends inland for *ca*. 200 m but reveals little about the internal variability of the bed. It also demonstrates that the WRFB wedges-out *ca*.100 m inland from the cliff. On the basis of these observations and the extent of current exposure, the WRFB is sinuous in the W–E direction, and it has a generally valley floor-like, channel form both in transverse and longitudinal section.

The internal sedimentary stratigraphy of the WRFB was first recorded by Reid (1890) and more recently by West (1980). The latter author differentiated seven subunits within the WRFB (units a–g), the variation of which is illustrated in his fig. 6. The descriptions presented here represent the sequence as exposed in 1995 and are described first. They are then related to those of West (1980). The sequence recorded by SB and PLG is presented in two cross-sections (Figs. 3 and 4), which were constructed from a series of 18 vertical logs. The sedimentary fill is divided into six units (units i–vi) on the basis of the logged profiles. In reality these individual units all show lateral variation which reflect minor facies changes. These units were defined by sharp lithological boundaries and, in some cases erosional contacts. However, they should not be taken as strictly defined but serve the descriptive purpose.

The deposits comprising the WRFB rest conformably on gravels, sands and pebbly sands, also observed by West (1980). The surface of this unit varies irregularly in height with an amplitude of 2 m in the exposures, although further to the east it rises to 3.4 m OD where the WRFB lenses out (see below). The basal contact of the bed and its lowest units are frequently covered by modern beach sand and are therefore only occasionally exposed. The internal sequence of the WRFB itself is characterised by considerable lateral and vertical discontinuity of individual units. The sequence described below is a synthesis of the overall pattern. This study has recognised a greater variation in sediment lithology than previous research, principally because the authors saw new sections not available previously.

The basal sediments are restricted to the deepest part of the channel between Goss' Gap and *ca*. 20 m east of the Mammoth site, Sections 11 to 4. The deepest sediment recorded in profile 2 comprises indistinctly laminated calcareous yellow-grey clayey silt marl up to 25 cm (unit i) thick that rests conformably on the undulating orange gravel and sand surface (Fig. 5). This passes upwards into over 30 cm of fine wispy-bedded cream brown marly silt (unit i) which includes isolated plant remains, bivalve shells and small pellets of fine grey green silt. In turn, this is overlain by up to 50 cm of brown to grey brown conglomeratic organic silt (unit ii), the pellets in which are composed of the same sediment as that immediately underlying the unit. These pellets are rounded and are up to 10 cm in diameter (Figs. 5 and 6). They are associated with broken shell fragments, wood fragments and isolated pebbles. This unit is then truncated and overlain with a sharply defined contact by 36 cm of dark yellowish grey silt, rich in organic detritus, wood fragments and broken shells (unit iii). This unit also contains smaller-sized silt clasts up to 3 cm in diameter. Finally this unit grades upwards into dark brown, finely laminated organic silt

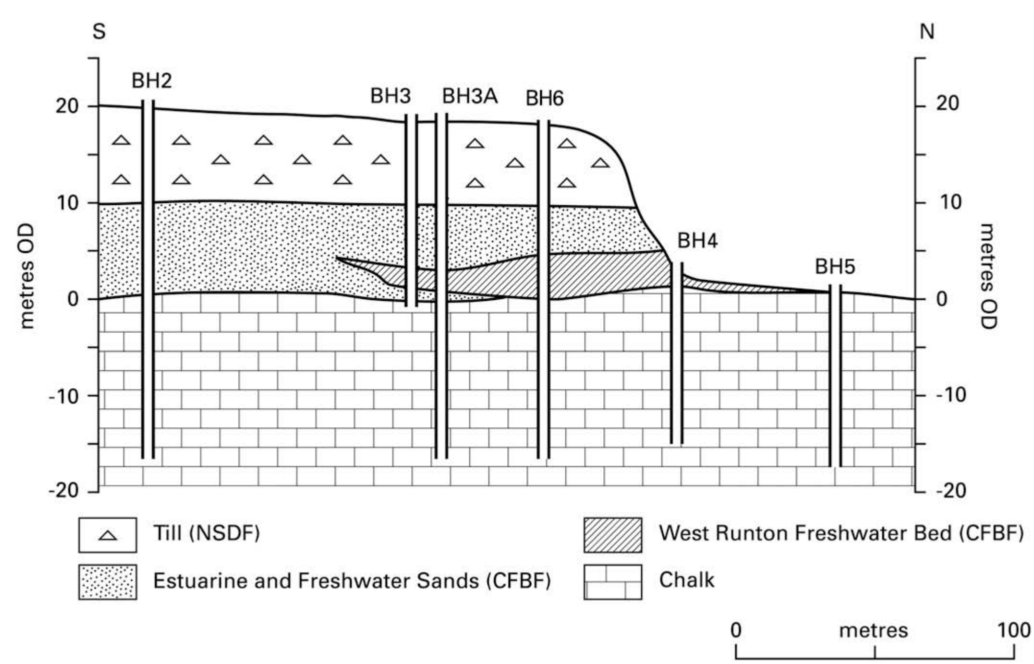

Fig. 2. Section constructed using the boreholes put down for Anglia Water and kindly supplied by A.F. Howland Associates. The sites of the boreholes are shown in Fig. 1. BH 1 is omitted. CFBF = Cromer Forest-bed Formation, NSDF = North Sea Drift Formation.

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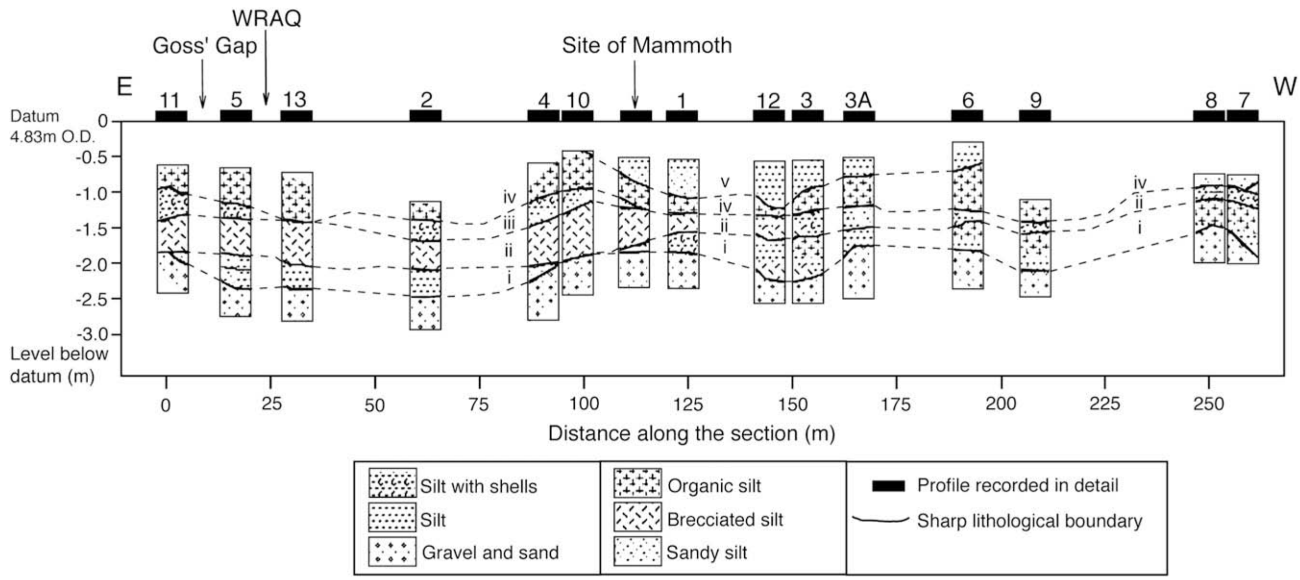

Fig. 3. Longitudinal section reconstructed from 15 logged profiles in August–November 1995, the position of which is indicated in Fig. 1. The profile for the Mammoth site sequences is a summary based on the main E–W stratigraphy of 3 adjacent logs (A, G, F). The relationship of the sequence at site WRAQ of West (1980) is also indicated.

18 cm thick (unit iv). This silt contains rare mollusc shells and wood fragments but the uppermost 10 cm, although indistinctly bedded, appears to lack fossils. The sediments are abruptly overlain by pebbly sand, the base of which is probably erosional.

West of the Mammoth site a comparable though internally considerably different sequence is present (e.g. profiles 3, 3A, 6: Fig. 5). Here the basal sediments are similar to those above but comprise 50 cm of orange medium to coarse sandy gravel, interbedded with laminae of up to 15 cm of brown organic silt containing plant fragments, small pebbles and shell fragments (units i–ii). This is abruptly overlain by dark brown organic silt that reaches 30 cm in thickness (unit iv). This stratum is extremely rich in shells, including whole, paired bivalves. Plant fragments are rare but wood and small pebbles up to 3 cm in diameter also occur. This unit is chaotically disturbed by load or turbation structures throughout, such that much of the indistinct bedding is aligned vertically or distorted laterally. Irregularly distributed throughout the exposure, and apparently closely related to the unit iii silts, is orange brown medium sand that is also greatly disrupted by loading and sediment injection (Fig. 6). This occurs as bodies up to 1.5 m in length and locally reaching 30–40 cm in thickness that are extremely rich in mollusc shell material. Resting on a truncated surface of this unit is a greenish brown clast-rich silt 25 cm thick (unit v), again containing abundant angular shell fragments, together with pieces of wood up to 10 cm long and occasional pebbles. This is abruptly overlain by finely bedded dark brown fossiliferous organic silt, 30 cm thick, containing much comminuted shell debris. It is succeeded by 20 cm of finely laminated creamy brown silt, which gives way to oxidised to reddish brown grey clay in the upper 13 cm.

Tracing the individual sediment bodies laterally, and allowing for variation in depositional facies, it is possible broadly to equate the units along the exposure, as shown in Fig. 3. From this it appears

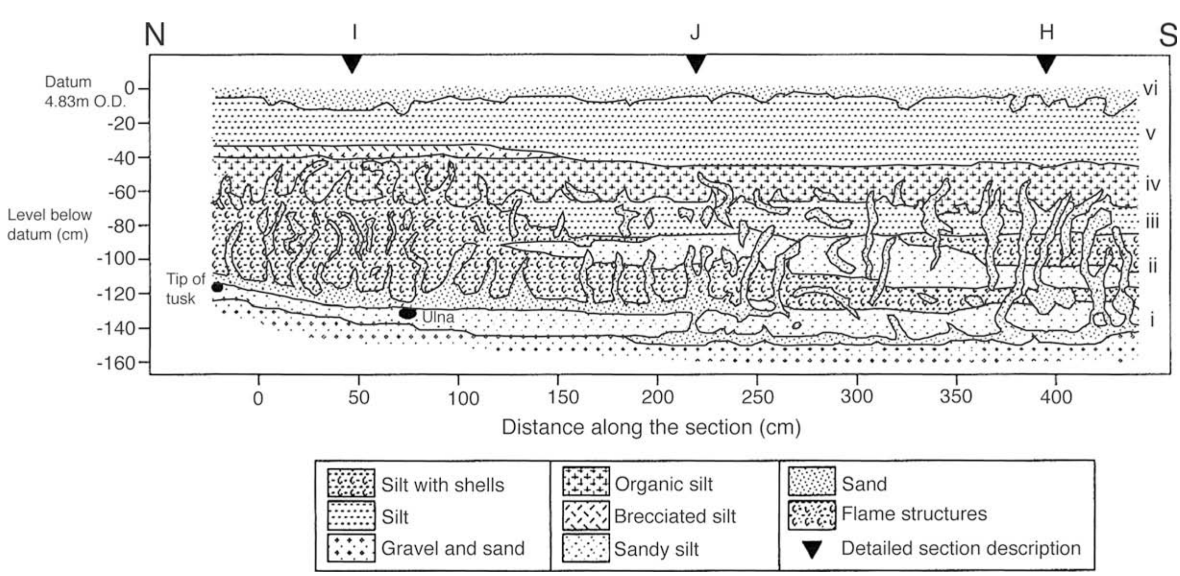

Fig. 4. Eastern-face section (profiles I, J, H) exposed in the Mammoth site excavations in November 1995 showing the detailed microstratigraphy and turbation structures. Unit sample datum at 0 m is 4.83 m OD.

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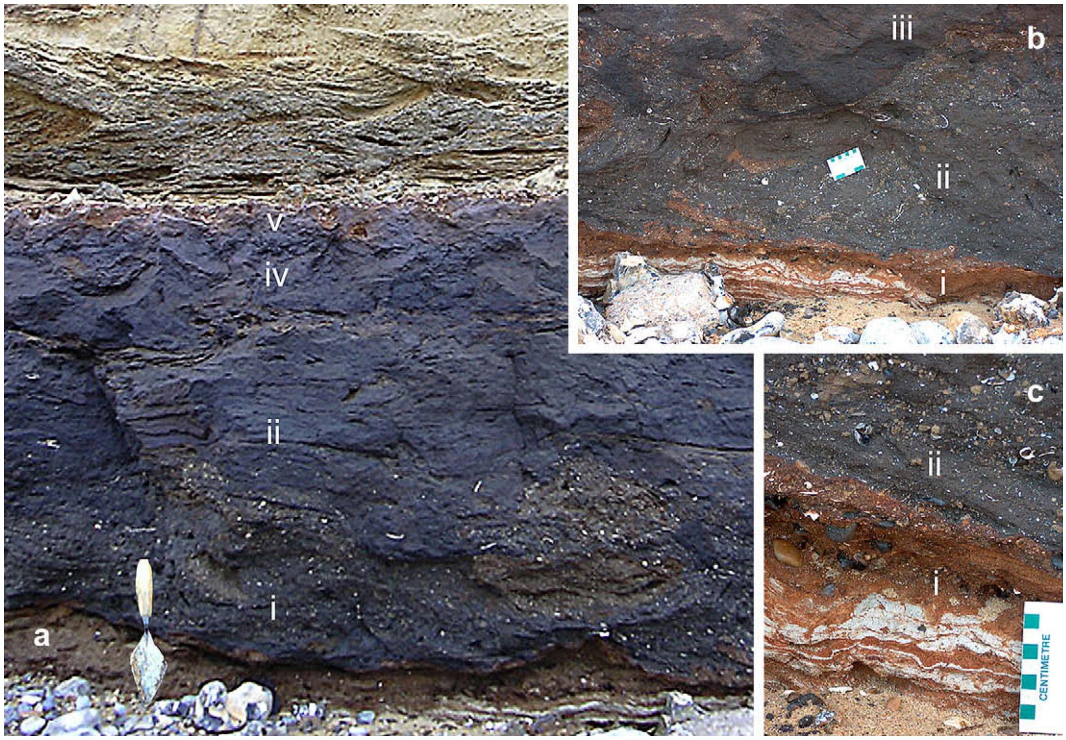

Fig. 5. The West Runton Freshwater Bed; (a) general view close to profile 3 showing the full thickness of the sequence at the site (units i, ii, iv and v) and the overlying sands, (b) basal part of the profile at site 2 (showing units i–iii) and (c) close-up of units i and ii at the same site.

that the earliest and lowest sediments of units i to ii are restricted to the eastern half of the fill, although they recur at 150 m at profiles 12 and 3a. The later fill of units iv to v thicken progressively further westwards such that the uppermost unit v is restricted to the western half of the sections. It is also in this area that the thin sand units and partings and also the substantial sand bodies occur. This further implies that the youngest sediments beginning with unit v are restricted to the area west of the Mammoth site.

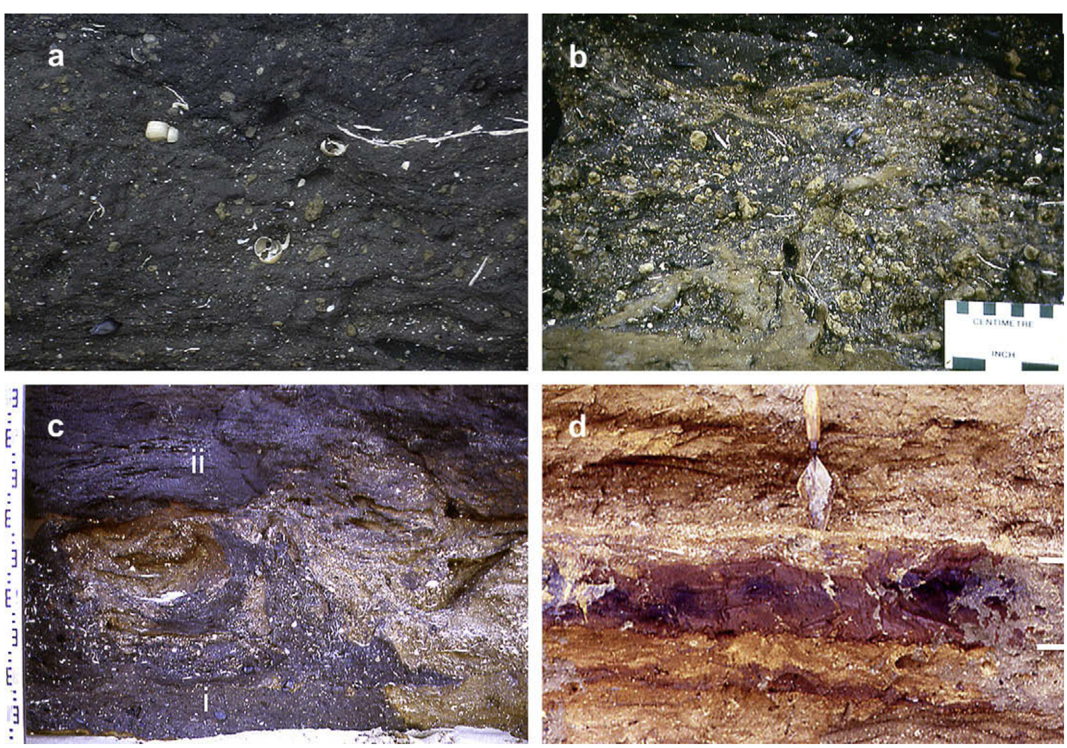

Fig. 6. The West Runton Freshwater Bed; (a) detail of brecciated silt with silt pellets and mollusc shells from unit ii at section (profile) 10; (b) brecciated silt with silt pellets from unit i showing disturbance and 'flame-structures' at section (profile) 12; (c) general view of basal part at section (profile) 1 showing 'ball and pillow'-like disturbance of shelly silts (unit i), overlain by unit ii; (d) unit v (indurated iron-cemented clayey silt – between horizontal lines) in an exposure 40 m east of Goss' Gap, showing sediments resting on an elevated surface of the underlying gravels.

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Throughout the exposure the units are disturbed by syndepositional loading and turbation structures. These structures vary in scale from a few centimetres to 40 cm in diameter. They take the form of load casts, flame structures and, in the case of the sand bodies which are particularly concentrated in the western part of the exposure from *ca*. 80 m (Fig. 6b, c) in the lower half of the sections. They occur as lenticular ball- or pillow-shaped bodies of medium sand containing abundant molluscan shells within the silts. These bodies vary considerably in diameter but may reach 1.5 m in lateral extent and 40–50 cm vertically. They rest in the silts, which are distorted about them, the silts forming flame-like upward protrusions between the sand bodies. The sands within the bodies show remnant bedding of current origin, but current directions could not be measured from these structures. These bodies were avoided when the sections were logged because of the disruption of the sequence associated with them.

The form of wood fragments in the sediments throughout the exposure consistently indicates compression and compaction of the sequence as a whole. Examination of samples of wood demonstrates an approximate 3:1 vertical compression of wood fragments that are from a few millimetres to over 15 cm in cross-section. When this occurred is difficult to determine but it is probably post-depositional, presumably relating to compactional dewatering.

3. Mammoth site succession

The sequence at the Mammoth site was recorded in detail at 10 separate profiles (A–J: Fig. 1), less than 5 m apart in each case, and the detailed logs were linked by field sketches of the stratigraphy. These sections show broadly the same unit divisions as described above. A detailed section drawn from the exposed eastern face is shown in Fig. 4. This section is located 3 m east of a parallel profile ('Section 4') that was sampled by other investigators for palaeontological analyses (by A.J. Stuart, A.R. Hall and D.H. Keen). The stratigraphy in this profile was recorded by the Norfolk Archaeological Unit.

Here the base of the WRFB was encountered at −1.60 m below the survey datum. Once again the surface of basal gravel and sands was very irregular, rising to 20 cm higher towards the northern end of the exposure. The gravels are overlain in the southern side of the excavation by over 22 cm of pebbly medium sand with wood fragments. This bed lenses out towards the north and is replaced by highly brecciated olive brown to black silt (unit i; 30 cm thick) with occasional light grey silt pellets, rare wood fragments and a few broken shell fragments that occurs across the entire section. This passes upwards into 50 cm of dark brown silt with fine stringers throughout where occasional brecciated fragments of chalk, silt, wood and abundant shell fragments occur (unit ii). This unit ii is not identical to that recorded in the longitudinal section (Fig. 3), and in the sampled 'Section 4' (*cf*. above: Fig. 7) the silt with brecciated silt pellets appears to underlie and have been eroded before emplacement of the overlying sediment present as unit ii in the eastern section. This is, in turn, overlain by grey medium sand 30 cm thick containing abundant plant and animal fossil fragments together with grey brown silt pellets. This unit is truncated by a sharp junction upon which 15 cm of fossiliferous black to very dark brown sandy silt occurs (unit iii). This is followed by 60 cm of very sandy light grey silt (unit iv), including several sand laminae, which passes upwards into dark brown, fossiliferous finely stratified silt, with occasional ripple-like structures in the uppermost 10 cm. This unit grades upwards into mottled grey-brown clay (unit v), locally containing oxidised aureoles up to 20 cm in diameter. In turn, this passes into 18 cm of highly indurated iron-cemented clayey silt (unit vi) the uppermost surface of which is penetrated by numerous small holes to a depth of a few centimetres, infilled by overlying sandy gravel. These holes appear to be borings of marine Mollusca, as they occasionally contain intact bivalve shells of *Mya* in life position.

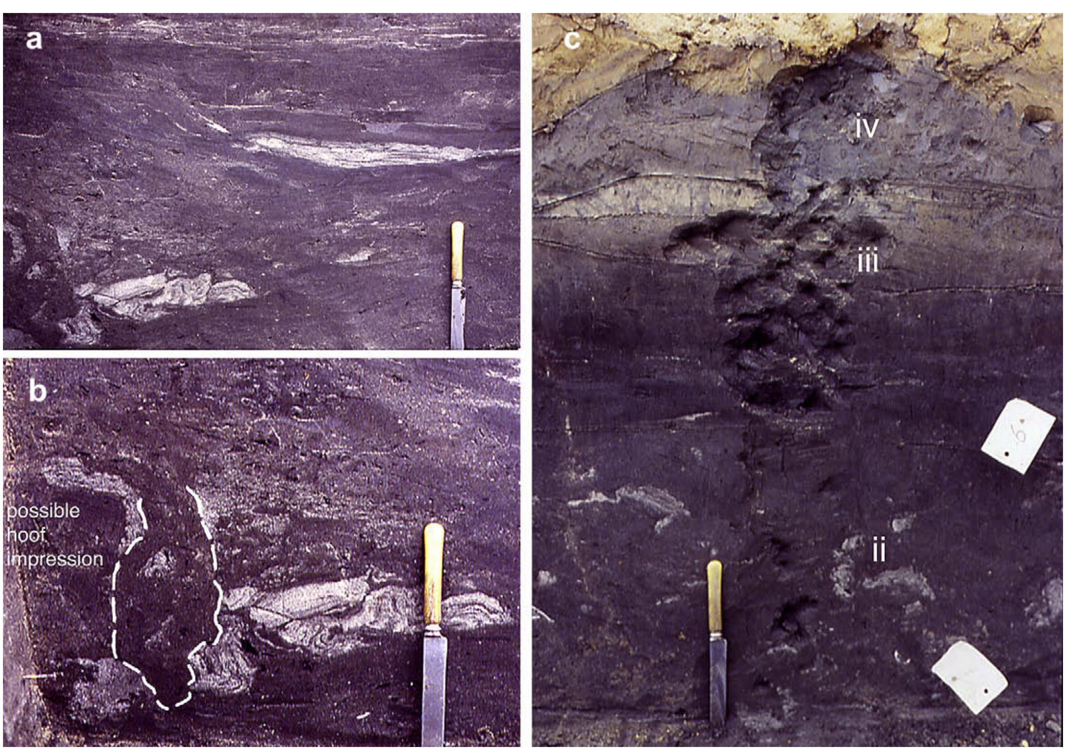

Fig. 7. The West Runton Freshwater Bed; Mammoth site (a) and (b) sequence exposed on the backwall of the excavation adjacent to section H, showing small-scale channel-like form resting on disturbed silt and sandy silt (unit ii) (a), and vertical injection structure and associated possible hoof impression (b); (c) general view of the stratigraphy on the southern half of 'Section 4', opposite site J showing units ii–iv.

Throughout the Mammoth site exposure, but particularly in the basal half of the section, the deposits are highly disturbed and contorted (especially units ii–iii), with sediment from below being injected upwards into overlying lithologies. These flame-like injections cause material from lower in the sequence to be incorporated in the higher, younger units. The structures vary in size and in distribution, some are very small, just a few centimetres in length or breadth, yet others are up to 50 cm long; some occur within individual sedimentary units and disturb only a few laminae, while others penetrate much of the lower part of the sequence. That these structures are syndepositional is indicated by the fact that the overlying units are undisturbed and therefore must have accumulated subsequent to the disturbances that triggered the contortion. Moreover, the contortions are polycyclic since some, from the lower parts of the sequence have been disturbed by structures higher in the deposits. However, not all the structures are injections from beneath. Frequently downward vertically or sub-vertically aligned injection structures that have carried sediments downwards also occur. Two examples have been recorded in dark brown silts of unit vi, one in particular was observed adjacent to profile H in the Mammoth excavations (Fig. 7a and b). Here, downturned laminar structures appear to occur intimately associated with an infilled 20 cm deep cylindrical injection 7.5 cm in diameter. In addition, adjacent to and intimately related to the mammoth skeleton, there is considerable disturbance of the stratification, the skeletal elements resting in the basal sediment units i–ii. In particular, an horizontal, elongate lens-like injection, 10–15 cm high, of sand was present immediately beneath the skeleton, implying injection of sediment from beneath by loading and water-release.

Comparison of the sequence described above with that observed and recorded by West (1980) from sections since removed by coastal erosion indicates a marked consistency of sequence. The basal sediments are rarely seen but the lowest deposit (bed a of West, 1980) is thickest in the area of West's (1980) WRAQ profile (intermediate between profiles 5 and 13 in this study, i.e. at point *ca*. 25 m in Fig. 1). Here he described (p. 17) the basal sediment as "light brown, stiff, sandy, calcareous [silt-rich] detritus mud with shells at the eastern end of the exposure to a yellow-light grey marl with shells at the west end". This deposit reached a maximum thickness of 90 cm at WRAQ and has an irregular surface on which the later deposits lie unconformably. These deposits are internally very variable and are laminated in places, e.g. 40 m west of Goss' Gap. They are overlain by 5–7 cm of brown stony mud, more clayey towards the east (West's bed b). In turn, this is overlain by an internally vary variable shelly sand which included single-clast thick gravel or grey silt or clay laminae. The deposits are unconformably overlain by dark grey conglomeratic organic silt that varies in thickness laterally. It contains clasts of silt and clay, up to 10 cm in diameter, that closely resemble the sediments immediately beneath. In places, they decrease in diameter upwards. It also contains isolated pebbles, molluscan shell fragments and small pieces of wood. The brecciated silts can be traced along the outcrop (Fig. 6) but they vary considerably internally in their contents and detailed composition.

Overlying the silts, and its contained sand bodies, is 30–50 cm of dark grey-yellowish dark grey organic silt, rich in organic material, plant remains and wood fragments, abundant shell fragments and isolated complete shells. A diffuse gradational junction separates this unit from the overlying unit, which is a very dark brown to blackish brown finely laminate silt which only very rarely contains molluscan shells but includes some plant fragments. The uppermost 10 cm or so of this unit is oxidised reddish brown silt which lacks plant macrofossil material.

At the eastern end of the exposure, 40 m east of Goss' Gap, the sediments thin markedly coming to rest on the elevated surface of the underlying gravels (Fig. 6d). Here the sediments are only 15 cm thick and oxidised, and comprise highly indurated iron-cemented clayey silt (unit vi). The uppermost surface of this bed is irregular and potholed to a depth of a few centimetres, the potholes being infilled by overlying sandy gravel, very similar to the uppermost unit seen in the Mammoth section. The sediments are cut-out completely further to the east.

The relationship of the units identified here to those previously described by West (1980, Fig. 6) needs to be attempted. The nature of the sequence, with its indistinct, laterally discontinuous lithologies makes this difficult. However, the following correlation is suggested:

West (1980; p.17)	this study
f, g	iv, v, vi
e	iii
d	ii
a, b, c	i

4. Diagenesis of the WRFB: pedogenesis or groundwater alteration?

Chemical analysis of the WRFB sequence (Bottrell et al., 1998) was undertaken to elucidate with its diagenetic history. The carbon and sulphur geochemistry of the unit is a product of early diagenesis in a freshwater environment (*cf.* Brough and Andrews, 2008), overprinted by the effects of later sulphur remobilisation. The latter probably occurred during leaching of the upper part of the bed by oxic groundwater transforming greigite to lepidocrocite and haematite/goethite and forming a pronounced concentration of reprecipitated greigite below this. In the lower 50 cm of the bed, conditions remained reducing and apparently unaffected by diagenetic modification.

The upper 20–30 cm of the WRFB is clearly a paler grey colour compared to lower units in the bed. This change in colour is caused by a lower organic carbon content (<1.8 wt% organic carbon) compared to that lower in the bed (typically between 5 and 10 wt% organic carbon), and more significantly, a total lack of iron sulphides (Hannam et al., 1996) which are present lower in the bed. Moreover, weathered surfaces show clear evidence of both red staining from iron oxides (West, 1980; Hannam et al., 1996), yellow staining from the presence of elemental sulphur, and selenitic gypsum crystals. This part of the bed is also devoid of calcareous fossils, vertebrate remains and Coleoptera (Hannam et al., 1996; Preece and Parfitt, 2000; Coope, 2000).

Taken together, these attributes all demonstrate that the upper part of the WRFB has been heavily oxidised and leached of calcium carbonate. A combination of geochemical and palaeomagnetic data (Hannam et al., 1996; Bottrell et al., 1998) has shown clearly that the depositional sulphides (probably greigite) in the upper part of the bed have been oxidised to lepidocrocite and haematite and/or goethite. Downwardly-diffused soluble sulphate from sulphide oxidation, was re-mineralized lower in the WRFB by sulphate reduction to form a reprecipitated (diagenetic phase) of greigite which has a distinctive, isotopically negative, sulphur isotope composition and high natural remanent magnetism (Bottrell et al., 1998). Sulphide oxidation generates acidity which explains why the upper part of the WRFB contains no calcareous macrofossils, explains the formation of gypsum crystals (Hannam et al., 1996) and why organic fossils such as beetles are not preserved. Sulphide oxidation also explains why weathered surfaces show evidence of elemental sulphur and iron-oxide staining.

The alteration of the upper part of the WRFB could have occurred in a subaerial setting associated with soil formation. Indeed, Stuart (1991), articulating a widely thought though unpublished view, suggested this, the implication being that

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oxidation was associated with pedogenesis. However, there is no positive evidence to suggest that the top surface of the WRFB represents all or part of a fossil soil. There is no visible horizonisation at outcrop and thin sections from undisturbed, resin-impregnated samples show no evidence of soil micromorphology (Hannam et al., 1996; Brough and Andrews, 2008). Neither is the clay mineralogy in the upper part of the bed distinctly different to that lower down (Hannam et al., 1996). It is possible that the rather planar upper surface of the WRFB represents an erosion surface (Preece and Parfitt, 2000; Davies et al., 2000). If this is accepted then it could be argued that a former soil horizon has been mostly eroded leaving only an altered lower part that shows few soil-zone features. However an equally valid and simpler interpretation is that the upper part of the WRFB has been leached and oxidised by post-depositional groundwater flow (Bottrell et al., 1998), when advecting groundwater in the overlying sandy sediments encountered the upper part of the rather impermeable WRFB: the bed acted as a local-scale aquitard, forming a perched water table in the sands above it. It is not possible to be certain when this happened, although it is highly likely that active groundwater circulation was promoted by melting of local ice sheets in the north Norfolk area.

5. Sediment magnetic properties

Site excavations during recovery of the West Runton mammoth skeleton enabled palaeomagnetic sampling of a freshly exposed vertical sediment section (‘Section 4’; Fig. 1), with orientated samples taken at 2.2 cm intervals from 0 to 110 cm depth. To preclude any post-sampling oxidation of the sediments, the samples were stored in airtight containers at 6 °C, and their natural remanent magnetisation (NRM) directions and intensity measured within days. To assess any down-section changes in the sediment magnetic properties, measurements were also made of room temperature magnetic susceptibility, changes in magnetic susceptibility with incremental heating, and room temperature acquisition of magnetic remanence in applied dc fields of 100, 300 and, for the ‘saturation’ remanence (SIRM), 1000 milliTesla (mT).

Through the entire section, all NRMs were of normal magnetic polarity, with all but two samples retaining this polarity upon pilot af demagnetisation at steps of 15, 20 and 40 mT. However, the magnetic mineralogy of the WRFB sediments shows marked variations between the upper ~30 cm and the lower portion of the sequence. The upper layer (unit vi) displays very low values of NRM intensity (~0.05 mA m^{-1}), in contrast to the black (unoxidised) layer (units iv–v) immediately beneath, with much higher NRM intensity, up to ~130 mA m^{-1} (Fig. 8). This black layer also displays the highest values of magnetic susceptibility (~25×10^{-10} m^3). Between ~35 and 50 cm, values of NRM intensity decline rapidly, before stabilising, at ~5–10 mA m^{-1}, for the interval from ~55 to 95 cm depth, where a subsidiary NRM intensity peak occurs.

The upper ~30 cm is also distinguished by its relative magnetic ‘hardness’; at the relatively high applied field of 300 mT, it has acquired only ~77–87 % of its total SIRM, in contrast to the sediments below this depth, which acquire ~98–99.5 % of their SIRM at this field. The upper 30 cm thus contains significantly higher concentrations of weakly magnetic minerals, such as goethite and/or haematite, compared with the ‘softer’, ferrimagnetic behaviour of the underlying sediments. Further magnetic contrast is evident from variations in the SIRM/magnetic susceptibility ratio down the section. The upper oxidised layer is characterised by relatively low values (~1 kA m^{-1}), the underlying layer with the NRM intensity peak displaying high values (~50 kA m^{-1}) and the lower section intermediate values (~20 kA m^{-1}). High values of this ratio are indicative of the presence of the ferrimagnetic iron sulphide, greigite (cf. above, e.g. Snowball and Thompson, 1990). The presence of

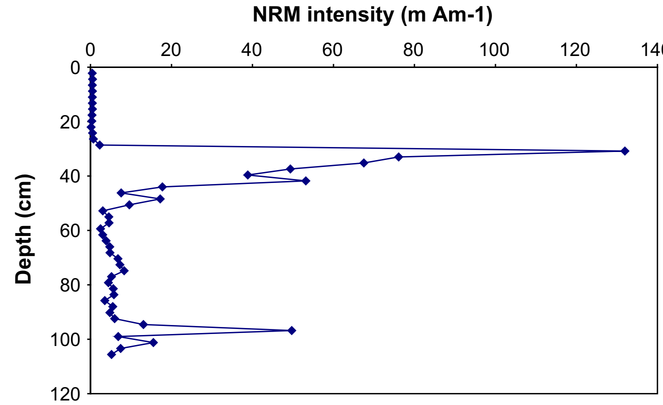

Fig. 8. Plot of Natural Remanent Magnetism (NRM) against depth for the WRFB at ‘Section 4’ (Fig. 1).

greigite can be confirmed by monitoring sample magnetic susceptibility upon heating; it is unstable in air and undergoes a major decrease in magnetisation between 250 and 350 °C (Roberts and Turner, 1993). Thermomagnetic analysis for a sample from the upper reddened layer shows increasing susceptibility values at temperatures ~250 °C, indicative of the thermal transformation of the weakly magnetic iron oxyhydroxide, lepidocrocite, to strongly magnetic magnetite (Van der Marel, 1951). In contrast, the black, strongly magnetic layer shows a major fall in susceptibility, from ~200 °C, characteristic of greigite oxidation.

Thus, the magnetic properties of the upper ~30 cm of the WRFB sediments (unit vi) indicate the presence of rather low concentrations of any ferrimagnetic minerals, and significant concentrations of the weakly magnetic, remanence-carrying minerals, haematite and/or goethite, together with the non-remanence-bearing oxyhydroxide, lepidocrocite. The sediment immediately underlying this layer contains peak concentrations of the ferrimagnetic iron sulphide, greigite, which then decline in concentration with depth reaching fairly stable levels within the interval ~55–95 cm depth (units iv–v), before a second, lower peak at ~95–100 cm depth (unit iii).

6. Succession interpretation

On the basis of these observations, supported by the pre-existing stratigraphical and environmental evidence noted above, the sedimentary sequence can be interpreted. The form and sediment infill indicates that the sediments represent a fluvially dominated valley floor fill, the overall width of which was at least 100 m. The stream valley trends generally in a west- to eastwards direction subparallel to the modern cliffline. The relationship of the fill indicates that the valley floor was bounded by highs of pre-existing gravel and sand, such as that seen east of Goss’ Gap. Comparison with lowland river valley fills in southern England implies that these gravel highs represent a stream braidplain morphology inherited from a pre-existing cold-climate stream.

Stabilisation of the gravel surface was initially followed by accumulation of silts interbedded with sands and pebbly sands indicating a marked decrease in flow with fine-grained silt deposited in standing water, punctuated by intermittent flood events that brought coarser detritus into the depressions. The latter is indicated by the interbedding of sand and pebbly sand bands. Continued decrease in flood intensity led to deposition of fine-grained marly silt which occurred by vertical accretion of fine-grained, organic, fossiliferous sediments that began in the braidplain depression(s) or in abandoned channels. The marly silt (unit i) was deposited in pools within partially abandoned channel(s), together with some dispersed plant fragments, wood, terrestrial and aquatic molluscs and vertebrate remains. The predominance of these basal marls implies that the stream was fed by carbonate-rich spring water. Holocene analogues (cf. Gibbard and Lewin, 2002; below) suggest that the transition from predominantly flowing to standing water facies occurred rapidly. This occurred under mild-climatic conditions (Preece, submitted for publication).

Subsequently, as a consequence of plant colonisation of the surrounding slope and drier floodplain areas, stagnation of the pool(s) occurred by accumulation of plant debris. This increase in organic matter produced a transition to black humus-rich detrital sediment (units ii–iii). During this phase, periodic flooding continued to affect the channel, represented by the sand beds or laminae rich in shell material. The frequency of occurrence of these sand units decreases upwards in response to progressive reduction in accommodation. Local erosion of channel banks and floors is also represented by diamictons of silty marl pellets in the detrital silts. These pellets closely resemble the basal sediment (unit i). This influx reworked the underlying marl to produce silty marl pellets or balls, recycling of sediment and associated biological materials, indicating that locally, and probably intermittently, erosion occurred probably during flood events. The sediments were also disturbed by water-release structures and bioturbation, the latter resulting from large mammals locally entering the channel and pools, loading and churning the deposits during walking, bathing and related activities.

Continued river-flow variability became diminished later in units iii–v as the soil-vegetation system stabilised ground surfaces and delayed and reduced the flood response. This no doubt reflects the establishment of a fully forested catchment vegetation cover. Throughout this period the stream potentially continued to flow relatively slowly all year round, except following severe storms when flood events occurred, but standing water and even partial drying-out of slightly higher areas within in the channel occurred from time to time. At this point therefore the channel was stabilised, and only minor deposition predominated representing low-velocity flowing water, and indeed standing water, indicated by the fine-grained silt-dominated deposits very rich in plant detritus. The high biotic productivity, dense vegetation cover and lack of channel erosion combined to yield only organic detritus, accompanied by virtually no inorganic detritus, except for very rare pebbles possibly introduced on the roots of floating plant detritus.

Progressive infilling of the channel occurred in silt-dominated pools (unit v–vi), the silt introduced by low velocity flowing water during flood periods. The virtual absence of fast-flowing water deposits indicates that vertical accretion dominated the entire system with infill of the remaining inherited depressions and pools by detrital or marsh/fen sediment in the moist floodplain woodland environment. The organic silts were deposited in an anoxic environment and organic sulphur from rotting organic matter allowed formation of early diagenetic sulphides (greigite) (Bottrell et al., 1998). It is likely the rotting organic matter also produced methane but no record of this is found in carbon isotopes in the shells of calcareous fossils (Davies et al., 2000). Eventually the channel infilled completely, the overall fining-upward infill sequence reflecting a progressive reduction in accommodation. Comparison of this sedimentation pattern with those of Holocene valley analogues indicates that the sequence reflects very low sediment production during high biotic productivity, occurring during the Holocene climatic optimum. In these situations, inorganic sedimentation, such as that found earlier in the sequence (units ii–iii), probably only occurred as a result of storm floods or beaver-dam bursts, e.g. Gao et al. (2000), Gao (1997, 2006). However, inorganic material could also have entered the channel in situations where large vertebrates gathered to drink; their activities leading to bank and the local floodplain woodland destruction, and the establishment of grass- or herb-dominated clearings.

Overall, therefore, the channel-like sediment body represents the infilling of a valley floor environment during a temperate or interglacial climatic event beginning in the immediately preceding late-glacial period, potentially *ca.* 5–6 ka overall (*cf.* above). No evidence of a discrete, predominantly flowing channel(s) is found, although hiatuses and minor erosion surfaces can be traced along the section (Figs. 5a, 6c, 7a). Although these structures could represent local erosional events, the general absence of truncated horizons implies that they more probably represent sites where non-deposition occurred for intervals. Nevertheless, the sequence appears to have been punctuated by influxes of high-energy floods during the first half of the period represented but they became progressively more limited until they ceased to occur in the second half of the infill (*cf.* also Preece, submitted for publication). This succession of events reflects that typically expected where accommodation decreases as the channel depression infilled with time. The infill comprises an overall fining-upward sequence, and the stream therefore adopted a stable meandering pattern that typifies those seen in southern British rivers in the Holocene (Brown et al., 1994; Brown, 1995, 1996; Brown and Quine, 1999).

The pattern of distribution of the sediments implies that the sequential development began, as might be expected, in the deepest area which in these sections was that east of the Mammoth site. Progressive, intermittent infill continued by vertical accretion with the depocentre migrating through the time represented to finish in the area immediately west of the Mammoth site, although these sediments were deposited across the whole channel/valley floor in a sheet-like form. The deposition apparently terminated by the complete infill of the depression, i.e. accommodation space was filled. Later erosion of the upper surface before emplacement of the overlying pebbly sands may have removed any later deposits, or possibly a fossil soil, that might have developed on the channel sediments. There is no evidence of change in base-level (sea-level rise) effecting the deposition.

Comparison of the sediment succession described with the pollen sequence determined by West (1980) matches very favourably, and indeed supports the observation that the depocentre changed with time. The deepest, and therefore the earliest sediments in the area east of the Mammoth site, were analysed by West (1980; his fig. 6) at the WRAQ, WRCGB (29 m east of WRAQ) and WRAR (59 m east of WRAQ) sites. These sequences span respectively the late Beestonian to Cromerian Cr IIa substages (WRAQ; the basal 35–90 cm being equivalent to units i–ii in the present study), CR Ia–IIb (WRCGB) and the more marginal WRAR profile having accumulated during CR II (this study units iv–v). West of the Mammoth site, the sequence was not analysed in detail for palaeontology, but at site WRBX the uppermost 5 cm of sediment (units iv–v of this study) is equivalent to Cr IIb.

Post-depositional compaction of the sediment sequence is indicated by the compressed form of the wood fragments in the deposits, especially in the organic-rich units vi–v.

7. Interpretation based on Holocene analogues

The general pattern of interglacial fluvial sedimentation in lowland Britain was recently reviewed by Gibbard and Lewin (2002). The interpretations of the WRFB sequence can be assessed and extended by comparison of this pattern with Holocene analogues.

As noted above, the West Runton sequence records the stabilisation of gravelly channels inherited from the immediately preceding cold phase followed by progressively decreased discharge accompanied by vertical floodplain aggradation by accumulation of fine, organic-dominated sediments. This concept of inheritance of channel pattern has been noted consistently in the early Holocene of southern Britain by Brown et al. (1994) and Gibbard (1985, 1989). Adjustment of the rivers to major climate changes, such as that from the late-glacial into an interglacial as at West Runton, demonstrably results in a 'lag' between a climatic event and the fluvial response. This occurs because rivers broadly had insufficient energy to transport gravel and alter gross channel form and distribution. Fluvial channel pattern transformation from relatively unstable braided or gravel-bed to stable meandering form, under conditions of relatively low, fine sediment input, took extended time periods. This transitional sequence is assigned to floodplain phase Fph i in the scheme of Gibbard and Lewin (2002). At the beginning of the Holocene, rivers apparently took at least 500 years to restore equilibrium following the rapid climate amelioration. This was followed by a pattern of flow dominated by little or no active meandering.

This pattern of fluvial response to Pleistocene climate amelioration explains why sediments are laid down early in interglacials. At the beginning of an interglacial, surface irregularities and channels are inherited from the immediately preceding cold-stage stream. These topographic complexities form a mosaic of 'accommodation space' in which deposition can occur, protected from the main river flow. This process leads to the complete burial of the pre-existing gravel river braidplain microrelief by fine, organic-rich floodplain sediments. This depositional pattern is included in Gibbard and Lewin's (2002) floodplain phase Fph ii.

Brown (1995) quoted a possible analogue for the later interglacial accumulation at West Runton that is characterised by a stable interconnecting channel pattern, small diamond-shaped islands, adjacent channels with different bed and flow conditions, much slack-water at medium and high flow, floodplain scour often related to vegetation, debris dams and the silting-up infill of abandoned channels. Where shifts in flow channel take place, they principally occur by avulsion into neighbouring depressions.

As accumulation continued across the valley floor, floodplain surfaces were levelled and raised but not deeply buried by vertically accreted overbank sediments as a consequence of the very limited inorganic debris load of the stream. A progressive transition from a channelised to an increasingly sheet-like depositional process is seen through the upper part of the sequence. Sedimentation ceased with flow possibly limited to a channel not seen in the current exposures.

On the basis of the observations it appears that the WRFB stream showed typical chalk-stream behaviour, i.e. low sediment load, occasional flooding, low-energy discharge and periodic drying-out of higher areas of the floodplain (Sear et al., 1999). Chalk streams are typically predominantly spring (or groundwater)-fed, so that apart from occasional flood events triggered by storms, normal flow is low energy, with an annual peak flow in early spring and lowest flow in autumn, followed by 6 months of aquifer recharge during which no flooding occurs.

Judging from compilations of Holocene alluviation in lowland Britain (e.g. Macklin and Lewin, 1993; Macklin, 1999), the early Holocene (Substage Fl I) was a period of relative stability with slow sedimentation (*cf.* Rose et al., 1980; Bell and Walker, 1992). This was followed by an apparent hiatus of around 1000 years at *ca.* 6.0 ka BP (early Substage Fl II). Alluviation throughout the region resumed shortly after 5.5 ka BP (Macklin, 1999) in the climatic optimum (the second half of Substage Fl II: *sensu* Gibbard and Lewin, 2002). Whilst the detailed pattern of alluviation will inevitably vary from event to event, dependent upon the individual conditions that prevailed at the time, overall it appears that slow sedimentation might be expected throughout the first half of a temperate period, such as that represented by the WRFB. This conclusion reinforces West's (1980) opinion that the WRFB represents slow sedimentation in terms that the unit spans the first half of the interglacial period, yet apparently individual events within the sequence indicate rapid sedimentation, e.g. the sands in units ii–iii. The latter represent flood events that punctuate the standing-water pool or local non-depositional or erosional conditions that occurred throughout much of the first half of the sequence.

8. Taphonomic implications

Initial accumulation of marly silt at the base in standing water calcareous-rich pools was accompanied by periodic influxes of fast-flowing water during floods (unit i–ii). This flow reworked the marly silt to produce the ball-like silt clasts or pellets derived, in part, from units that were not necessarily represented in the modern sections, i.e. they were probably derived from upstream, and were deposited in eutrophic organic silty mud sediment (also noted by West, 1980). This reworking of fine-grained cohesive sediment during flood events indicates the apparent lack of relatively coarse inorganic particulate material to the stream. This is further evidence that the catchment surfaces had by this time (the Beestonian late-glacial to earliest Cromerian) been stabilised by vegetation such that only local floodplain sediments and associated biological detritus were available for reworking and inwash.

The very slow moving to standing water during the non-flood periods provided pools for aquatic plants and animals to flourish, although periodic higher-energy water flow reworked the underlying sediment and organic materials, particularly in the basal half of the sequence (units ii–iii). These influxes transported and distributed shells, wood, vertebrate skeletal material, insect and macroscopic plant detritus. Inwashed sediment and especially plant and animal detritus could potentially 'blur' the palaeontological interpretation of the sequence.

Macroscale synsedimentary disturbance by water-release structures and bioturbation is particularly common in the lower half of the fill, especially in units ii–iii. Although some of these structures resulted from differential loading leading to natural water-release, of particular significance are the bioturbation structures that apparently resulted from large animals entering the channel to drink, bathe, feed, etc. The repeated impact of their feet in the water-saturated mud or silt-dominated sediments was probably the predominant process by which the bioturbation occurred. Indeed the recognition of unequivocal hoof or foot impressions, such as that adjacent to point H at the Mammoth site (cf. above, Fig. 7b) emphasise the importance of this process. The differential water content, and therefore cohesion of the presumably interbedded sand and silt sediments, probably gave rise to the structures visible in the lower part of the exposures. Moreover, judging from the occurrence of a nearly complete skeleton, animals occasionally became mired. This may have encouraged scavenging by predators who, in turn, may have further disturbed the sediments by walking and defecating in the water. It is also possible that cadavers, especially those of small animals, could have been washed into the channel during flood events. Macro-bioturbation and sediment dewatering represent a serious cause of successional disruption in the lower half of sequence.

Subsequent infill of the channel/valley floor culminated in a relatively dry surface that could have been exposed subaerially, although no soil formation has been demonstrated in these uppermost sediments (cf. above; unit vi). The oxidation and disappearance of fossil components by dissolution was therefore a post-depositional phenomenon that apparently resulted from groundwater activity.

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9. Palaeomagnetic interpretation

The magnetic polarity recorded by the 46 samples from the WRFB sediments appears to be normal. However, and in common with many of the East Anglian Pleistocene sediment sequences (Maher and Hallam, 2005a,b), it is difficult to identify whether these palaeomagnetic directions are reliable because not only are these sediments poor in detrital magnetite but they have been subjected to significant post-depositional diagenesis. Evidence suggests (Bottrell et al., 1998) that the upper part of the WRFB has been oxidised by groundwater flow, with the layer immediately beneath enriched as a result in the ferrimagnetic iron sulphide, greigite, which thus carries a post-depositional chemical remanent magnetisation (CRM). It is possible that the lowest section of the WRFB ($> \sim 65$ cm depth) retains greigite as a 'syn'-depositional magnetic carrier, precipitated at or soon after deposition due to the prevalence of anoxic conditions and the presence of organic sulphur from decaying organic matter (Bottrell et al., 1998). It is not possible to infer the time intervals between sediment deposition and either the inferred 'early' diagenesis of greigite and/or the post-oxidative, groundwater-induced episode of soluble sulphate translocation and additional resultant greigite formation (at $\sim$30–65 cm depth). The reliability of the palaeomagnetic record of these sediments is thus somewhat tenuous, given the timing of remanence acquisition (relative to sediment deposition) cannot be determined, nor is the magnetic recording material stable through time. However, in the magnetite-deficient sediments of the Crag basin, authigenic formation of greigite provides the key means of palaeomagnetic recording capability for these sequences, and reliable polarity determinations have been made from a small number of sites where the greigite CRM has been judged to be 'contemporaneous' with sedimentation and preserved from post-depositional oxidation (Hallam and Maher, 1994; Maher and Hallam, 2005a,b). From studies of modern dissolved sulphide concentrations in marine and freshwater sediments (Canfield and Berner, 1987), and assuming sedimentation rates of the order of ~ 1 m ka^{-1} (Funnell and Pearson, 1989), greigite precipitation might occur within ~ 1 ka of sediment deposition, i.e., effectively 'syn'-depositionally with respect to the resolution of the geomagnetic polarity timescale. Conversely, 'late' and normal overprinting of an originally reversed, Matuyama-age CRM has been reported for North Sea borehole samples (Thompson et al., 1992).

These normal polarities for the WRFB sediments are consistent with normal directions reported for Cromerian sediments at Sugworth (cited in Thompson, 1991) and also match reliable normal determinations from the Colchester Sub-Formation (from the Ardleigh Member) of the Kesgrave Formation (Maher and Hallam, 2005a). Such consistency must again be viewed with caution given that late overprinting during the Brunhes normal Chron is widespread in many of the East Anglian Pleistocene sequences. Nevertheless, the palaeomagnetic data currently available indicate a Brunhes age for each of the Cromerian interglacial events, and thus suggest, amidst some contention (Preece and Parfitt, 2000; Hamblin et al., 2000; Lee et al., 2004) that they post-date mid-Marine Isotope Stage (MIS) 19.

10. Conclusions

The sedimentary succession of the WRFB has been divided into six units. The units are defined by sharp lithological boundaries and, in some cases erosional contacts. These individual units are all laterally variable, reflecting minor changes of facies.

The form and sediment infill represents the fluvially dominated sedimentation of a valley floor, the overall width of which was at least 100 m. The stream valley trended generally in a west- to eastwards direction subparallel to the modern cliffline. Local highs of pre-existing gravel and sand, such as that seen east of Goss' Gap bounded the valley-floor fill. Comparison with lowland river valley sequences in southern England implies that these gravel highs represent a braidplain morphology inherited from a pre-existing cold-climate stream.

Initial stabilisation of the stream channels was followed by accumulation of fine-grained silt deposited in standing water. Intermittent flood events, that brought coarser detritus into the depressions, punctuated the still-water deposition. Progressive decrease in flood intensity led to deposition of fine-grained marly silt that began accumulating in the braidplain depressions or abandoned channels. The predominance of these basal marls implies that the stream was fed by carbonate-rich spring water. They were followed by vertical accretion of fine-grained, organic, fossiliferous sediments.

Colonisation of the surrounding valley sides and drier floodplain areas by vegetation caused stagnation of the pool(s) plant debris accumulated, giving rise to a transition to black humus-rich detrital sediment. In response to progressive reduction in accommodation, the continued periodic flooding affected the channel, but the frequency of occurrence of these sand units decreased upwards. Channel margins were locally eroded during these events and this resulted in deposition of silty marl pellets in the detrital silt diamicton sediments.

River-flow variability and velocity diminished later as the fully forested vegetation stabilised the catchment and valley-floor ground surfaces, and delayed and reduced the flood response. The stream continued to flow throughout this period, although standing water and even partial drying-out of slightly higher areas occurred at times. This channel stabilisation resulted in minor deposition under low-velocity flowing and standing water conditions. The lack of inorganic sediments, except for a few, rare pebbles, emphasises the high biotic productivity in the immediate area that ensured that only organic detritus was available to the stream. The virtual absence of fast-flowing water deposits in the uppermost part of the succession indicates that sheet-like, vertical accretional deposition dominated the entire valley floor, infilling the remaining inherited depressions in the moist floodplain woodland environment.

The organic silts were deposited in an anoxic environment and organic sulphur from rotting organic matter allowed formation of early diagenetic sulphides (greigite). It is likely the rotting organic matter also produced methane but no record of this is found in carbon isotopes in the shells of the calcareous fossils.

On the basis of the sedimentary sequence described, combined with that determined from the biological evidence, deposition apparently began during the late-glacial (Beestonian Stage) and continued into the first half of a temperate-climate, interglacial period (the Cromerian Stage *s.s.*). This sequence reflects that typically expected where accommodation decreases as the channel or valley floor depression is infilled with time. Indeed, the infill comprises an overall fining-upward sequence and the stream therefore adopted a stable meandering pattern that compares closely with those seen in southern British rivers in the Holocene.

Comparison of the succession described with the pollen sequence obtained by West (1980) matches very favourably and indeed supports the observation that the depocentre migrated with time from east to west.

Fluvial channel pattern transformation from relatively unstable braided or gravel-bed to stable meandering form, such as that seen in the WRFB, occurred under conditions of relatively low, fine sediment input and took extended time periods, as suggested by analogue examples. The slow moving to standing water during the non-flood periods provided pools for dense colonisation by aquatic plants and animals, but periodic higher-energy water flow reworked the underlying sediment and organic materials, particularly in the basal half of the sequence. These floods transported and distributed shells, wood, vertebrate skeletal material, insect and macroscopic plant detritus.

Judging from the nature of the deposits and their lateral and vertical relationships, it seems that the WRFB stream showed typical chalk-stream behaviour, with low sediment load, occasional flooding, low-energy discharge and periodic drying-out.

Macroscale synsedimentary disturbance by water-release structures and bioturbation is particularly common in the lower half of the succession. Although some of these structures resulted from differential loading leading to natural water-release, most apparently resulted from large animals entering the channel to drink, bathe, feed and so on, their activities mixing and churning the deposits. This disturbance of the sediment succession makes high resolution of internal stratigraphy extremely difficult in any one profile. The sediments were subjected to post-depositional compaction.

The magnetic polarity from the WRFB sediments appears to be normal. However, post-depositional diagenesis and rarity of detrital magnetite in the sediment make it difficult to determine whether these palaeomagnetic directions are reliable. In spite of the problems encountered with the palaeomagnetic data at this site, a Brunhes age has been recorded for each of the Cromerian interglacial events so far identified, suggesting that the deposits post-date mid-MIS 19.

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