A tephra-based correlation of marine and terrestrial records of MIS 11c from Britain and the North Atlantic

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ABSTRACT: Resolving marine and terrestrial records of glacial and interglacial stages has long been a challenge for Quaternary studies. We present a tephra-based correlation for MIS 11c of a North Atlantic marine core and a British terrestrial record (Marks Tey). A varved chronology is presented for the annually laminated lake sequence at Marks Tey and the proxy data from this site are plotted on an annual timescale for the first time. This record shows clear evidence for an abrupt cold event and corresponding ecological and landscape response. Varve counting shows that the abrupt event lasted for ca 185 a but the impact on the landscape persisted for ca 560 a. The co-occurrence of a single tephra layer in Marks Tey and ODP 980 allows these two records to be correlated. Furthermore, this synchronisation shows that the abrupt cold event in Marks Tey was coincident with a centennial-scale cold event in ODP 980, as evidenced by an increase in Neogloboquadrina pachyderma (s) percentage. In both ODP 980 and Marks Tey the age of this abrupt event was ca 414 500 a indicating that, at this point in MIS 11c, a widespread cold event occurred in the northeastern Atlantic and the British Isles. © 2021 The Authors. Journal of Quaternary Science Published by John Wiley & Sons Ltd.

KEYWORDS: MIS 11c; Tephra; Abrupt Change; Interglacial; North Atlantic

Introduction

The interglacial known as Marine Isotope Stage (MIS) 11c has long been of interest to the palaeoclimate community (see Candy et al. 2014 for review). Not only is it often cited as being a good analogue for the current interglacial (Loutre and Berger, 2003), it was also characterised by major shifts in the Earth system that may be relevant to understanding future warming scenarios, i.e. largescale ice-sheet wastage (de Vernal and Hillaire-Marcel, 2008; Reyes et al., 2014) and global sea levels 10–14 m above the present (Roberts et al., 2012; Raymo and Mitrovica, 2012). Furthermore, terrestrial records of MIS 11c from western and central Europe, along with marine archives from the North Atlantic, contain the clearest evidence for abrupt cold events in any pre-Holocene interglacial (Koutsodendris et al., 2012; Candy et al., 2014). Our ability to explore the linkages between these different phenomena, i.e. the relationship between abrupt climate change and ice-sheet instability, is limited, however, by the chronological constraints of MIS 11c archives.

For example, key European records of MIS 11c are annually laminated, or varved, lake sequences that allow the character and the impact of abrupt events to be reconstructed at an annual seasonal-scale (Turner, 1970; Müller, 1974; Nitychoruk et al., 2005; Koutsodendris et al., 2012). However, these records are fragmented and provide only floating chronologies. Consequently, it is not possible to directly correlate the high-resolution record of abrupt change that they contain with the history of ice-sheet dynamics and palaeoceanographic change preserved in the marine realm. Whilst North Atlantic marine sediment cores preserve proxy records of oceanographic processes and ice-sheet history (Reyes et al., 2014; Kandiano et al., 2017; Ivaldi et al., 2020, etc.), set on the absolute timescale of the LR04 stack (Lisiecki and Raymo, 2005), the low resolution of these records means that abrupt climate events are frequently recorded in only a small number of data points (Kandiano et al., 2017). Consequently, whilst marine records allow abrupt events to be placed into a wider palaeoclimatic and palaeoceanographic context, it is not possible to study the duration, structure or impact of these events from these records alone. The absence of a mechanism that allows the direct synchronisation of marine and terrestrial records of MIS 11c means that our ability to understand both the character and the drivers of such events is significantly hindered.

The aim of this study is to present a correlation of a British varved record of MIS 11c, Marks Tey in southern Britain (Turner, 1970; Tye et al., 2016), with a high-resolution marine record from the North Atlantic, ODP 980 on the eastern slope of the Rockall Plateau (Oppo et al., 1998; McManus et al., 1999). Proxy data already exist for both Marks Tey (pollen and δ18O of lacustrine calcite (Tye et al., 2016)) and ODP 980 (percentage Neogloboquadrina pachyderma (s), percentage Ice Rafted Debris (IRD) and both benthic and planktonic δ18O (Oppo et al., 1998; McManus et al., 1999)). This study presents, for the first time, the Marks Tey varve chronology and the cryptotephra record of both Marks Tey and ODP 980. The varve chronology is used to place the Marks Tey proxy data onto an annual timescale whilst a tephra marker horizon is used to correlate this record with the proxy record of ODP 980, presented on the independent LR04 timescale. This is the first time that a direct tephra-based correlation has been made between a varved terrestrial record of a pre-Holocene interglacial and a high-resolution North Atlantic marine core (although see Wastegard et al. (2005) for an example of a tephra-based
correlation between a non-varved terrestrial record and a North Atlantic marine core). Furthermore, both of these sequences contain clear evidence for an abrupt cold event that occurred under fully interglacial conditions. Consequently, a major aim of this correlation is to investigate the apparent timing of these events under chronologies formed via different methods (i.e. to allow direct, robust comparisons at centennial scales). The paper concludes by discussing the implications of this correlation and its wider significance for palaeoclimate studies.

Abrupt events in Marine Isotope Stage 11

European lake sequences (Fig. 1) have long provided evidence for abrupt events within MIS 11c, through the pollen analysis of deposits of the Hoxnian/Holsteinian interglacial of Britain/central Europe, the terrestrial equivalent of MIS 11c (see Kukla, 2003; Koutsodendris et al., 2012; Candy et al., 2014 for reviews). At sites such as Hoxne (West, 1956) and Marks Tey (Turner, 1970; Tye et al., 2016), both eastern England, and Dethlingen (Koutsodendris et al., 2012) and Munster Breloh (Müller, 1974), both in northern Germany, pollen records indicate that during the early temperate phase (an interval dominated by thermophilous tree taxa) a short-lived climatic oscillation occurred. In Britain, this ca 300 a long climate reversal is identified through a largescale increase in grass pollen at the expense of all tree species and is referred to as the non-arboreal pollen phase (or NAP phase; Turner, 1970). Whilst varved records such as Marks Tey offer the opportunity to investigate the structure and impact of the NAP phase at an annual-scale resolution, to date no detailed work has been done on this event since the pioneering work of Turner (1970, although see Tye et al., 2016).

In continental Europe the climatic oscillation, which occurs at the same point in the pollen stratigraphy as the NAP phase and is, therefore, considered synchronous, was characterised by an increase in birch and pine pollen at the expense of deciduous tree species (Müller, 1974; Kukla, 2003; Koutsodendris et al., 2012). The event is known as the Older Holsteinian Oscillation (OHO) and has been estimated to have lasted, on the basis of detrital laminae (late summer/autumn inwash). This recurring pattern has been used in many other lacustrine sequences to infer a seasonal signal (Peglar et al., 1984). However, it is important to note that, to date, no detailed analysis of the Marks Tey laminations has been carried out to confirm Turner’s (1970) model of annual cycles of sedimentation. Although the lowermost 6.5 m of the Marks Tey record is laminated, it has been shown that the laminations in the lowermost 2 m of the record (18.47–16.47 m below surface, or mbs) are too irregular in structure, thickness and recurrence to be considered varves (Tye et al., 2016). Only between 16.47 mbs and 12 mbs are the laminations regular enough to be considered annual/seasonal in origin (Tye et al., 2016). Sediments of this type continue above 12 mbs but here they are heavily brecciated, probably as a result of lake surface level reductions (Turner, 1970). The seasonal nature of the regular laminations was tested by sampling each laminaton for both pollen and diatoms (see I1). This analysis suggests the regular changes in pollen and diatom taxa between different lamination types confirm the seasonal nature of these structures reported by Turner (1970). Consequently, microscopic varve counting allows a timescale for sedimentation to be constructed.

The construction of a varve chronology was based on lamination counting from a set of 119 continuous, overlapping thin sections constructed from boreholes 1 and 2. Thin sections were prepared using the methods of Palmer et al. (2008) and analysed using an Olympus BX-50 microscope with magnifications from 20x to 200x and described using the microfacies approach. The overlap between each thin section was matched using a light box to identify co-occurring prominent laminations/bands. Once this correlation was carried out, each slide was divided into smaller counting sections. The thickness of each laminaton and its component subannual layers were measured whilst each count was undertaken. The chronology was then

Methodology

The work presented in this study is based around two main methodologies. Firstly, the production of an annually resolved record of palaeoenvironmental change through the NAP phase of the Marks Tey lake sequence. All pollen, isotope and varve thickness data are available in Supplementary Tables 1 and 2. Secondly, the application of high-resolution tephrostratigraphy through the Marks Tey and the ODP 980 records in order to correlate and align the two sequences. All tephra geochemistry data presented here are provided in Supplementary Table 3. This section outlines the methods employed in both of these steps.

Varve chronology construction for the Marks Tey sequence

The Marks Tey lake beds were recored in 2010 by a team from Royal Holloway, University of London, UK (Tye et al., 2016). A sediment sequence (MT-2010) comprising two overlapping boreholes (Boreholes 1 and 2, TL 91081, 24431 and TL91082, 24432 drilling from a surface elevation of 15.80 m OD) was obtained in 2010, within 10 m of the original ‘GG’ borehole that was the key sequence recovered by Turner (1970). The cores were drilled using a wet rotary drilling rig, extracting cores in 3 m 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 m in length (see Tye et al., 2016). The pollen data and δ13C0 data presented in this study were originally published in Tye et al. (2016).

The Marks Tey record has previously been interpreted as varved (Turner, 1970; Tye et al., 2016) on the basis of recurring triplets of laminations; a diatom lamination (spring bloom), a calcite lamination (summer precipitation) and a detrital lamination (late summer/autumn inwash). This recurring pattern has been used in many other lacustrine sequences to infer a seasonal signal (Peglar et al., 1984). However, it is important to note that, to date, no detailed analysis of the Marks Tey laminations has been carried out to confirm Turner’s (1970) model of annual cycles of sedimentation. Although the lowermost 6.5 m of the Marks Tey record is laminated, it has been shown that the laminations in the lowermost 2 m of the record (18.47–16.47 m below surface, or mbs) are too irregular in structure, thickness and recurrence to be considered varves (Tye et al., 2016). Only between 16.47 mbs and 12 mbs are the laminations regular enough to be considered annual/seasonal in origin (Tye et al., 2016). Sediments of this type continue above 12 mbs but here they are heavily brecciated, probably as a result of lake surface level reductions (Turner, 1970). The seasonal nature of the regular laminations was tested by sampling each laminaton for both pollen and diatoms (see SI 1). This analysis suggests the regular changes in pollen and diatom taxa between different lamination types confirm the seasonal nature of these structures reported by Turner (1970). Consequently, microscopic varve counting allows a timescale for sedimentation to be constructed.

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Figure 1. Map showing the location of key MIS 11 localities in the North Atlantic region. The red circles show the location of the main annually laminated MIS 11 records in Europe, DE - Dethlingen (Germany) (Koutsodendris et al., 2012), OS - Oswáka (Poland) (Nitychoruk et al., 2005), MT – Marks Tey (UK) (Turner, 1970; Tye et al., 2016). All three of these sites preserve annually laminated (varved) evidence for an abrupt climatic event at the same stratigraphic level. Inset shows the location of MIS 11 sites in the British Isles which show evidence for abrupt change (mostly non-varved). The white circles show the location of key marine records from this time period. The interglacial sections of ODP 983 (Barker et al., 2019), M23414 (Kandiano et al., 2017) and ODP 980 (Oppo et al., 1998; McManus et al., 1999) are also shown to highlight climate stability/instability in the North Atlantic during this time period. All three of these records show evidence for an abrupt cooling event (grey bar) between 415 000 and 412 000 a in either the relative abundance of *N. pachyderma* (s) (with higher abundances representing colder surface waters) or foraminifera-based temperature reconstructions. The discrepancy between the timing of these events is within the ±4 a uncertainty that is cited as the predicted uncertainty of records tuned to the LR04 stack at this time interval (Lisiecki and Raymo, 2005). The location of ODP 646 is shown as it contains the key evidence for long-term changes in ice coverage over southern Greenland which may be a driver of abrupt change during MIS 11 (de Vernal and Hillaire-Marcel, 2008; Reyes et al., 2014). The base map for this figure was created using Ocean Data View (https://odv.awi.de). [Color figure can be viewed at wileyonlinelibrary.com]
constructed on the basis of: 1) two separate counts carried out a month apart on borehole 1 using borehole 2 for the overlaps; and 2) a count based entirely on borehole 2 with the aim of identifying the magnitude of differences between the cores. This approach of multiple counts for each section allowed discrepancies to be identified and a counting error to be estimated for distinct parts of the core and for the entirety of the sequence. Count 1 yielded 3432 varves, whilst count 2 yielded 3483 varves; a difference of 51 but producing a counting error of 131 when both positive and negative counts are taken into consideration between these two estimates. By interpolating between these two counts, a final varve chronology of 3529 was produced with a counting uncertainty of ±131 (approximately ±3.75%). Much of this uncertainty occurs in the early part of the sequence (counting section 1–45) where varve preservation is poor.

**Tephrochronology**

For Marks Tey the whole varved section of MIS 11c was processed to determine its cryptotephra content (depth interval 16.45–12.00 mbs at 5 cm resolution). ODP 980 was sampled continguously, again at 5 cm resolution, from 50.37 to 56.13 m covering the entirety of MIS 11c (Oppo et al., 1998; McManus et al., 1999). For the Marks Tey sequence, cryptotephra layers were detected using the stepped density separation technique (Turney, 1998) but with the modifications outlined by later authors (Blockley et al., 2005). The samples were sieved at 15 μm (with no upper size fraction limit) to maximise the chances of discovering any tephra shards present. ODP 980 was also initially processed using the stepped density separation technique as outlined above; however, it was found that every sample contained millions of tephra shards per gram (dry wt) with hindering effective counting. Additionally, a number of brown iron-rich shards were noted in the extraction residues suggesting a denser component of basaltic shards with a specific gravity greater than 2.55 g/cm³. Therefore, a different approach was employed in order to identify meaningful layers. Contiguous sediment samples were treated in 10% hydrochloric acid before being wet-sieved into two size fractions (>63–125 and 125–200 μm) and then directly counted. This approach effectively biases the findings towards large tephra shards, which when found in abundance, allow the identification of the most significant cryptotephra layers, even if the resulting concentrations are relatively low (i.e. 10 s of shards per gram). Whilst it is still possible to reliably quantify shard counts, using Lycopodium spores as a spiking technique, in such tephra still possible to reliably quantify shard counts, using

Results

**Annually resolved palaeoenvironmental data from Marks Tey**

The Marks Tey isotope ($^{{\text{18}}}O$ and $^{{\text{13}}}C$) pollen (selected taxa) and varve thickness data are shown against depth (Fig. 2) and on a varve year timescale (Figs. 3 and 4). There is a large degree of interannual variability within the isotope data. This is not, however, uncommon for varved sequences (Mangili et al., 2007, 2010) due to the seasonal resolution of the records (Figs. 2 and 3). As each sample is derived from a single lamination, the isotopic value represents that of carbonate precipitated during a few weeks in any given year. Scatter is, therefore, produced not just by climatic changes but also year-to-year variability in weather and lake conditions. In such records environmental trends/shifts/events are indicated not by single high or low values but by clusters of high or low values. Consequently, trends in the datasets are best seen in the context of 3-point moving averages. Such analysis shows relatively clearly that there is a lower (OZ1) and upper (OZ3) zone of the oxygen isotope record that is characterised by relatively stable values with minimal variability and a low standard deviation (0.37 and 0.55, respectively). Between these, however, a middle zone occurs (OZ2) which shows considerable isotopic variability (standard deviation of 0.63) with four noticeable events (OE1 to 4) characterised by persistently low oxygen isotopic values.

Only OZ2 and OZ3 occur within the varved sequence; the lower zone (OZ1) is found within non-anual laminated sediments. The varve chronology indicates that the high degree of isotopic variability that characterises OZ2 occurred between 290 and 1485 varve years after the onset of varve formation. OZ2, therefore, persisted for ca 1200 a, whilst OZ3 continued for the rest of the varved section, ca 2000 a. The characteristics, i.e. duration and magnitude, of OE1 to 4 are best defined with reference to their deviation from the long-term average of the dataset, which is –3.69‰. OE1 to 4 are all characterised by an isotopic decline of 0.6 to 0.7‰ below the long-term average and in all cases these declines persist for at least 100 years (ranging between 116 a for OE2 and 185 a for OE4). OE4 is the most clearly expressed of all of these events, having both the longest duration (185 a) and being characterised by the largest decline (0.7‰).

The pollen record of MT2010 was described in Tye et al. (2016), so the characteristics of this proxy will not be discussed in detail here. The onset of OE4 is coincident with the onset of the NAP phase. The timing of the decline in tree taxa, seen across all taxa but particularly clearly expressed in Corylus, and the rise of non-arboreal taxa, such as grass, matches the decline in $^{{\text{18}}}O$ values that occurred at the onset of OE4. Whilst OE4 lasted for ca 185 a, the varve chronology indicates that the NAP phase itself, constrained following the protocol of Turner (1970) by the timing of the first decline in percentage Corylus to its recovery to pre-NAP levels, lasts for 565 a/12 a. Corylus was chosen as the marker for the start/end of the NAP because it shows the strongest response to this event of...
any taxa. Previous work (Turner, 1970; Koutsodendris et al., 2012) on Hoxnian/Holsteinian abrupt events have chosen to divide the NAP phase/OHO into a regressive phase (defined as the period between the first decline in tree taxa to the point at which these taxa first begin to recover) and a recovery phase (defined as the period between the beginning of the recovery in tree taxa to the point at which they have returned to pre-NAP phase levels). Using these markers it is possible to show that, at Marks Tey, the regressive phase of the NAP persisted for 371 +/−16 a, whilst the recovery phase lasted for 194 +/−15 a. It is worth highlighting that the decline in tree species seen in pollen percentage values is just as clearly expressed in the concentration data (percentage data tend show the clearest response in the most heavily impacted taxa, i.e. Corylus and Poaceae). Pollen concentration values (Fig. 2b) show that all tree species show a strong decline in association with the NAP phase, although the timing of the recovery of tree species varies between taxa.

The onset of the NAP phase is also marked by an increase in varve thickness (see Fig. 4). Prior to this event, average varve thickness (the average of the sum of the thickness of all three laminations in each triplet) is 690 μm and this increases to an

![Intergral pollen succession at Marks Tey](image1)

![Non-arboreal pollen phase at Marks Tey](image2)
average of 1090 μm during the interval of the NAP phase; an increase of approximately 60%. A large amount of this increase is seen in the detrital laminations that increase in thickness from an average of 332 μm prior to the NAP phase to 520 μm during the NAP phase. However, there is also an increase, albeit more subdued, in the thickness of both the diatom and calcite laminations.

**Tephrostratigraphy of Marks Tey and ODP 980**

A single cryptotephra layer was discovered in the Marks Tey sequence (Fig. 2B). This occurred as a discrete horizon at 15.47 mbs (15.375–15.470) with no tephra shards being found in the neighbouring samples. Despite relatively low shard abundances of ~100 shards per gram (dry wt) the layer contained some very large shards, considering the distal nature of the British Isles to active volcanic centres. In contrast, ODP 980 contained significant concentrations of tephra shards (Fig. 5) throughout the entirety of MIS 11 (though no visible tephra layers), suggesting multiple closely spaced eruptions or more likely, the secondary input of shards via iceberg rafting or other reworking processes (Griggs et al., 2014; Abbott et al., 2018). This can also be seen via the strong positive correlation between IRD values and shard concentrations seen towards the end of

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**Figure 3.** Marks Tey proxy data plotted on the varve timescale. Percentage arboreal pollen and non-arboreal pollen are plotted as are percentage changes in Corylus and Poaceae, the taxa that show the strongest response within this event. A clear increase in varve thickness occurs in association with the NAP phase. [Color figure can be viewed at wileyonlinelibrary.com].

**Figure 4.** Variation in varve thickness, plotted against varve age, through the varved section of the Marks Tey record, from left to right; total varve thickness (combined thickness of diatom, calcite and detrital lamination for each year), diatom laminae thickness, calcite laminae thickness, detrital laminae thickness. Location of NAP zone is marked in grey. [Color figure can be viewed at wileyonlinelibrary.com].
MIS 11c (~50.4–51 m) (Fig. 5). Despite this, several peaks in tephra concentrations are discernible in the >63–125 μm particle size fraction; for example, in the early-to-mid part of the interglacial the two largest peaks in colourless shards occur at 54.79–54.83 m (18.6 shards/g) and 55.79–55.87 m (18 shards/g). In brown shards the two largest peaks occur in different parts of the sequence at 55.31–55.35 m (40.2 shards/g) and 55.51–55.55 m (28.9 shards/g). All peaks in shard concentration, including known IRD events, were targeted for geochemical analysis. This approach meant that the recycling of tephra via ice rafting or secondary ash remobilisation could be assessed throughout the sequence, whilst peaks in chemically distinctive ash that may reflect primary deposition could also be identified. It was felt this approach provided the most robust way to attempt a formal correlation with the tephra layer discovered in the Marks Tey record. All raw shard count data are provided in the supplementary data file.

Overall, 240 EMPA-WDS geochemical assays were attained across the ODP 980 sampled horizons and 19 for the Marks Tey cryptotephra layer (supplementary data file). The Marks Tey tephra layer (15.47 mbs) is a highly evolved rhyolite which, apart from one outlier, forms a discrete homogeneous geochemical envelope with ranges of: 76.96–78.08 wt% SiO₂, 11.11–11.95 wt% Al₂O₃, 4.40–4.81 wt% Na₂O and 2.98–3.52 wt% K₂O.

Whilst the tephra recovered from Marks Tey represents a single, discrete cryptotephra layer, the tephrostratigraphy of MIS 11c at ODP 980 is far more complex. It is characterised by:

1. a consistently high background concentration of tephra with apparent, but poorly defined, peaks;
2. chemical data with a wide range of geochemical classifications including basalts, basalt trachy-andesites, basalt andesites, trachyte trachydacite and rhyolites (see Fig. 6);
3. heterogeneous chemistries with no level being characterised by a single unique chemical population;

Figure 5. Summary of the ODP 980 tephra stratigraphy. Tephra counts are calculated as shards/gram dry wt. The >63–125 μm size fraction data are plotted (bold line) as total shards (green line), brown shards (green line) and colourless shards (yellow line), total shards of the >125 μm size fraction are also presented. For all >63–125 μm tephra plots also note ×20 exaggeration lines (faint line). Intervals sampled for geochemical analysis are also highlighted by vertical, dashed grey lines. Existing proxy data, taken from McManus et al. (1999), are also shown, these include: Planktonic (N. pachyderma d., light blue line), Benthic (C. wuellerstorfi, red line) foraminifera δ¹⁸O values and Ice Rafted Debris (% , black line). [Color figure can be viewed at wileyonlinelibrary.com].

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(4) the same admixture of heterogeneous chemistries recurring in all the analysed layers.

We consider these criteria as indicative of reworking or secondary input of tephra shards throughout the MIS 11c interval at ODP 980 rather than repeating chemistries from the same sources being input throughout the period. The latter explanation does not seem feasible when compared with Holocene tephrostratigraphies throughout the North Atlantic which still show distinct phasing of chemical signatures (Gudmundsdóttir et al. 2011).

Abbott et al. (2018) proposed five main categories of marine North Atlantic cryptotephra deposits based on shard distribution, peak characteristics and geochemistry. In this scheme the ODP 980 sequence is typical of Type five deposits which are characterised by a setting where: 1) there is constant background deposition of shards with limited variability in concentration between levels; 2) a wide variability in deposit spreads occur; and 3) the shards express a heterogeneous chemistry strongly related to underlying deposits. Type five deposits are, therefore, laid down in an environment where the continual deposition of reworked, or secondary tephra, occurs. In such a setting there is a constant background input of glass shards to the point of deposition and as these are primarily derived from reworking by oceanic processes, they consequently lack real stratigraphic integrity. Whilst it is possible that sequences of Type five character may contain stratigraphically significant layers, their presence will often be masked by the background accumulation of secondary tephra.

Based on the criteria outlined above for ODP 980 and those reported in the Abbott et al. (2018) study we classify the MIS 11c interval of ODP 980 as a Type five deposit. The high concentrations of reworked tephra are entirely consistent with ODP 980’s oceanographic setting as it is situated south of the Iceland–Scotland ridge on the slopes of the Rockall Plateau. Here the constant input of reworked and heterogeneous tephra in the silt fraction likely reflects the continued deposition of volcanic material that has been eroded upstream and subsequently deposited by the Nordic Seas overflows, which form Feni Drift and where ODP 980 is located. Whilst the largescale input of IRD is unlikely during fully interglacial conditions this does not discount the input of detrital material from sea ice/drift ice as demonstrated during the Holocene of this region (Bond et al., 1997; Helmeke and Bauch, 2003).

Despite the issues outlined above, the input and detection of primary tephra is still possible, and our sampling approach (designed to optimise the identification of primary layers by analysing all peaks in concentration identified across the entire period of interest and the large IRD tephra inputs that occurred before and after MIS 11c) was able to identify chemical signals which were stratigraphically distinct. For instance, several tephra shards from 54.79–54.83 m depth yield chemistries that are not found anywhere else in the MIS 11c section of the ODP 980 sequence (although they do appear in the subsequent IRD levels that post-date MIS 11c). The majority of shards (n = 15) in this level yield chemical signatures which are consistent with all of the levels analysed in this study. However, six shards contain a distinctive rhyolitic chemical signature. This distinctive chemistry can be seen across multiple chemical parameters, but particularly in the total alkali, silica and Al2O3 values (Fig. 6). In a system dominated by tephra reworking processes, the fact that tephra shards with a chemistry that is found nowhere else in the interglacial and is restricted to a single level suggests that a secondary/reworked origin for this tephra is unlikely. We suggest that with the sampling strategy employed here the most likely reason for the occurrence of such a tephra is a single event input (i.e. airfall from a volcanic eruption) that was affected by negligible transport time to deposition. It is also noticeable that the evolved rhyolitic shards that occur at 54.79–54.83 m are the only shards within MIS 11c that provide a robust geochemical match with the Marks Tey tephra and that this match can be seen in multiple geochemical parameters. Despite the complexity of the ODP MIS 11c tephrostratigraphy,
the uniqueness of the 54.79–54.83 m tephra and the fact that it is chemically indistinguishable from the Marks Tey tephra strongly suggests a match between the two layers and that they are products of the same volcanic eruption. The depth interval at which this tephra occurs within ODP 980 gives it an age, based on the LR04 age model, of 415 365–415 145 a (Fig. 7).

The data presented here represent the first contiguous MIS 11c North Atlantic cryptotephra record; indeed there is a severe paucity of tephrachronological data from this timeframe to which it can be compared. However, the tephra found both within the Marks Tey (15.47 mbs) and ODP 980 (54.79–54.83 m) archives does show a geochemical affinity to a visible tephra layer termed ‘985‐CL1’ reported from ODP 985, which is located over 1300 km to the northeast of ODP 980 (Lacasse and Garbe‐Schönberg, 2001). They describe this tephra layer as relating to a major explosive eruption (probably originating from Iceland), but unfortunately only averaged geochemical data have been published, which precludes further correlation here.

Interpretation

Palaeoenvironmental interpretation

In Quaternary studies of northwest Europe, the δ18O of lacustrine carbonates is routinely interpreted as being a proxy for temperature variability (see Candy et al., 2011, 2016; Blockley et al., 2018). This is because the δ18O of lacustrine carbonate reflects the δ18O of lake waters mediated by the temperature at which mineral precipitation occurs. In mid‐latitude temperate regions, the δ18O of lake waters reflects the δ18O of meteoric water (i.e. precipitation) which shows a positive correlation with prevailing air temperature (Rozanski et al., 1992, 1993). Carbonates with low δ18O values are, therefore, interpreted as being precipitated under colder temperatures than carbonates with high δ18O values and this can be observed empirically in lake carbonate δ18O records that span periods of known climatic instability such as the last glacial/interglacial transition and the 8200 yr event (see Marshall et al., 2002, 2007; Candy et al., 2016; Blockley et al., 2018). If such an interpretation is applied here, then OZ2 would represent a millennial‐scale episode of climatic instability characterised by at least four centennial‐scale abrupt cold events (OE1 to 4).

The clearest isotopic event is the last of these intervals, OE4. This interval contains the lowest δ18O values and consists of more than 20 analyses spread over 45 cm of core depth that are lower than the average of the dataset. Varve counts show that this interval of low δ18O values persisted for 185 +/− 7 a indicating the occurrence of a centennial‐scale ACE at this point in the interglacial. The other intervals (OE1–3) are neither as long‐lived nor as significant in terms of the magnitude of isotopic decline as OE4. Significantly, the fact that the onset of OE4 is coincident with the onset of the decline in arboreal taxa indicates that the change in vegetation assemblage was a response to this ACE. The decline in arboreal taxa suggests that the sudden cooling that occurred during OE4 placed the ecosystem under environmental stress resulting in a die back of thermophilous trees and an expansion of grassland. None of the other oxygen isotopic events generated a noticeable response in pollen assemblages,
potentially indicating that they were neither of sufficient duration or magnitude to force the ecosystem across an environmental threshold and trigger a vegetation response. From this point on, the term ‘Marks Tey ACE’ is used to refer to the climatic event, as witnessed by the shift in δ18O values, whilst the term ‘NAP phase’ is used to refer to the ecological response to this event as seen in the pollen record.

The fact that the duration of the NAP phase (565+/−12 a) is approximately three times the duration of the Marks Tey ACE implies that the ecosystem was still recovering several 100 a after the cold event had finished. Whilst a lag between climatic driver and ecological response is unsurprising, it is likely that part of the delay in ecosystem recovery may relate to the impact of the Marks Tey ACE on the wider landscape. The increase in varve thickness, particularly the average thickness of detrital/inwash laminations, which occurred throughout the NAP phase implies that sediment supply to the basin increased during this time interval. This is most reasonably explained by an increase in soil erosion, as a result of the ecological disturbance, which increased sediment yield to the lake system. This, in turn, would explain the increase in the thickness of diatom and calcite laminations that occurred during the NAP phase as the enhanced loading of nutrients into the system, through reworked soil material, would elevate in-lake productivity leading to greater diatom blooms and calcite precipitation. If this model is correct then it implies that soils in the wider landscape were eroded and degraded, making it more difficult for trees to re-establish themselves after the climate had ameliorated. Consequently, it is likely that the particularly long recovery time of the woodland ecosystem that occurred after the Marks Tey ACE had ended can be partially explained by the impact of the ecological disturbance on erosion rates and soil quality.

The Marks Tey record, therefore, contains a very detailed record of an ACE within this interglacial. Three key observations can be made from the proxy data described above. First, that the Marks Tey ACE was of centennial-scale duration, persisting for ca 185 a. Second, that the ACE triggered a response in both ecological and geomorphic systems. Finally, that the impacts of the ACE on the terrestrial environment were still expressed in the landscape hundreds of years after this event had finished.

**Correlation of the Marks Tey and ODP 980 record on a tephrostratigraphic basis**

Despite the inherent complexity of the ODP 980 tephra taphonomy, the presence of geochemically indistinguishable tephra layers in both the Marks Tey and ODP 980 records means that these two sequences can be aligned. Furthermore, the fact that both of these records have independent timescales, a varve chronology in the case of Marks Tey and an LR04-based timescale in the case of ODP 980, means that the relative timing of any climatic events that these sequences record can be compared on the basis of the tephra without a reliance on any tuning techniques (Fig. 7). This correlation shows that the ACE preserved in the Marks Tey record is coincident with a cold event in ODP 980 which is characterised by an increase in N. pachyderma (s) % values (Oppo et al., 1998). This increase is recorded over just three data points; however, on the basis of the chronology of each archive, the lowest δ18O value in the ACE of the Marks Tey record is coincident with the highest N. pachyderma (s) % value in the ACE of the ODP 980 record.

Given that Marks Tey and ODP 980 have independent timescales it is noticeable that the estimated time difference between the tephra horizon and the start of the abrupt event, taking into consideration the depth range over which the tephra samples span, is 475–535 a (varve) and 443–662 a (LR04), respectively. In addition, the age difference between the tephra horizon and the coldest point in the abrupt event is 595–660 a (varve) (Marks Tey ACE) and 552–773 a (ODP 980). Within the uncertainties associated with the sampling resolutions of both the tephra and the proxies the events are effectively synchronous, although it is not possible to discuss the synchronicity/asynchronicity of the onset/end of this event in the two records. In ODP 980 the age of the highest N. pachyderma (s) % value within the ACE is 414 571 a. If the age of the tephra horizon, as derived from its position in the ODP 980 core, is transferred to the Marks Tey record then the number of varves between the tephra and the lowest δ18O value in the ACE can be used to calculate the age of this event in the British Quaternary record. Using the potential age range for the tephra layer presented above (415 365–415 145 a), this would produce an age for the Marks Tey ACE of 414 780–414 480 a.

**Discussion**

This study is the first time that a direct synchronisation between an annually resolved record of a pre-Holocene interglacial in Europe and a high-resolution marine record from the North Atlantic has been possible. This synchronisation has a number of wider implications for Quaternary palaeoecological studies. Firstly, it shows that, under fully interglacial conditions in MIS 11c an ACE occurred that affected both sea surface temperatures in the northeastern Atlantic and air temperatures in western Europe. That this event occurred under fully interglacial conditions is supported by the fact that: 1) in Marks Tey the event occurred after deciduous woodland, the climax ecosystem of interglacials in the British Isles, had become established; and 2) in ODP 980 the event occurs 4000 years after the last IRD layer associated with Termination V. The fact that abrupt events of comparable character and stratigraphic context are also seen in European sequences in Germany and Poland (Nitychoruk et al., 2005; Koutsodendris et al., 2012; Candy et al., 2014) implies that the impact of this event was likely even more extensive but the absence of tephra studies in these locations means that absolute synchronicity of these sites with Marks Tey cannot be demonstrated. The magnitude and duration of the δ18O decline associated with this event (185 a and ca 0.7‰) was consistent with the magnitude/duration of the decline associated with the early Holocene 8200 year event as preserved in British lake records (Marshall et al., 2007; Daley et al., 2011; Holmes et al., 2016). Whilst this does not imply that the Marks Tey ACE and the 8.2 ka event were responses to similar forcing factors it does imply that they were broadly comparable in terms of the magnitude of climatic deterioration.

Secondly, there has long been a debate within the Quaternary community of Europe of how the sequence of interglacial stages, defined on the basis of pollen stratigraphy, should be correlated with the record of marine isotope stages (Shackleton and Turner, 1967; Sarnthein et al., 1986; Bowen et al., 1989; Geyh and Müller, 2005; Nitychoruk et al., 2006). It has been argued that the Hoxnian interglacial of Britain and the Holsteinian of central Europe are the terrestrial correlative of MIS 11c (see Candy et al., 2014 for discussion). However, this is not universally accepted with many researchers arguing that these interglacials should, in fact, be correlated with MIS 9 (Geyh and Müller, 2005). This discussion is partly complicated by the fact that the age of MIS 11c, ca 405 000 a, puts it at the limit of the age range of many of the most widely used
dating techniques such as optically stimulated luminescence and U-series (Candy et al., 2014). This study, through the tephrostratigraphic correlation presented here supports the correlation of the Hoxnian interglacial with MIS 11c. Although it should be noted that as no tephra analysis has been carried out on the MIS 9 section of ODP 980, it cannot be definitively proven that a tephra of similar chemistry does not occur in this interglacial as well. However, on the basis of the correlation presented here it is suggested that the numerous sites in Britain that share biostratigraphical affinities with the Hoxnian interglacial are likely to be MIS 11c in age.

Currently, no detailed cryptotephra stratigraphies exist for Holsteinian deposits in central Europe. The similarity of the palaeoecology of Hoxnian and Holsteinian interglacials has often been used as evidence to suggest they are the same interglacial (Kukla, 2003; Koutsodendris et al., 2012; Candy et al., 2014). Part of this evidence is the presence of the ACE itself with the relative similarity of the OHO and NAP phase in terms of their position in the interglacial vegetation history being used as a stratigraphical marker. If such events are accepted as a robust basis for correlation then this would support the Holsteinian as representing MIS 11c in central Europe. The tephra analysis presented here is perhaps a template for future studies looking to resolve this issue and the analysis of Holsteinian lake records for tephra in central and eastern Europe should be a priority.

Finally, it has recently been shown, through high-resolution CO₂ analysis of the EPICA Dome C core that multiple abrupt jumps in atmospheric CO₂, known as carbon dioxide jumps or CDJs, occurred during MIS 11 (Nehrbass-Ahles et al., 2020). Whilst the majority of these occurred under glacial climates at the very end of MIS 11, during the climatic downturn into MIS 10, a very clear CDJ event occurred during the fully interglacial conditions of MIS 11c. The land–ocean-based correlation presented here shows that the age of the Marks Tey ACE and the cold event recorded in ODP 980, ca 414 500 a, was coincident with the age of the MIS 11c CDJ, which occurred at ca 414 500 a (Fig. 8). It has been proposed that the MIS 11c CDJ, if comparable events from the last glacial are used as comparisons, is likely to have occurred in association with: 1) disruption in Atlantic Meridional Overturning Circulation; and 2) pronounced cooling/stadial conditions in the North Atlantic (Monnin et al., 2001; Marcott et al., 2014; Nehrbass-Ahles et al., 2020). Our correlation supports this association between an interglacial CDJ and North Atlantic cooling. Whilst the uncertainties associated with both the EPICA Dome C and LR04 timescales make it impossible to demonstrate that these events are synchronous, this is the first time that it is possible to show a link between climatic disruption in the North Atlantic and abrupt changes in atmospheric CO₂ under fully interglacial conditions. It is notable that no such CDJ occurred in association with the 8200 yr cold event or any early Holocene abrupt event. If the link between the Marks Tey ACE and the MIS 11c CDJ is valid it implies that some aspect of the Earth system was operating in a different mode during this cold event when compared with those events that occurred in the early part of the current interglacial and this may imply a different forcing mechanism.

Conclusions

This study is the first time that tephrostratigraphy has allowed the direct synchronisation of an annually resolved record of a
pre-Holocene interglacial with a North Atlantic marine record. This correlation has shown that during MIS 11c a centennial-scale ACE occurred that impacted sea surface temperatures and air temperatures across the northeastern Atlantic and western Europe. The climatic event lasted for ca 180 a but in southern Britain it impacted the ecosystems for ca 560 a. The results shown here lead to three major conclusions that are of international significance to Quaternary science:

(1) That the Hoxnian interglacial of the British Isles, and probably the Holsteinian interglacial of the continent, should, on the basis of the tephrastrography presented here, be correlated to MIS 11c in the marine records.

(2) Abrupt climate events in MIS 11c have close affinities, in terms of magnitude and duration, to abrupt events, such as the 8.2 ka event, in the early Holocene. The climates of pre-Holocene interglacials were, therefore, characterised by ACEs similar to the current interglacial.

(3) Abrupt events in the North Atlantic appear to be coincident with abrupt jumps in atmospheric CO₂, as recorded in the Antarctic ice cores. Whilst the uncertainties associated with the respective chronologies mean that it is currently impossible to test whether these events are absolutely synchronous, it does show that, under fully interglacial conditions, sudden changes in the carbon cycle occurred in association with periods of pronounced climatic instability in the North Atlantic. This association has been previously proposed but is difficult to validate because of the lack of empirical data.

Acknowledgements. Much of this work was supported by a NERC PhD studentship awarded to GT (Studentship award T636208). IC and AP planned and supervised the research. IC contributed to the isotopic analysis and wrote the manuscript. AP supervised the varve analysis. GT carried out the varve analysis, isotopic analysis and helped sample for all other proxies. PC carried out the pollen analysis and MH and IM carried out the sampling and analysis of Marks Tey and ODP 980 for tephra analysis. Data that were generated during the course of the RCUK studentships are available as supplementary information and can be downloaded from the article website (S1 = pollen data, S2 = varve data, S3 = tephra data) The re-coring of the Marks Tey sequence was partially supported by funds from the Leverhulme Trust ‘Ancient Human Occupation of Britain’ project. We would like to acknowledge Dr Dave Lowry (Earth Sciences, RHUL, UK) for help in the analysis of the isotope samples, Katy Flowers (Geography, RHUL, UK) for help in preparation of the tephra samples, Dr Chris Hayward (Tephra analytical unit, University of Edinburgh) for assistance with the electron microprobe analysis, and Walter Hale (University of Bremen, Germany) for samples and sending the samples of ODP 980 material to the UK. Thanks to S. Barker (Cardiff), E. Kandiano (Kiel) and C. Nehrbass-Ahles (Cambridge) for supplying data. None of the authors have any conflicting interests.

Supporting information
Additional supporting information can be found in the online version of this article. This article includes online-only Supplemental Data.

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