The δ^{18}O stratigraphy of the Hoxnian lacustrine sequence at Marks Tey, Essex, UK: implications for the climatic structure of MIS 11 in Britain

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Abstract

Marine Isotope Stage 11 (MIS 11) is widely considered to be one of the best analogues for the current interglacial. In the UK a number of long lacustrine records ~~record~~ detail part or all of the Hoxnian interglacial, the British correlative of MIS 11. In this study we present a new 18.5 metre record from the Hoxnian lake sediments of Marks Tey, Essex which represents one of the most detailed and complete records of this interglacial in Britain. Lithostratigraphy and pollen stratigraphy record the existence of sediments spanning the pre-, early and late temperate intervals of this interglacial as well as cold climate sediments that post-date the Hoxnian. This interpretation is supported by biomarker analysis which record changes in the characteristics of vegetation and aquatic ecosystems across this record. Authigenic carbonates occur throughout the 18.5 metre sequences and a δ^{18}O and δ^{13}C record is produced for the sequence. The δ^{18}O signal produces a number of clear patterns that are interpreted as reflecting the climatic structure of the interglacial. ~~These isotopic patterns are used to make a number of observations on the climatic structure of the Hoxnian.~~ Firstly, the Hoxnian interglacial ~~it~~ is a period of relatively stable climate with two potential temperature peaks, one early and one late~~, in the interglacial~~. Secondly, ~~that~~ there is strong evidence for a significant stadial/interstadial oscillation directly after the end of the interglacial. Thirdly, ~~that,~~ within the early temperate phase of the interglacial (pollen zone HoIIc), there is evidence for a number of short-lived isotopic shifts that are interpreted as abrupt cooling events, one ~~of these~~ occur~~s~~ring in association with a short-term expansion of grassland in the pollen record (the non-arboreal pollen (NAP) phase). These climatic interpretations are discussed in the context of climatic records of this interglacial from Europe and the North Atlantic. The paper concludes by discussing the similarity between the isotopic shifts associated with the NAP phase in the early Hoxnian and the 8.2ka event that occurs in the early Holocene, ~~and~~ highlighting the significance of the Marks Tey ~~is~~ signature ~~event~~ as one of the best examples currently known for an abrupt event in a pre-Holocene interglacial.

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Introduction

Marine Isotope Stage 11 (MIS 11, ca 405 ka BP) is often suggested to be the most appropriate analogue for the Holocene (Droxler and Farrell, 2000; Berger and Loutre, 2002; Loutre and Berger, 2003; Candy et al., 2014). This suggestion is based on the observation that the pattern of orbital forcing, and consequent insolation variability, that has occurred during the Holocene matches that which occurred during MIS 11 more closely than in any other interglacial of the past 500 ka (Berger and Loutre, 2002; 2003; Loutre and Berger, 2003). As temporal variations in insolation patterns will partially control the duration and climatic structure of interglacials, climate records from MIS 11 allow the study of how the climate of a Holocene-like interglacial would evolve in the absence of anthropogenic forcing (Candy et al., 2014). Long climate records that provide data on the structure of MIS 11, including the EPICA Dome C ice core (EPICA, 2004; Jouzel et al., 2007), marine cores (McManus et al., 1999; Kandiano et al., 2012) and long lake records (Prokopenko et al., 2002; 2006; 2010; Tzedakis et al., 2010) are now providing high-resolution evidence for the extended duration, complex structure and potential instability of this climatic episode (Candy et al., 2014).

Despite the importance of marine and ice core archives there is an increasing need to understand the expression of MIS 11 in the terrestrial realm. Western and central Europe are ideal locations for such studies as; 1) they contain a number of long lacustrine records that have been correlated with MIS 11 (Nitychoruk et al., 2005; Diehl and Sirocko, 2007; Koutsodendris et al., 2010; 2011; 2012), and 2) they occur in close proximity to the large number of high-resolution palaeoclimatic records that are found in the North Atlantic. Despite the often-fragmentary nature of such records they have the clear advantage over ice and marine core archives in that they are frequently annually laminated, or *varved*, and, therefore, they allow environmental change to be reconstructed at a much greater temporal resolution, (Turner, 1970; Meyer, 1974; Müller, 1974; Nitcyhoruk et al., 2005; Mangili et al., 2007; Koutsodendris et al., 2010; 2011; 2012). Many of these records have not be studied for almost 40 years, and consequently, much of the palaeoenvironmental information that has been derived from them is based upon pollen analysis with only limited application of other proxy techniques. Marks Tey (Figure 1), in southern Britain (Turner, 1970), is a good example of this. The lacustrine sequence at Marks Tey contains the most complete record of the Hoxnian interglacial, the British correlative of MIS 11 (Shackleton and Turner, 1967; Shackleton, 1987; Candy et al., 2014). Much of this sequence has been proposed to be varved and a key component of each varve is a summer lamination of authigenic carbonate, ideal for O and C isotopic analysis. Consequently, ~~a record, such as that which is preserved at~~ Marks Tey~~,~~ holds great potential for increasing our understanding of the expression of the climates and environments of MIS 11 in western Europe.

This paper presents a re-investigation of the Hoxnian lake beds preserved at Marks Tey, through the analysis of a new sediment core that was recovered in 2010. The paper describes the lithostratigraphy of the new core and the micromorphological characteristics of the different lithofacies that are present. A pollen diagram for the sequence is also presented which allows~~,~~ not only~~,~~ the correlation of this new record with that of Turner's (1970) original borehole, but also, a reconstruction of the vegetation succession preserved in this record. This record of ecological change is supported by the analysis of lipid biomarkers preserved within the sediments that allow long-term patterns of environmental/biological change to be discussed. The $\delta^{18}O$ and $\delta^{13}C$ record of this sequence is also presented. Some of the variability within the isotopic signal can be explained by changes in the style of sedimentation, however, a number of patterns exist that are interpreted as reflecting climatic, primaril~~l~~y temperature, shifts. These include two episodes of abrupt change; 1) a period of climatic instability that occurs during full interglacial conditions, and 2) an abrupt warming event which occurs in the cold, post-Hoxnian sediments. The paper concludes by discussing the significance of the climatic stratigraphy of this record particularly in the context of other records of MIS 11 from Britain and the North Atlantic.

Marine Isotope Stage (MIS) 11 in the British terrestrial record

Marks Tey is one of a number of sites within central and southern Britain that preserve lacustrine sediments which span all, or a major part, of the Hoxnian interglacial (West, 1956; Kelly, 1964; Turner, 1970; Coxon, 1985; Preece et al., 2007; Coope and Kenward, 2007; Ashton et al., 2008). The majority of these sequences have accumulated in sedimentary basins that formed as kettle holes or sub-glacial scour features during the preceding Anglian glaciation and became lacustrine systems during the immediate post-glacial period and the subsequent interglacial. An abundance of litho-, bio- and morpho-stratigraphic evidence, coupled with a range of geochronological data, has been used to robustly correlate the Anglian glaciation with MIS 12 and the Hoxnian interglacial with MIS 11, or more specifically with MIS 11c the interglacial interval of this warm isotopic stage (see Candy et al., 2014 for a recent review of these arguments). Marks Tey, located in southeastern England (Figure 1a and b), is a para-stratotype for the Hoxnian interglacial, a temperate episode defined by West (1956) on the basis of pollen stratigraphy at the stratotype site of Hoxne (Mitchell et al., 1973). The Marks Tey record is relatively unique as, unlike the majority of other Hoxnian sequences, it details~~records~~ the full interglacial vegetation succession from the end of the Anglian through the entire Hoxnian interglacial into the subsequent cold interval.

The pollen stratography of the Hoxnian (Figure 2) is sub-divided into four major pollen zones (West, 1956; Turner and West, 1968; Turner, 1970). The *pre-Temperate* zone (Hoxnian I or HoI), where total arboreal pollen (AP) first exceeds total non-arboreal pollen (NAP), is characterised by the closed boreal forest species *Betula* and *Pinus*. The *early-Temperate* zone (HoII), which see the expansion of mixed *Quercus* forest that undergoes a succession of changing species dominance from *Quercus* (HoIIa) to *Alnus* (Ho IIb) to *Corylus* (HoIIc). The *late-Temperate* zone (HoIII) is characterised by the progressive decline of mixed *Quercus* forest and an increase in late-migrating temperate trees such as *Carpinus* (HoIIIa) and *Abies* (HoIIIb). Finally the *post-Temperate* zone (HoIV) is characterised by a return to boreal and heathland species such as *Pinus* and *Empetrum* (HoIVa) as well as *Betula* and *Gramineae* (HoIVb). At Marks Tey the Hoxnian sediments are underlain and overlain by beds that contain a high NAP:AP ratio which have been ascribed to the lateglacial of the preceding late-Anglian and the subsequent cold stage, respectively.

A key characteristic of the pollen record of many Hoxnian sequences is the occurrence of a short-lived increase in NAP relative to AP (Figure 2) during the early-Temperate zone (HoIIc), commonly referred to as the NAP phase (see Turner, 1970 and Candy et al., 2014 for discussion). This is well expressed at Marks Tey where the varved sediments suggest that the NAP phase lasted for ca 300 years (Turner, 1970). A comparable event is seen in Holsteinian, the continental correlative of the Hoxnian, deposits in Germany (Dethlingen and Döttingen) and Poland (Ossawaka), where it has been referred to as the Older Holsteinian Oscillation, or OHO (Nitychoruk et al., 2005; Diehl and Sirocko, 2007; Koutsodendris et al., 2011; 2012; Candy et al., 2014). The forcing mechanism for this event is unclear as the occurrence of charcoal fragments at the start of the NAP phase at Marks Tey led Turner (1970) to suggest that it was driven by wildfire, whilst other researchers have suggested that it was climatically driven (e.g. Kelly, 1964; Turner, 1975; Koutsodendris et al., 2011; 2012).

It is important to highlight the fact that the Marks Tey summary pollen diagram that is widely cited (Figure 2) is a composite diagram constructed from pollen records derived from a number of different cores that were extracted from different parts of the Marks Tey basin (Turner, 1970; Rowe et al., 1999). The longest of these records, labelled borehole ‘GG’, was extracted from the deepest part of the basin and contains sediments, mostly fine silts and clays, which cover the interval from the late-Anglian through pollen zones HoI through to HoIIIb. A hiatus then occurs between the sediments of HoIIIb and sediments of the subsequent cold climate interval. The later parts of HoIIIb and units corresponding to HoIV are found in boreholes ‘AA’ and ‘BB’. In the sediments of ‘GG’ deposits of the late Anglian and HoI through HoII and much of HoIIIa are intact and finely laminated, whilst the sediments that correspond to HoIIIb are finely laminated but intensely brecciated, possibly due to the lowering of lake waters and sediment desiccation (Turner, 1970; Gibbard and Aalto, 1977; Gibbard et al., 1986). The laminations within the sediments of HoI through HoIIa are irregular and highly variable with respect to their thickness (Turner, 1970). From the approximate onset of HoIIb through HoIIIa and within the brecciated fragments of HoIIIb sediments, the sediments have a more regular structure. These laminations consist of triplets of laminae which comprise; 1) a diatom laminae, 2) a calcite laminae and 3) a detrital laminae. It is these lamination “triplets” that have been suggested to be varved (Shackleton and Turner, 1967; Turner, 1970, Candy, 2009; Candy et al., 2014), although no quantitative work to validate the varved nature of these laminations has been published.

It is the authigenic calcite laminations within the Marks Tey deposits that has the greatest potential for increasing our understanding of British palaeoenvironments during MIS 11 (Candy, 2009; Candy et al., 2014). The analysis of the $\delta^{18}O$ and $\delta^{13}C$ values of lacustrine carbonates in British Quaternary sequences has become increasingly widespread over the past 20 years (Whittington et al., 1996; Marshall et al., 2002, 2007; van Asch et al., 2012; Candy et al., 2015). It is primarily the $\delta^{18}O$ value of lacustrine carbonates which receive most attention because, within open-lake systems under mid-latitude temperate climates, temperature is suggested to be the primary driver of this proxy (Leng and Marshall, 2004;

Candy et al., 2015). This has been proposed because the $\delta^{18}O$ value of lacustrine carbonate is strongly related to the $\delta^{18}O$ of the lake water which is, in turn a function of the $\delta^{18}O$ of rainfall (Andrews, 2006; Candy et al., 2011). In mid-latitude regions there is a positive linear relationship between prevailing air temperature and the $\delta^{18}O$ of rainfall (Dansgaard, 1964; Rozanski et al., 1992, 1993). In general this means that the $\delta^{18}O$ of lacustrine carbonates should increase under warmer climates and decrease under cooler climates. This temperature relationship is clearly seen in numerous last glacial to interglacial transition (LGIT) lacustrine carbonate records, which provide the most convincing evidence in the British Isles for abrupt climatic shifts that are comparable to those preserved in the Greenland ice core records (Marshall et al., 2002).

Methodology

Core recovery and sedimentology

A sediment sequence (MT-2010) comprising two overlapping boreholes (TL 91081, 24431 and TL91082, 24432 drilling from a surface elevation of 15.80 metres O.D.*)* was obtained in 2010, within 10 metres of the original 'GG' borehole of Turner (1970). The cores were drilled using a wet rotary drilling rig, recovering cores in three-metre lengths, which were then cut in half for ease of transport. The two boreholes were correlated by the identification of key marker beds that were present in both sequences. This produced a composite sequence that was 18.5 metres in length. In the laboratory, macroscopic sediment description of the cores was undertaken to determine facies changes throughout the sequence and to identify the main sedimentary units, or lithofacies. 1cm^3 samples were taken from throughout the sequence to determine the organic carbon content by titration (Walkley and Black, 1934), and calcium carbonate content using a Bascomb Calcimeter (Gale and Hoare, 1991).

Micromorphology

Samples of undisturbed sediment were taken from each lithofacies for the production of thin sections. The aim of this was to support the macroscopic description of the different lithofacies with observations made at the microscale. Furthermore, microscopic analysis of the sediments can provide information on detrital inwashing, which may act as a source of detrital contamination during the isotopic analysis of the authigenic carbonate. Thin sections were prepared from fresh sediment blocks (100 x 30 x 20 mm) using standard impregnation techniques involving slow curing crystic resin developed in the Centre for Micromorphology at Royal Holloway, University of London (Palmer et al., 2008). Thin sections were analysed using an Olympus BX-50 microscope with magnifications from 20x to 200x and photomicrographs were taken with a Pixera Penguin 600es camera.

Pollen

1cm^3 sediment samples were taken for pollen analysis Pollen samples were prepared following standard techniques, including sample weighing, treatment with sodium pyrophosphate ($Na_4P_2O_7$), hydrochloric acid (HCL, 10%), hydrofluoric acid (HF, 40%), heavy liquid separation with sodium polytungstate ($Na_6[H_2W_{12}O_{40}]$, acetolysis ($C_2H_4O_2$), and slide preparation using glycerine jelly. The samples were spiked with *Lycopodium* spores to enable concentrations (grains/g) to be calculated.

Biomarkers

Lipid biomarkers were extracted from freeze-dried and homogenised subsamples of c 1cm^3 following the microwave-assisted extraction methodology of Kornilova and Rosell-Melé (2003). Known concentrations of 2-nonadecanone, 5α-cholestane and hexatriacontane (all Sigma-Aldrich) were added as internal standards. An aliquot of each lipid extract was separated into apolar, ketone and polar fractions using silica column chromatography (5% H_20) using *n*-hexane, dichloromethane and methanol, respectively. The apolar fractions were analysed by gas chromatography-mass spectrometry (GC-MS) using a 30 m HP-5MS fused silica column~~, fitted with a fused silica column (30 m –~~ (0.25 mm i.d.~~nner diameter,) coated with~~ 0.25µm of 5% phenyl methyl siloxane ~~(HP-5MS~~). The carrier gas was He, and the o~~i~~ven temperature was programmed as follows; 60-200°C at 20°C/min, then to 320°C (held 35 min) at 6°C/min. T~~t~~he mass spectrometer was operated in full-scan mode (50-650 amu/s, electron voltage 70eV, source temperature 230°C). Quantification was achieved through comparison of inte~~r~~grated peak areas in the total ion chromatograms and those of the internal standards.

Stable isotopes

Samples for stable isotope analysis were taken from individual carbonate laminations using a fine bladed scalpel and needle under a magnifier stand. It is common procedure to sieve bulk lacustrine sediment samples, prior to isotopic analysis, to remove the coarser fraction, typically greater than either 125µm or 63µm (Marshall et al., 2002; Leng et al., 2010; Candy et al., 2015), which is more likely to contain detrital material or shell fragments. This was not done in the current study because the sediments are silt grade, consequently, the process of sieving does not remove any material from the sample. All samples were then left to dry, were powdered and then weighed using a Mettler Toledo XP6 microbalance. The $\delta^{18}O$ and $\delta^{13}C$ values of each samples were determined by analysing CO_2 liberated form the reaction of the sample with phosphoric acid at 90°C using a VG PRISM series 2 mass spectrometer in the Earth Sciences Department at Royal Holloway. Internal (RHBNC) and external (NBS19, LSVEC) standards were run every 4 and 18 samples respectively. 2σ uncertainties are 0.2‰ ($\delta^{18}O$) and 0.3‰ ($\delta^{13}C$). All isotope data presented in this study are quoted against VPDB.

Results and data

1. Core stratigraphy and sedimentology

The composite stratigraphy and sedimentology of the MT-2010 core is presented in Figure 3. Based on changes in macroscale and microscale sedimentology throughout the sequence the core can be divided into five main lithofacies associations (LFa-1 to 5). The main characteristics of these associations are described in Table 1. The lowermost two units, LFa-1 (18.47-16.47 mbs) and 2 (16.47-12.00 mbs), comprise intact and *in situ* laminated sediments that are rich in organic and authigenic materials. The laminations that comprise LFa-1 are irregular with carbonate laminations becoming more frequent upwards through this unit. LFa-2 comprises regular millimetre scale laminations comprising the repeating organic/diatom/calcite triplets described in section 2. It is sediments from LFa-2 that are varved, as the sediments from LFa-1, though laminated, do not exhibit a regular enough pattern of sedimentation to be considered of annual origin. LFa-3 (12.00-4.10 mbs) consists of blocks of brecciated and deformed sediment ranging in size from millimetre to centimetre scale. The blocks comprise sediments with the same regular lamination structure as LFa-2 but these frequently show evidence for folding and faulting. LFa-4 (4.10-1.35 mbs) and LFa-5 (1.35-0 mbs) are distinct from LFa-1-3 in that they are dominated by minerogenic material and represent a return to *in situ* material after the brecciated beds of LFa-3. Both units are characterised by graded beds of silt, frequently of centimetre scale, with LFa-4 containing a higher $CaCO_3$ and TOC content than LFa-5. A noticeable increase in $CaCO_3$, from 20 to 40%, occurs mid-way through LFa-4.

Pollen

Two pollen diagrams spanning LFa-1, 2 and the lowermost part of LFa-3 (18.50-10.50 mbs) and the uppermost part of LFa-3 and LFa-4 and 5 (7.00-0.00 mbs) are presented in Figure 4a and 4b. The lower pollen diagram records a characteristic interglacial vegetation succession from a pre-temperate *Pinus-Betula-Poaceae* assemblage (18.50-16.75 mbs) through an early temperate assemblage of deciduous woodland taxa, primarily *Ulmus-Quercus-Alnus-Corylus* in varying proportions (16.75-13.60 mbs), to a post temperate assemblage characterised by a rise in *Abies* (13.50 onwards and into the brecciated sediments of LFa-3). A short-lived expansion of grass pollen at the expensive of deciduous taxa (particularly *Corylus*) occurs between depths 15.00-14.50 mbs, producing a pronounced non-arboreal pollen phase (NAP phase). The brecciated sediments of LFa-3 in the upper pollen diagram also record a post-temperate vegetation assemblage dominated by *Abies*. From 4.00 mbs onwards temperate tree pollen is still abundant but it declines in response to an increase in grass and other open ground taxa.

The pollen sequence presented is characteristic of the Hoxnian interglacial and replicates almost exactly the vegetation succession record in the 'GG' borehole of Turner (1970). The lowermost pollen diagram records pollen zones Ho I, Ho IIa to IIc and Ho IIIa with the onset of Ho IIIb being broadly consistent with the onset of brecciated sediments in LFa-3. The position of the NAP phase, midway through Ho IIc, is identical to that described in Turner (1970). Between 7.00-4.00 mbs in the upper pollen diagram the dominance of Abies within the pollen assemblages highlights a continuation of Ho III, however, the overlying sediments (4.00-0.00 mbs) are marked by a significant cooling with the expansion of non-arboreal taxa even though temperate pollen is still present. Turner (1970) argued that a sedimentary hiatus occurred at this level with the uppermost sediments in 'GG', the equivalent of LFA 4 and 5, accumulating during a cold climate interval immediately after the Hoxnian. In this model sediments of Ho IV are absent from this sequence and the temperate taxa present in the pollen spectrum reflects reworking of material from interglacial sediments exposed at the lake margin, a common taphonmic issue in Hoxnain lake sequences (West, 1956). This proposal is also accepted in this study to explain the pollen record of LFA 4 and 5 and these sediments are suggested to reflect a post-Hoxnian cold interval.

Biomarkers

Here, we focus on the distributions of the biomarkers found within the apolar fraction at Marks Tey, which is dominated by mid-chain (C_{20}-C_{26}) and long-chain (C_{27}-C_{33}) *n*-alkanes, with summed concentrations ranging from 5.4-26.3 μg g^{-1} and 2.4-18.6 μg g^{-1}, respectively. The dominant *n*-alkane varies between C_{27} (5.0-12.4 μg g^{-1}; 1773-1838 cm), C_{29} (1.8-3.4 μg g^{-1}; 1633-1211 cm) and C_{23} (4.5-10.2 μg g^{-1}; above 1016 cm). Minor contributions are also recorded from taraxast-20-ene (0-0.6 μg g^{-1}), which has been linked to Ericaceae (Pancost et al., 2002) and the C_{31} methylhopanes sourced from aerobic bacteria (0-1.1 μg g^{-1}; Sinninghe Damsté et al., 2004).

The relative distributions of the *n*-alkanes provide useful indicators of the dominant contributions of different higher plants to sediment sequences, alongside indications of the relative importance of aquatic algal inputs (Castaneda and Schouten, 2011). For example, short- and mid-chain *n*-alkanes dominate aquatic algae (C_{17}-C_{21}; Cranwell et al., 1987) and submerged macrophytes (C_{23}-C_{25}; Ficken et al., 2000), whereas long chain length *n*-alkanes (C_{27}-C_{33}) are important components of the epicuticular waxes of higher plants (Eglinton and Hamilton, 1967). The contribution of submerged vegetation is calculated using the P_{aq} ratio (Ficken et al., 2000). Furthermore, the relative importance of different long-chain *n*-alkanes, described by the 'average chain length (ACL)' has been linked to changes to the higher plant assemblage and/or shifts in temperature and humidity (Gagosian and Peltzer, 1986; Hinrichs et al., 1997; Rinna et al., 1999; Pancost et al., 2003; McClymont et al., 2008). In contrast, the P_{wax} ratio has been inferred to distinguish between contributions from plant roots and the above-ground parts, albeit from peatland environments (Zheng et al., 2007; Ronkainen et al., 2013).

Values of the ACL, P_{aq} and P_{wax} indices all vary across the MT-2010 sequence (Figure 3). The lowest ACL values (28.5-29) occur within sediments of LFa-1 (HoI) and the LFa-4 (the post Hoxnian sediments). ACL values peak in LFa-2, HoIIc to HoIIIa (29.5-29.8), and then decline in the later part of the interglacial, LFa-3 or HoIIIb (29-29.5). It should be highlighted that the samples analysed from HoIIIb are from the brecciated zone, and the extracted material includes both brecciated fragments and the intra-fragment clay which were mixed after freeze-drying (it was not possible to separate these components before extraction). These lower values may, therefore, represent an "averaging" of the ACL values of HoIIIb sediments and the clays that were deposited post-brecciation. P_{wax} values show a similar pattern to ACL values in that they peak in LFa-2 (0.7-0.8 in HoIIc and HoIIa) but are low in the early (ca 0.6 in LFa-1/HoI) and late (ca 0.4 in LFa-3/HoIIIb) interglacial. There is a slight increase in P_{wax} values from HoIIIb into the post-Hoxnian sediments (0.5-0.6 in LFa-4). In contrast, P_{aq} values show the reverse trend to P_{wax} (reflecting the different emphasis on long versus mid-chain n-alkanes between the two indices). P_{aq} values decline from 0.55 in HoI, are

Comment [ELM2]: You don't show Paq but show Pwax. I think if you're only going to show 2 of the 3 ratios, I would be inclined to go for ACL and Paq, rather than using Pwax since the latter is less often applied and so less well grounded in literature studies. Paq in contrast gives you a good signal of your lake vs terrestrial plant inputs

It isn't always clear to see the data points on figure 3 – can they be a bit larger? Or maybe make one set open and one set closed circles? (so that you can distinguish what is TOC, ACL or Pwax/Paq…?

low (0.25-0.38) through HoIIa, IIb, IIc and IIIa, before increasing to 0.68-0.73 through HoIIIa-IIIb. A slight decline to values of 0.60 occurs in HoIIIb.

$\delta^{18}O$ and $\delta^{13}C$ values of the lacustrine carbonates

The Marks Tey sequence is divided into five isotopic zones (Figure 5 and Table 3). These zones are delimited on the basis of variations and patterns with the $\delta^{18}O$ signal, rather than the $\delta^{13}C$ signal. This is proposed because in all isotopic studies of lacustrine marl sequences in the British Quaternary it is the $\delta^{18}O$ values that provide the most useful climatic/environmental data because of their relationship to prevailing temperature (as outlined in section 2). $\delta^{13}C$ values record more localised information on hydrology, biological activity, carbon sources and organic decay (Leng and Marshall, 2004; Candy et al., 2015). Consequently both $\delta^{18}O$ and $\delta^{13}C$ values are described in the following section but it is the $\delta^{18}O$ values that are used to sub-divide the sequence.

Comment [ELM3]: As an aside, when we get our new GC-IRMS system up and running during 2015 your samples might be good candidates to run compound-specific d13C analyses as well as D/H. d13C might tell you about changing plant type in more detail, whereas the D/H ratios ought to relate to precipitation and how that is expressed in the higher plants…

MT isotopic zone 1 (18.47 – 16.48 mbs, LFa-1, pollen zone HoI to HoIIb)

The $\delta^{18}O$ (mean = -3.13‰) and $\delta^{13}C$ (mean = 1.80‰) values in MTIZ 1 are relatively high with relatively low standard deviations ($\delta^{18}O$ $1\sigma = 0.32$; $\delta^{13}C$ $1\sigma = 1.2$). $\delta^{18}O$ values decrease from 18.28 mbs (-2.65‰) to 16.48 mbs (-3.40‰). This declining trend is also seen in the $\delta^{13}C$ signal but the scale of the decline s much greater; from 3.62‰ at 18.37 mbs to a value of -0.82‰ at 16.48 mbs. There is no co-variance between $\delta^{18}O$ and $\delta^{13}C$ ($r^2 = 0.03$).

MT isotopic zone 2 (15.48 – 12.00 mbs, LFa-2, pollen zones HoIIc –IIIa)

MTIZ 2 is characterised by average $\delta^{18}O$ and $\delta^{13}C$ values that are lower than MTIZ 1 ($\delta^{18}O$ mean = -3.68‰ and $\delta^{13}C$ mean = 0.82‰). The standard deviation in $\delta^{18}O$ increases from that of MTIZ 1 ($\delta^{18}O$ $1\sigma = 0.65$) whilst that of $\delta^{13}C$ decreases but is still high ($\delta^{13}C$ $1\ \sigma = 0.85$). $\delta^{13}C$ values continue to decrease across the boundary between MTIZ 1 and 2 to a low of -1.10‰ at 15.06 mbs, after which they increase across the rest of this zone. Within MITZ 2 there is no clear trend in $\delta^{18}O$, however, the lowermost part of this zone (15.88 to 14.71 mbs) has a lower mean $\delta^{18}O$ value (-3.92‰) than the uppermost part (14.71 to 12.00 mbs) which has a mean $\delta^{18}O$ value of -3.61‰. The lower mean $\delta^{18}O$ value of 15.88 to 14.71 mbs is a function of two factors; 1) the lowest individual $\delta^{18}O$ values occur between these depths, and 2) the occurrence of a 30 cm section of sediment (15.02 to 14.71 mbs) where $\delta^{18}O$ values are persistently low (mean $\delta^{18}O$ value = -4.06‰). These low values occur at the same depths within the sequence as the NAP phase. There is no co-variance between $\delta^{18}O$ and $\delta^{13}C$ values ($r^2 = 0.20$).

MT isotopic zone 3 (12.00 – 4.00 mbs, LFa-3, HoIIIa-IIIb)

MTIZ 3 covers the "brecciated" zone. Samples for isotopic analysis from this lithofacies were taken from carbonate laminations from within the brecciated fragments at regular depths across this interval. As this zone has been brecciated and disturbed this lithofacies does not have stratigraphic integrity. That is to say that, although, on the basis of pollen content, the fragments of lake sediments that make up this zone (HoIIIb) are younger than the sediments of LFa-2 and older than the sediments of LFa-4, within LFa-3 depth does not equate to age. The isotopic value of the samples taken from across this lithofacies do not, therefore, provide information on how the environment evolved across this interval but provide an indication of the isotopic characteristics of lacustrine carbonates that precipitated during this time. The mean $\delta^{18}O$ (-3.22‰, 1σ = 0.53) and $\delta^{13}C$ (3.49‰, 1σ = 0.91) values both show an increase from those of MTIZ 2. MTIZ 3 contains some of the highest $\delta^{18}O$ values of the whole record. There is no evidence of co-variance between $\delta^{18}O$ and $\delta^{13}C$ values (r^2 = 0.31)

MT isotopic zone 4 (4.11 – 1.35 mbs) and MT isotopic zone 5 (1.35 – 0.98 mbs)

The sediments of Lithofacies 4 are characterised by major oscillations in $\delta^{18}O$ values, with a zone of relatively low values (mean $\delta^{18}O$ = -4.97‰, 1σ = 0.97) between 4.11 and 1.35 mbs and a zone of relatively high values (mean $\delta^{18}O$ = -4.13‰, 1σ = 1.27) between 1.35 – 0.98 mbs. It is these characteristics that are used to define MTIZ4 and 5. As indicated by the high standard deviation values of MTIZ-4 and 5 there is significant scatter within the data of both zones, however, the $\delta^{18}O$ values effectively show a decrease, in MTIZ 4, to the lowest values of the whole dataset and then an increase, in MTIZ 5, to values as high as those seen in MTIZ 1, 2 and 3. At the end of MTIZ 5 $\delta^{18}O$ values decrease again to values consistent with those seen in MTIZ 4. $\delta^{13}C$ shows no trend, with mean values (MTIZ 4 = 3.43‰, 1σ = 2.23; MTIZ 5 = 3.12‰, 1σ = 1.34) being relatively consistent across the two zones. In both of these zones r^2 values are low indicating little co-variance between $\delta^{18}O$ and $\delta^{13}C$ (MTIZ 4 r^2 = 0.36; MTIZ 5 r^2 = 0.03).

General characteristics of the Marks Tey isotopic record

The isotopic dataset presented above is characteristic of an open-system lake basin in a temperate climate (Figure 7). The $\delta^{13}C$ values (mean = 1.80‰, 1σ = 1.67) are typical of lake waters that have equilibrated with atmospheric CO_2 (Talbot, 1990; Leng and Marshall, 2004), whilst the absence of any significant relationship between $\delta^{18}O$ and $\delta^{13}C$ values (the r^2 of the whole data set = 0.05, never exceeding 0.36 for any isotopic zone) suggests that evaporation was not a major environmental control on lake basin hydrology (Leng and Marshall, 2004). It is also proposed that it is unlikely that the dataset is effected by detrital contamination. Samples of the carbonate rich Lowestoft Till, the Anglian deposits underlying and surrounding the Marks Tey basin that are the main possible source of detrital contamination, are plotted against the lacustrine carbonate dataset in Figure 6.

The detrital values and the lacustrine samples overlap, which is not unusual as marine limestone, the source of the carbonate in the Lowestoft Till, and lake carbonates have similar $\delta^{13}C$ values (Candy et al., 2015). However, the overlap is between Lowestoft Till samples and samples from LFa-2, the authigenic rich sediments that show the least evidence for detrital contamination in the entire Marks Tey sequence. There is no overlap between the isotopic values of the minerogenic rich sediments of LFa-4 and 5, the units that have the greatest potential for detrital contamination, and those of the Lowestoft till samples. It is, therefore, suggested that the impact of detrital contamination on the Marks Tey isotopic record is negligible, with any apparent overlap between the isotopic values of bedrock samples and the samples from LFa-2 being coincidental.

Finally, it is important to note that some shifts within the isotopic dataset may be a function of changes in sedimentary style. For example, there is a large increase in the standard deviation of the $\delta^{18}O$ values from MTIZ 1 (coincident with LFa-1, the laminated but un-varved sediments) to MTIZ2 (coincident with LFa-2, the varved sediments). This can be explained by the change in the resolution of the archive from a unit where each carbonate bed/lamination may reflect many years or even decades of accumulation to a unit where each lamination represents carbonate that has accumulated in a single summer. This increase in resolution, as a result of a change in sedimentology, will automatically produce an increase in scatter within the dataset. In such contexts this change in scatter has no environmental/climatic significance, however, averaging the $\delta^{18}O$ datasets from MTIZ 1 and 2 removes the effect of changes in sample resolution and allows the $\delta^{18}O$ values of these two datasets to be compared. Consequently, the decrease in mean $\delta^{18}O$ values that occurs from MTIZ 1 to MTIZ 2 is considered to have an environmental significance.

Discussion

Lithostratigraphy, ~~and~~ pollen stratigraphy and n-alkane biomarkers in ~~of~~ the Marks Tey sequence

The lithostratigraphy and the pollen stratigraphy of MT-2010 replicates the sequence recovered from borehole GG by Turner (1970). MT-2010 records intact sediments preserving continuous sedimentation across the early to middle part of the Hoxnian interglacial (HoI to HoIIIa, in LFa-1 and 2). The later part of the interglacial (HoIIIa and b) is preserved in the brecciated and deformed sediments of LFa-3. As with the GG borehole sequence there is no evidence for intact sediments of HoIV, consequently the very end of the Hoxnian interglacial is absent from this sequence. The brecciated sediments of HoIII are directly overlain by the minerogenic sediments of LFa-4 and 5. The accumulation of deposits dominated by allogenic sediments, $CaCO_3$ concentrations decrease to 15 – 20%, suggests that these lithofacies represent a cold climate interval. Reduced vegetation cover, during such an interval, would increase allogenic sediment supply and dilute the input of authigenic material.

That the sediments of MT-2010 record the major part of an interglacial and the subsequent return to cold climate conditions is supported by the biomarker studies. The *n*-alkane ~~Alkenone~~ chain length (ACL) is generally used as a broad indictor of climatic conditions, with longer chain lengths occurring under warmer/drier conditions [need references here – use those given in the section above, since some may dispute this statement]. In the Marks Tey record, ACL increases across HoI and is highest during HoII and HoIIIa, suggesting that peak interglacial conditions may have occurred during these pollen zones. ACL then declines within the brecciated sediments of LFa 3, which may be a function of the later part of the interglacial being cooler, although as mentioned earlier this may also be an artefact that sediments from this unit are a mixture of the brecciated fragments and the clay matrix that

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they occur within. ACL values of sediments from Lithofacies 4 and 5 are low, supporting the idea that these represent a cold climate interval. P~~w~~$_{aq}$~~ax~~ provides an indication of the proportion of ~~alkenones~~*n*-alkanes within each sample coming from higher (terrestrial plants) relative to aquatic plants. The low P$_{aq}$ ~~wax~~ values from HoI to HoIIIa ~~are high~~ indicat~~e~~ing a dominance of input from terrestrial plants (Ficken et al., 2000). From HoIIIb onwards there is a shift to a greater contribution ~~to the alkenone signal from aquatic plants as seen through a reduction in Pwax values~~ from submerged/floating macrophytes (Ficken et al., 2000) given the increasing P$_{aq}$ signal. The mirror-image pattern of the P$_{wax}$ ratio (high in HoI to HoIIIa, low from HoIIIb) may also indicate a shift towards a reduced contribution from higher plants and emergent macrophytes through time (Zheng et al., 2007). Although this increase in aquatic plant markers could be related to sediment mixing as described above, alternative environmental controls on the observed trends include ~~It is important to consider the impact of mixed sediment samples in LFa-3, as discussed above, on the Pwax signal. However, the increase in the contribution of alkenones from aquatic plants in this zone, if unrelated to sediment mixing, could reflect~~ either; 1) long-term changes in nutrient availability in the basin as the lake system evolves over time, or 2) an environmentally controlled reduction in vegetation cover around the lake basin.

δ^{18}O stratigraphy of the Marks Tey sequence

The δ^{18}O stratigraphy of the Marks Tey sequence, figures 5 and 7, show two zones, MTIZ-1 (HoI to HoIIb) and MTIZ-3 (HoIIIa and b), with high mean δ^{18}O values (-3.12‰ and -3.21‰ respectively), separated by a zone, MTIZ-2 (HoIIc and HoIIIa) with a lower mean δ^{18}O value (-3.68‰). In the interpretation of this signal it must be remembered that the samples of MTIZ-3 come from brecciated fragments of lake. The magnitude of the isotopic decline between MTIZ-1 and MTIZ-2 and the recovery into MTIZ-3 is relatively small (ca 0.6 – 0.7 ‰). Across a large part of the Hoxnian interglacial (HoI through HoIIIb) there is, therefore, minimal evidence for major, long-term shifts in mean δ^{18}O values. This is not the case for the post-Hoxnian sediments of LFa-4 and 5 where values decline to -6.49‰ early in MTIZ-4 (LFa-4) increase to -2.83‰ early in MTIZ-5 and then decline again to -5.63 at the end of MTIZ-5 (figure 5).

It is common, in the majority of lacustrine carbonate δ^{18}O signals in the Quaternary of western Europe to interpret isotopic shifts in the context of temperature changes (Marshall et al., 2002; 2007; Marshall and Leng, 2004; Candy, 2009; Candy et al., 2011; 2015; van Asch et al., 2012). Such interpretations are based on the well-recorded control that air temperature exerts on the δ^{18}O of rainfall (Dansgaard, 1964; Rozanski et al., 1992, 1993; Darling, 2004), which is, in turn, the main control on the δ^{18}O of meteoric waters and, through groundwater recharge, the main control on the δ^{18}O of lake waters. Following this approach the δ^{18}O value of the Marks Tey carbonate record can be interpreted in terms of long-term temperature variations if the following two assumptions are accepted. Firstly, that the δ^{18}O value of the Marks Tey lacustrine carbonates is primarily controlled by the δ^{18}O value of the lake water that its precipitates from. Secondly, that the modification of the δ^{18}O value of lake water by processes such as evaporation is minimal.

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Comment [ELM4]: Wrong index – the text is right but this should be Paq.

Paq is a much better understood indicator than Pwax. Use the refs given in the section above to add to this here – especially Ficken who developed the method.

Make sure there is no mention of alkenones anywhere in this paper – we looked at n-alkanes (I doubt that there are any alkenones present)

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If these assumptions are accepted then the following observations can be made. Firstly, that the Hoxnian interglacial was characterised by long-term climate stability, with minimal changes in mean $\delta^{18}O$ value from HoI through HoIII. The higher mean $\delta^{18}O$ values in MTIZ-1 and MTIZ-3, relative to MTIZ-2, suggests that two temperature peaks may have occurred during the Hoxnian, one early in the interglacial and one in the mid-/late part of the interglacial. It must be stressed, however, that the changes in mean $\delta^{18}O$ values across the Hoxnian sediments preserved at Marks Tey are small, consequently if there are two periods of warmer temperatures then the degree of cooling between them must have been relatively minor (as witnessed by the occurrence of deciduous woodland across this interval). Such a suggestion is heavily reliant on the isotopic values generated from samples within the brecciated zone of LFa-3.

The pronounced variation in $\delta^{18}O$ values that occurs within LFa-4 is suggested, for two main reasons, to represent a more convincing climatic oscillation. Firstly, because the scale of the $\delta^{18}O$ variations (ca 3‰) are significant shifts. Secondly, because the oscillation occurs in association with significant changes in allogenic versus authigenic sediment input. In LFa-4 (MTIZ-4) the low $\delta^{18}O$ values occur in association with reduced $CaCO_3$ concentrations (20% or less), implying increased allogenic input. The increase in $\delta^{18}O$ values in the later part of LFa-4 (MTIZ-5) occur in association with a return to higher $CaCO_3$ concentrations (25-30%), implying an increase in authigenic carbonate precipitation in the lake basin or a reduction in allogenic inputs from the catchment. The reduction in $\delta^{18}O$ values in the later parts of MTIZ-5 are associated with a reduction in $CaCO_3$ (20% or less), again implying that allogenic inwashing has increased and erosion is dominating the catchment. The magnitude of the isotopic shifts, combined with the evidence for changing sedimentology is, therefore, used to suggested that, during LFa-4, a significant post-Hoxnian cold interlude occurred, followed by a short-lived return to interglacial like temperatures, i.e. the $\delta^{18}O$ values at this point are consistent with those of the underlying Hoxnian beds. This warm event is then followed by a return to lower $\delta^{18}O$ values and, consequently, colder temperatures.

These suggestions assume that temperature is the driving control on the $\delta^{18}O$ signal, however, a number of recent studies have argued that, under interglacial climates, rainfall and, in particular the seasonality of rainfall, may have a major influence on the $\delta^{18}O$ value of lacustrine carbonates in western and central Europe (Nitychoruk et al., 2004; Deifendorf et al., 2006; Candy et al., 2015). These studies have proposed that the occurrence of more continental style climates at the onset of interglacials may produce, because of high levels of summer rainfall (enriched in $\delta^{18}O$) relative to winter rainfall (depleted in $\delta^{18}O$), high $\delta^{18}O$ values in recharging surface and groundwaters. As the interglacials progress the onset of more maritime climates, characterised by an increase in winter rainfall (and, therefore, an increase in the contribution of relatively depleted $\delta^{18}O$ precipitation), will result in a decline in the $\delta^{18}O$ value of recharging waters. This has been used to explain an early interglacial peak in the $\delta^{18}O$ signal of both Holocene and Hoxnian/Holsteinian lacustrine carbonate records (Nitychoruk et al., 2004; Deifendorf et al., 2006; Candy et al., 2015). It is, therefore, possible that the decline in $\delta^{18}O$ values that occurs between MTIZ 1 and 2 could reflect a shift in the seasonality of rainfall regime in the early part of the Hoxnian rather than, or as well as, a decrease in temperature.

It should also be highlighted that any isotopic record of the early part of MIS 11 may be influenced by the uniquely long and protracted deglaciation that occurred across Termination V (Rohling et al., 2010; Candy et al., 2014). Termination V, as well as being characterised by the most extreme deglaciation of the past 500,000 yrs (Droxler et al., 2003), also lasted for approximately twice the length of most other terminations (Candy et al., 2014). This would have meant that during the early part of MIS 11, when interglacial conditions were already established in much of Europe, Atlantic waters, the source of British precipitation, would have remained relatively enriched, with respect to $\delta^{18}O$, because a significant proportion of $H_2{}^{16}O$ was still held within the residual ice masses. This may have elevated the $\delta^{18}O$ value of rainfall during the early part of the Hoxnian until significant ice melt had occurred. The decline in $\delta^{18}O$ values across pollen zones HoI to HoII could, therefore, represent a complex environmental signal of temperature, precipitation and source water controlled change.

Significant oscillations in $\delta^{18}O$ values occur during MTIZ-2 in association with the NAP phase of HoIIc. The scatter in the $\delta^{18}O$ dataset of the varved sediments of LFA 2 obscures this pattern, however, the depth at which the NAP phase occurs at is relatively unique within MTIZ-2 in that it correlates with a zone of consistently low $\delta^{18}O$ values. The mean $\delta^{18}O$ value of MTIZ-2 is -3.68‰ and between 15.10 – 14.70 mbs, the depth of the NAP phase, all the individual $\delta^{18}O$ values (mean = -4.08‰) are either below the mean value or within uncertainties of the mean value. This situation is unique within MTIZ-2 where low $\delta^{18}O$ values do occur but rarely as part of a consistent pattern of low values. The occurrence of a $\delta^{18}O$ excursion or event in association with the NAP phase can be clearly seen if a 5 or 10 point running average is plotted through the dataset (Figure 7b-c) as this removes scatter and highlights areas of persistently low of high values.

The NAP phase is, therefore, characterised by a pronounced low in $\delta^{18}O$ values and is followed by a return to higher mean $\delta^{18}O$ values, however, the pattern of $\delta^{18}O$ variations prior to the NAP phase is relatively complicated. This section of the sequence is characterised by three zones of low $\delta^{18}O$ values separated by a short-lived increase in $\delta^{18}O$ values. It has long been debated whether the NAP phase of HoII is a climatic event, possibly analogous to the 8.2 ka event of the early Holocene, or a regional event driven by wildfire or volcanic eruptions (Candy et al., 2014). If it is assumed that changing $\delta^{18}O$ values in the Marks Tey record reflect temperature variability then the NAP phase does occur in association with a significant climatic oscillation. However, this oscillation may not be a single cold event but part of a more complex series of cold/warm oscillations that occur in the early part of this interglacial.

The Marks Tey sequence in the context of MIS 11 in Britain, Europe and the North Atlantic

The application of stable isotopic analysis to the Marks Tey sequence has identified three key characteristics of the Hoxnian (MIS 11c) interglacial in Britain. Firstly, over the scale of the entire interglacial the climate of this interglacial is one of relative stability. Secondly, that at least one post-Hoxnian (MIS 11c) climatic oscillation occurs. Finally, that the NAP phase is associated with a significant decline in δ^{18}O values and, therefore, is likely to have occurred in association with an abrupt cooling event. These three points will be discussed here with reference to other site in Britain, Europe and the North Atlantic.

The Hoxnian as an interglacial of prolonged climatic stability

The suggestion that the Hoxnian interglacial is a time of prolonged climatic stability is consistent with records from the North Atlantic (McManus et al., 1999; 2003; Martrat et al., 2007; Stein et al., 2009). In particular the work of McManus et al. (2003) on ODP 980 has highlighted the occurrence of relatively stable sea surface temperatures at the same approximate latitude as Britain. This is consistent with the δ^{18}O signal of the Marks Tey sequence which shows remarkably little variation in mean δ^{18}O value across the major part of the interglacial (HoI to HoIIIb). The apparent occurrence in the Marks Tey sequence of an early and a late peak in δ^{18}O values ~~is~~, if they are interpreted as being temperature maxima, is consistent with many of the North Atlantic records of MIS 11 (Figure 8), e.g. MD01-2443 (Martrat et al., 2007), ODP 982 (Lawrence et al., 2009), U1313 (Stein et al., 2009), MD03-2699 (Voelker et al., 2010). All of these workers show that North Atlantic SSTs during MIS 11c were characterised by an early (centred on ca 425ka BP) and a late (centred on 405ka BP) temperature peak, separated by a short-lived and relatively minor cooling interval.

If the high δ^{18}O values that occur in HoI are not a function of high temperatures, but a function of precipitation changes or the prolonged pattern of deglaciation, then the fact that the highest δ^{18}O values occurred in HoIII (the later part of MTIZ-2 and MTIZ-3) might imply a thermal maximum relatively late in the Hoxnian. This would again be consistent with North Atlantic SST records which typically show that the later temperature peak that occurs during MIS 11c contained the interglacial thermal maximum (Candy et al., 2014). It is also consistent with British records of the Hoxnian which show tentative evidence for climates during HoIII being warmer than during HoI and Ho II. In the last interglacial, MIS 5e, fossils of the warmest thermophilous species are concentrated in pollen zone IpII, i.e. the early temperate phase (Candy et al., 2010). In Hoxnian sequences there is less convincing evidence for the extreme warmth that is seen in MIS 5e but where evidence for exotic taxa does occur, i.e. seeds of *Trapa natans*, that indicate summer temperatures of >20^{o}C (Candy et al., 2010), they are found in sediments of HoIII, i.e. the late temperate phase (Gibbard and Aalto, 1977; Coxon, 1985; Gibbard et al., 1986). Although, at Marks Tey, the evidence of warm climate conditions in HoIII is heavily reliant on isotopic data from brecciated sediments it is consistent with palaeoclimatic data from other Hoxnian sites.

A post-Hoxnian/MIS 11c stadial/interstadial oscillation

The sedimentological/isotopic oscillations observable in LFa-4 suggest the occurrence of climatic instability directly after the Hoxnian. There is now a growing body of evidence, supported by the work at Marks Tey, for the existence of short-lived warm climate episodes after the end of the Hoxnian interglacial in Britain. This is seen at both Hoxne (West, 1956; Ashton et al., 2008) and Quinton (Coope and Kenward, 2007) where a combination of floral and faunal data indicates that post HoIII a cold interlude occurred during which summer temperatures decreased by ca 7^{o}C and winter temperatures decreased by at least 10^{o}C from their interglacial peak. This cold interlude was followed by a return to warm, but not fully interglacial conditions (Coope and Kenward, 2007; Ashton et al., 2008; Candy et al., 2014). That this later "interstadial" occurred directly after the Hoxnian and did not relate to a later interglacial, MIS 9 for example, is supported by the amino acid racemisation values of shells from this bed at Hoxne (Ashton et al., 2008; Penkman et al., 2011) and the mammalian fauna which has Hoxnian affinities (Schreve, 2000, 2001).

Ashton et al. (2008) tentatively correlated the cold interlude with MIS 11b and the later interstadial with MIS 11a. A lack of radiometric dating makes it impossible to provide a direct correlation between this interstadial and the marine record or even to prove that the post-Hoxnian climatic oscillations seen at Quinton, Hoxne and now Marks Tey are even the same event. This situation is complicated by the fact that there is now growing evidence from marine (Martrat et al., 2007), ice core (Jouzel et al., 2007) and long lake records (Prokopenko et al., 2006) that the latter part of MIS 11 was punctuated by multiple stadial/interstadial cycles (Candy et al., 2014). The record from Marks Tey does not aid the stratigraphic correlation of post-Hoxnian stadial/interstadial events between sites or provide a greater understanding of the number of stadial/interstadial events that occurred in Britain during the transition from MIS 11 to 10. However, it supplies evidence from a third British site for post-Hoxnian climatic complexity, indicating that the British mainland was sensitive and susceptible to such events.

The occurrence of abrupt climatic events in pre-Holocene interglacials

There is now clear evidence for abrupt climatic events in the early part of the current interglacial (Daley et al., 2011). A key research question is whether or not such events are common in pre-Holocene interglacials (Tzedakis et al., 2009). Within Europe the most convincing evidence for an abrupt "event" in any pre-Holocene interglacial is the NAP phase/Older Holsteinian oscillation (OHO) that occurs in multiple Hoxnian/Holsteinian interglacial sequences across Europe (K0utsodendris et al., 2011;2012; Candy et al., 2014). The duration of this event is approximately 300 years (Turner, 1970; Koutsodendris et al., 2011; 2012) and although it is not possible to absolutely date this event it is frequently considered to be synchronous across Europe because it occurs in the same position in the regional pollen stratigraphy (Candy et al., 2014).

Although the NAP phase/OHO clearly represents an ecological "event" it has long been debated about whether it is a response to a climatic trigger (Kelly, 1964; Koutsodendris et al., 2011; 2012), a wildfire (Turner, 1970) or a major volcanic eruption (Diehl and Sirocko, 2007). The study of the δ^{18}O signal of the lake sequences that the NAP phase/OHO occurs within would address this issue, however, in many of these lacustrine records, carbonate precipitates are absent. Koutsodendris et al. (2012) attempted to address this by analysing the

δ^{18}O value of diatom silica across the OHO interval at Dethlingen. Although a reduction in δ^{18}O values was evident in the OHO, the section of the sequence analysed was short making it difficult to establish whether this shift was significant in the context of long-term changes within the δ^{18}O signal. The Marks Tey data presented here is the first time that; 1) the study of the NAP phase is directly compared to the δ^{18}O value of lacustrine carbonate, and 2) the δ^{18}O values associated with the NAP phase can be placed into the context of the δ^{18}O signal of an entire interglacial. As outlined above the NAP phase is associated with an interval of persistently low δ^{18}O values and, therefore, occurs during a period of climatic cooling. Figure 7 clearly shows that three distinct episodes of low δ^{18}O values occurred during HoIIc, implying that: 1) HoIIc is characterised by numerous abrupt cooling events, and 2) the NAP phase occurs in association with the last of these.

Koutsodendris et al. (2012) have argued that the OHO may be analogous to the 8.2 ka event of the early Holocene both in terms of; 1) its relatively timing within the stratigraphy of the interglacial, and 2) the expression of this event in terrestrial sequences. A number of studies in Europe have used the δ^{18}O of early Holocene lacustrine carbonates in Europe to characterise the 8.2 ka event (Daley et al., 2011), in Britain the best example is from Hawes Water in Northwest England (Marshall et al., 2002; 2007). A comparison between the isotopic record of Marks Tey and that of Hawes Water highlights two key similarities between the isotopic characteristics of the abrupt events in these records. Firstly, the 8.2ka event is just one of a number of isotopic oscillations, and, therefore, abrupt cooling events, seen in the early Holocene record of Hawes Water (Marshall et al., 2007). As well as the 8.2 ka event, the 9.3 ka event is also expressed as are other shorter lived δ^{18}O oscillations that are not named. The 8.2 ka event is not, therefore, an isolated cooling event but one of a number of early Holocene abrupt shifts, a situation comparable to that seen in HoIIc. Secondly, although the 8.2 ka event is clearly expressed in the Hawes Water sequence the scale of the δ^{18}O shift it produces is <1‰ away from the moving average of the dataset. The largest isotopic shift, in the 10 point running average, in HoIIc is 0.6‰ from the average of the dataset and is, therefore, of the same scale as the isotopic shift see within British lacustrine records of the 8.2 ka event.

It is apparent that the NAP phase in Marks Tey occurs in association with a period of climatic instability. It is, therefore, likely that it is a vegetation response to an abrupt cooling event and, given its position within the early Hoxnian, this event may be comparable to the 8.2 ka event. The Marks Tey sequence has the potential to address this further as; 1) the δ^{18}O signal of this time interval can, with further sampling, be constructed in much greater resolution, and 2) the varved nature of this archive can be used to quantify the absolute duration of the isotopic events, the intervals between them and the lag time between climatic shifts and vegetational response/recovery. The duration of these events can then be compared to the known duration of the 8.2 ka event, as preserved in the Greenland ice cores (Thomas et al., 2006). The data presented in this study which links, for the first time, the NAP phase to significant oscillations in a δ^{18}O signal presents convincing evidence that abrupt events did occur in pre-Holocene interglacials and that these events had significant impacts on the ecosystems of western Europe.

Conclusions

The recovery and analysis of overlapping boreholes (MT-2010) from the Hoxnian deposits at Marks Tey replicates the previously published record of Turner (1970) and allows, through the application of pollen, biomarker and stable isotopic analysis the following conclusions to be drawn:

- The sequence preserved in MT-2010 records sediments spanning the pre-, early and late temperate phases of the Hoxnian and cold climate sediments deposited in the immediate post-Hoxnian.
- The $\delta^{18}O$ record of the authigenic carbonates from this sequence record the climatic structure of this interglacial which is characterised by; 1) relative long-term climatic stability, 2) the existence of a possible early and late temperature peak and 3) a stadial/interstadial oscillation in the immediate post-Hoxnian.
- The $\delta^{18}O$ record from the early temperate phase records a number of short term fluctuations that are interpreted as abrupt cooling events
- The most pronounced of these occurs in association with the well-documented NAP phase during which grassland expands at the expense of deciduous woodland taxa
- The implication is that the NAP phase represents a response to a short-lived cooling event (possibly analogous to the 8.2 ka event of the early Holocene) and consequently provides one of the best recorded examples of an abrupt climatic event in a pre-Holocene interglacial.

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