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MIS 13-12 in Britain and the North Atlantic: understanding the palaeoclimatic context of the earliest Acheulean

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Abstract :

Research over the last two decades has revealed a rich record of Lower Palaeolithic occupation in Britain before 450 000 years. Acheulean industries (Mode II) first appear in the later part of the early Middle Pleistocene [Marine Isotope Stage (MIS) 19-13]. This paper reviews: (i) the age of the earliest Acheulean in Britain; (ii) the climates under which the earliest Acheulean industries occur, as recorded by the palaeoecological assemblages that are found at key archaeological sites; and (iii) the spatial and temporal pattern of regional climate change, i.e. the magnitude of glacial/interglacial cycles that occurred as a backdrop to the first arrival of Mode II archaeology in Britain. This review suggests that in Britain, the earliest Acheulean populations arrived during MIS 13 and that early occupation occurred under a range of climatic/environmental settings but frequently under post-temperate late interglacial or interstadial-type cool boreal environments. Furthermore, this review shows that the pattern of climate forcing in Western Europe during MIS 13-12 was not analogous to the interglacial cycles of the past 450 000 years as latitudinal climate gradients appear to have been less pronounced. The paper concludes by discussing the significance of these observations for understanding the arrival of the earliest Acheulean in Britain.

Keywords : Acheulean, Britain, early middle Pleistocene, interglacial, lower palaeolithic

Abbreviations

AAR	amino acid racemization
EMP	early Middle Pleistocene
LMP	late Middle Pleistocene
MBE	mid-Brunhes Event
MCR	mutual climatic range
MIS	Marine Oxygen Isotope Stage
MOTR	Mutual Temperature Ostracod Range
OSL	optically stimulated luminescence
SST	sea surface temperature

Introduction

The last two decades have seen major revisions to our understanding of the timing of the earliest human occupation of northern Europe (Parfitt et al., 2005; 2010a; Hosfield, 2011). Until recently, it had been widely accepted that the earliest known evidence for hominin activity in Europe north of the Alps was approximately 500,000 years old, corresponding with Marine Oxygen Isotope Stage (MIS) 13 and pre-dating the Anglian (MIS 12) glaciation (Roberts et al., 1994, 1995; Andrews et al., 1999; Roberts and Parfitt, 1999; Proctor et al., 2005; Roebroeks, 2005). This evidence consisted of rare occurrences of Acheulian stone tool assemblages (Mode II technologies, i.e. those characterized by handaxes) and hominin fossils from sites such as Boxgrove (UK) and Mauer (Germany). However, two major developments have revealed a longer and more diverse record of early human occupation in this region. First, discoveries of Mode I (core and flake) technologies at Pakefield and Happisburgh III (both in the UK), dated as early as 750,000 to 1 million years ago (Parfitt et al., 2005; 2010a), indicate that the first human occupation of Britain, and by extension northwest Europe more generally, occurred considerably earlier in the Pleistocene. Second, an increasing number of Acheulian sites can now be reliably assigned a pre-Anglian age, demonstrating that evidence for human occupation (represented by either Mode I or II archaeology) during the early Middle Pleistocene (or EMP, ca 780 – 450 ka, MIS 19-13) is more abundant than previously thought and that the British Pleistocene contains an extensive and diverse Lower Palaeolithic record (Rose, 2009; Hosfield, 2011 and references therein).

Several recent studies have focused on the climates and environments of early human occupation (Parfitt et al., 2005; 2010a; Candy et al., 2011a and b). Much of this debate has centred on the climatic conditions that existed during specific occupation phases, the evidence for which is derived from palaeoecological and isotopic proxies associated with lithic assemblages (Parfitt et al., 2005; Coope, 2006; Candy et al., 2011b; Hosfield, 2011; Ashton and Lewis, 2012). Whilst this is undoubtedly important, equally significant is the background pattern of climate forcing, i.e. the magnitude and frequency of the glacial and interglacial cycles and changes in large-scale climatic gradients, the resulting changes in environmental conditions and the impact that these had on hominin dispersal patterns (Maslin et al., 2014). This is particularly important with respect to the EMP because marine and ice core records indicate that this interval was characterised by glacial/interglacial cycles that were significantly muted or subdued (Fig. 1) in comparison to those that occurred from MIS 12 onwards (Jansen et al., 1986; EPICA, 2004; Candy et al., 2010; Lang and Wolff, 2011).

The apparent low intensity of EMP interglacials in ice and marine core records (Fig. 1) means that they are more comparable with interstadials of the late Middle and Late Pleistocene than with full interglacials such as MIS 5e (EPICA, 2004; Lisiecki and Raymo, 2005). This is particularly true of MIS 13, the interglacial during which Acheulian industries are generally proposed to first appear in northern Europe, which is suggested to be the coolest interglacial of the past 800,000 yrs (Lang and Wolff, 2011). However, it has been argued that the complex climatic setting of the EMP meant that Europe and the North Atlantic would have been characterised by much stronger latitudinal and longitudinal climate gradients than occurred during the past 450 ka (Candy and McClymont, 2013). It is therefore unlikely that the late Middle Pleistocene (LMP) climate cycles from MIS 11 onwards are good analogues for those that occurred during the EMP. Consequently, the climate forcing and the environmental gradients that provide the background to, and may to some extent control, the dispersals of the earliest humans in northern Europe are clearly complex, poorly understood and deserving of further investigation.

This paper reviews the palaeoclimatic context of the earliest Acheulian in Britain. This review will include both: 1) the palaeoclimatic reconstructions generated for specific Acheulian localities and 2) the regional palaeoclimates that existed in the North Atlantic at the time. The widely-held view that the earliest Acheulian artefacts in Britain can be correlated with MIS 13 is tested against a brief review of the stratigraphic and chronological evidence from these localities. We summarise the palaeoclimatic data from British terrestrial sequences spanning MIS 13 to 12, characterising this major climatic transition in Britain and placing the earliest Acheulian into this environmental framework. The British record is compared to sea surface temperature (SST) records from the North Atlantic and palaeoenvironmental records from southern Europe.

The palaeoclimatic framework of the early Middle Pleistocene

Research in Pleistocene terrestrial settings, where Quaternary sequences are often highly fragmented and discontinuous, now routinely uses the marine benthic $\delta^{18}O$ record (and other long marine and ice core records) as a climatic framework for understanding the succession of glacial and interglacial episodes with which terrestrial deposits may be correlated (Bridgland, 2000; Schreve, 2001a; Lee et al., 2004; Penkman et al., 2011). Although these records are important for establishing the timing and number of global glacial/interglacial cycles, the relative intensities of interglacial peaks and glacial troughs can vary significantly on a regional scale. It is therefore problematic to assume, for example, that a glacial stage characterised by high global ice volume in a marine record (as recorded by high benthic $\delta^{18}O$ values), should necessarily correspond with evidence for extreme cooling or major glaciation within local terrestrial stratigraphic records; high volumes of global ice provide no indication of where that ice might have accumulated. Despite these difficulties, it is becoming increasingly clear that there are some climatic transitions that have a globally consistent character (Lang and Wolff, 2011; Candy et al., 2014).

A good example of this is the mid-Brunhes Event (MBE), a climatic shift that is recorded in a large number of long marine, ice and lacustrine records from around the world (Fig. 1; Jansen et al., 1986; EPICA, 2004; Lang and Wolff, 2011). The key characteristic of the MBE is a shift from low magnitude, relatively subdued glacial/interglacial cycles during the EMP to extreme and large scale LMP glacial/interglacial cycles from MIS 11 onwards (Jansen et al., 1986; EPICA, 2004). In many palaeoclimatic records, the interglacial stages in the interval MIS 19-13 are more similar to the interstadials of the past 450,000 years than to post-MIS 12 interglacials, implying that interglacial peaks in the EMP were relatively cool and that significant volumes of ice persisted during these warm isotopic stages. Furthermore, many of the EMP glacial stages, such as MIS 14, are characterised by only very minor increases in global ice volume (Lee et al., 2004; Lisiecki and Raymo, 2005). The clearest expression of these low magnitude climate cycles is in MIS 13, which is routinely the coolest interglacial of the past 800,000 years in various long palaeoenvironmental records from around the world (Lang and Wolff, 2011; Candy and McClymont, 2013). In the EPICA Dome C ice core record, the thermal peak of MIS 13 is some 7^{o}C cooler than that of MIS 5e (Jouzel et al., 2007), and in marine records from the Nordic seas (e.g. MD 992277; Fig. 2) it has even been argued that interglacial conditions were entirely absent during this interval (Helmke et al., 2003). It is important to note that the broad pattern of insolation variability does not vary across this interval, rather the "cool" interglacials of the EMP are associated with average CH_4 and CO_2 concentrations that were respectively 40ppm and 90ppb lower than those of MIS 11-5 (Loulergue et al., 2008; Luthi et al., 2008). The globally "cold" interglacial climate of MIS 13 is therefore associated with some of the lowest greenhouse gas concentrations of any interglacial of the past 800,000 yrs (Loulergue et al., 2008; Luthi et al., 2008; Lang and Wolff, 2011).

It is within this context of low magnitude glacial/interglacial forcing that the earliest occupation of northern Europe by humans using Acheulian industries occurred (Fig. 1; Roberts and Parfitt, 1999; Coope, 2006; Rose, 2009; Preece and Parfitt, 2012). This raises important questions about both the climatic context of the earliest Acheulian in Britain and the possible role of climate as a driver for human dispersals during MIS 13. In particular, it is important to assess: 1) the extent to which the climate cycles that accompanied the earliest Acheulian differed from those that occurred during the late Middle and Late Pleistocene as this may mean that early human occupation occurred against a different pattern of climatic conditions, 2) whether the cool interglacial environments of MIS 13, resulting from muted climatic forcing, provided conditions that aided or hindered early human occupation of this region and 3) whether this meant that early humans occupied a significantly different set of environmental and landscape conditions to those that occurred during the LMP. It is currently impossible to address these questions in much of western and northern Europe because it is unclear how the MBE is expressed in the Quaternary record. However, the record for MIS 13 in Britain potentially offers new and important insights into some of these issues. The British record preserves a significant number of deposits with detailed palaeoclimatic information dated to MIS 13 and early MIS 12, and is also a region rich in Acheulian archaeology; it is therefore an ideal region in which to investigate the links between climate and the earliest Acheulian. In addition, the terrestrial palaeoclimatic data can be placed into the context of the archive of SST records recovered from the adjacent North Atlantic (Fig. 2).

Stratigraphy and chronology of the earliest Acheulian in Britain

Rationale

The British Acheulian sites under discussion are limited to those that have yielded strong lithostratigraphical, biostratigraphical or geochronological evidence indicating that they were deposited (and therefore that early human occupation occurred) prior to the Anglian glaciation during the EMP (Rose, 2009; Hosfield, 2011; Preece and Parfitt, 2012)). This interval (~780 -450 ka, MIS 19-12) contains a number of distinct temperate-climate episodes (Fig. 1) and is referred to in the British Quaternary stratigraphic sequence as the “Cromerian Complex” (Preece and Parfitt, 2000; 2008; 2012; Preece, 2011), following the recognition in the Netherlands of additional climatic complexity (Zagwijn et al., 1971; Zagwijn, 1996) in deposits that had been originally assigned to a single "Cromerian" interglacial (West, 1980). Acheulian assemblages that can be defined as pre-Anglian on the basis of site lithostratigraphy are generally those that occur in deposits that underlie glaciogenic sediments of Anglian age, typically the chalky Lowestoft/Walcott Till or the sandy Corton and Happisburgh Tills (Lee et al., 2011). The Anglian glaciation has been robustly correlated with MIS 12 using a number of independent lines of evidence discussed in detail elsewhere (Bridgland, 1994; Pawley et al., 2008; Toucanne et al., 2009; Candy et al., 2014).

Palaeolithic sites overlain by deposits of Anglian age are restricted to regions where the extensive till sheets of that glaciation overlie EMP sequences, notably in East Anglia and the east and west Midlands (Fig. 2; Rose, 2009). In this respect, the stratigraphy of the Bytham river terraces is central to understanding pre-Anglian archaeology (Rose, 1994; 2009; Westaway, 2009a; Hosfield, 2011). This major fluvial system existed for much of the EMP and flowed eastwards from the west Midlands/Welsh borders, through the east Midlands, the Fen basin and East Anglia, before exiting what is now the British mainland in the region of Lowestoft (Rose, 1994; 2009). The Bytham system was overridden by ice during the Anglian ice-advance with sediments of this glaciation in-filling the Bytham valley; consequently any archaeology that occurs within Bytham river deposits is, by definition, either early Anglian or pre-Anglian in age. The Anglian glaciation also caused the diversion of the Thames into its current valley and the burial, by glaciogenic sediments, of the Early and early Middle Pleistocene Thames terraces (Whiteman, 1992; Whiteman and Rose, 1992; Bridgland, 1994). The pre-Anglian Thames sequence has, however, yielded relatively little archaeology in comparison with the Bytham sequence (although see Hosfield, 2011 for discussion).

Deposits of river systems that lie beyond the influence of the Anglian glaciation have also yielded Lower Palaeolithic archaeology, such as the terrace sequence of the Solent river and its associated tributaries (Westaway et al., 2006; Hosfield, 2011). However, these archives lack a clear lithostratigraphic link to Anglian deposits, so that the pre-Anglian age of any contained archaeology is difficult to ascertain, particularly as many of these deposits are free-draining siliceous gravels that do not favour the preservation of vertebrate, molluscan or floral fossil assemblages that might provide a biostratigraphical age attribution (Briant et al., 2006). This is not the case for the famous raised beach sequence and overlying fine-grained sediments at Boxgrove in West Sussex, which has yielded both Acheulian archaeology and a rich fossil assemblage and is one of the few early archaeological sites beyond the Anglian ice limits that can be convincingly argued to be of pre-Anglian age (Roberts et al., 1994; Roberts and Parfitt, 1999).

The biostratigraphy of the Cromerian Complex has been described and synthesised in a number of publications (e.g. Preece and Parfitt, 2000; 2008; 2012). These studies have defined a series of at least five separate biostratigraphical assemblages, based primarily on mollusc and small mammal fossils, which have been proposed to represent five separate temperate episodes (Preece and Parfitt, 2012), not all of full interglacial status. The separation of these assemblages is based upon the presence and absence of a number of species, but the clearest (and most widely cited) distinction is between those deposits that have yielded the extinct water vole *Mimomys savini*, which pre-date deposits that contain its descendant species *Arvicola terrestris cantiana* (Stuart, 1996; Preece and Parfitt; 2000; 2012; Stuart and Lister, 2001). Amongst other features, *Mimomys* is characterised by rooted molars whereas *Arvicola* has continuously growing molars. However, because *Arvicola* is an extant genus additional biostratigraphic or lithostratigraphic control is required to confirm a pre-Anglian age where it is found in association with Acheulian assemblages (Koenigswald and Kolfschoten, 1996).

The age of the Cromerian Complex deposits (>450,000 yrs) is beyond the age range of most absolute dating methods routinely applied to the Quaternary, such as uranium-series and optically-stimulated luminescence (OSL). Attempts to generate absolute age estimates for the earliest Acheulian are therefore problematic. However, recent advances in amino acid racemisation (AAR) dating have focused on the analysis of the calcitic opercula of the freshwater gastropod *Bithynia*, rather than the less stable aragonitic shells favoured by earlier studies, and this has aided the stratigraphic resolution of the British EMP (Penkman et al., 2007; 2010; 2011; 2013). The AAR technique does not allow absolute ages to be calculated, but uses the degree of racemisation of multiple amino acids to place fossil assemblages in a relative order and, through comparison with the AAR properties of assemblages of known ages, allows age estimates to be inferred (Penkman et al., 2011; 2013). AAR analysis has been carried out on fossil assemblages that are known to be of EMP age, and attributed to the Cromerian Complex. These show: 1) a greater degree of racemisation than for opercula from sites attributed to MIS 11, thus supporting their pre-Anglian/MIS 12 age and 2) an apparent age separation between sequences that have yielded *Arvicola*, which have lower AAR ratios than those that have yielded *Mimomys*, supporting a younger age for the former (Preece et al., 2009; Penkman et al., 2011; 2013). This combination of AAR analysis and biostratigraphy indicates that sites such as Waverley Wood (Warwickshire) and Sidestrand (Norfolk), both of which have yielded fossils of *A. t. cantiana*, represent younger temperate episodes within the Cromerian Complex than sites such as Pakefield (Suffolk), Sugworth (Oxfordshire), Little Oakley (Essex) and West Runton (Norfolk), all of which contain *M. savini*.

Age attribution of the earliest Acheulian and MIS 13

There is increasing agreement in the literature that pre-Anglian Acheulian sites in Britain should be correlated either with MIS 13, the interglacial that occurs immediately before the Anglian, or with the early part of MIS 12 (Coope, 2006; Westway, 2009a and b; Hosfield, 2011; Penkman et al., 2011; Preece and Parfitt, 2012). It is important to highlight that this correlation is not based on any absolute age estimates but on a combination of lithostratigraphy, biostratigraphy, AAR analysis and uplift modelling. These lines of evidence, when combined, suggest that all of the early Acheulian sites correspond with the late EMP, and fit most comfortably with an MIS 13 age. The rationale for this correlation is laid out in the following section. It is important to highlight that this rationale is based around the traditional glacial stratigraphy that assumes that the glaciogenic sequences in northeast Norfolk are all MIS 12 in age (Bowen, 1999), rather than following a multiple glaciation theory that proposes that the oldest tills in these sequences correlate to MIS 16 (Lee et al., 2004). Furthermore, this rationale follows the traditional view that sites such as High Lodge are pre-Anglian (Ashton et al., 1992) rather than post-Anglian (West et al., 2014).

Firstly, at sites where Acheulian assemblages occur in association with biostratigraphically-significant small mammal assemblages (Happisburgh I in Norfolk, Boxgrove and Waverley Wood), they are always associated with *A. t. cantiana* and never with *M. savini* (Preece and Parfitt, 2012). The rarer British Mode I archaeological sites have yielded the more archaic *M. savini*, supporting the view that these industries pre-date the Acheulian and fall earlier within the EMP (Parfitt et al., 2005; Preece and Parfitt, 2012). Since the transition from *M. savini* to *A. t. cantiana* occurred during the early Middle Pleistocene, this biostratigraphical association *de facto* places the Acheulian sites within the later part of the Cromerian complex. There is now good evidence to suggest that the transition from *M. savini* to *A. t. cantiana* occurred during MIS 15 (see Preece and Parfitt, 2012 for discussion). This is based on evidence from the sequences at Isernia la Pineta, Italy, and Mauer, Germany, which have yielded water vole molars that appear to represent a transitional form between *M. savini* and *A. t. cantiana*. Dating evidence from both sites (Ar/Ar of volcanic tuffs in the case of Isernia and coupled

ESR/U-series dating of tooth enamel in the case of Mauer) provides relatively consistent mid-MIS 15 ages for this transition: 610,000 yrs (+/-10,000 yrs) and 606,000 yrs (+/-2,000 yrs) from Isernia and 609,000 yrs (+/-40,000 yrs) from Mauer (Coltorti et al., 2005; Wagner et al., 2010). Further support for this age comes from the Don basin of western Russia, where fossils of *M. savini* have been found within temperate sediments that directly overlie glacial deposits attributed to the Don glaciation (correlated with MIS 16), thereby implying that in eastern Europe *Mimomys* was still extant during MIS 15 (Agadzhanyan et al., 2012; Preece and Parfitt, 2012)

Similar 'transitional' water vole morphotypes have not yet been reported from British sites. Although the evidence does not preclude independent evolution in Britain (as is apparently the case in Italy and Germany), it is probable that *A. t. cantiana* radiated out from the continental mainland to reach Britain. The pre-Anglian deposits in Britain that contain *A. t. cantiana* are therefore constrained to late MIS 15 or MIS 13 at the earliest. It has been further suggested that two distinct EMP biostratigraphical associations containing *A. t. cantiana* are apparent, an older one that also contains *Microtus gregaloides* (recorded at Westbury-sub-Mendip, Somerset and tentatively at Sidestrand/Trimingham in Norfolk) and a younger one, which contains the more derived *Microtus gregalis* (recorded at Boxgrove; Preece and Parfitt, 2008; 2012). At other Cromerian Complex sites that have yielded *A. t. cantiana* (Waverley Wood and the Ostend Freshwater bed in Norfolk (West, 1980; Preece and Parfitt, 2012), the microtine rodent assemblages are too small to allow definitive correlation with either of these two groups. It is tempting to suggest that the older *Arvicola* association (with *M. gregaloides*) might correlate with late MIS 15 and the younger (with *M. gregalis*) with MIS 13. However, such a correlation is argued here to be unlikely; it is more probable that all pre-Anglian faunas contaning *A. t. cantiana* correspond with MIS 13, for the following reasons.

First, there is no evidence to support the notion that the two *A. cantiana* faunal groups represent distinct interglacials. Although there is clear climatic complexity within the Westbury sequence, none of the palaeoclimatic evidence is indicative of glacial/interglacial-scale variability (Schreve et al., 1999; Preece and Parfitt, 2012); similarly, the sequence at Boxgrove spans only the middle and later part of a single interglacial. Consequently, there is nothing in the palaeoclimatic record from either site to contradict the suggestion that both of the *Arvicola* groupings occur within the same interglacial (probably MIS 13). In contrast, the biostratigraphical groupings with *Mimomys savini* identified by Preece and Parfitt (2000) more convincingly represent stratigraphically distinct interglacial stages (e.g. Parfitt et al., 2005; Coope, 2006; 2010). It is unlikely that sediments dating to MIS 19 are represented in the British Quaternary record, since much of this interglacial was magnetically reversed and there are currently no reversed polarity Cromerian Complex deposits known (Maher and Hallam, 2005). Consequently, it can be argued that all of the *M. savini* groups should be placed within MIS 17 and 15 (Fig. 3). The unique climatic structure of MIS 15, as shown by marine and ice core records, is noteworthy (Fig. 3), since this interglacial was characterised by two separate peaks of fully temperate climatic conditions (Lisiecki and Raymo, 2005; Sosdian and Rosenthal, 2009; Elderfield et al., 2011). The preceding MIS 17 interglacial, in contrast, is more typical of LMP interglacials such as MIS 11, 9 and 5e, characterized by a single temperate peak. The biostratigraphic complexity shown by the three *M. savini* groups therefore suggests that this species was characteristic of British Pleistocene small mammal faunas for much of the Cromerian Complex, spanning MIS 17 and, in all probability, all of MIS 15. This further restricts the two biostratigraphic groupings containing *Arvicola terrestris cantiana* to MIS 13.

Second, a number of age constraints on the lithostratigraphy, biostratigraphy and lower Palaeolithic archaeology of the British early Middle Pleistocene have been proposed through a combination of uplift modelling, ages generated by AAR and correlation with the Bytham river terrace sequence (Westaway 2009a & b; 2010). Some of the conclusions of this work are controversial, for example the argument that all deposits with *M. savini* can be attributed to different substages of MIS 15, including sites such as Pakefield and Happisburgh III, which have been published as pre-dating 700ka by Parfitt et al. (2005, 2010a). Nevertheless, it provides support for the hypothesis that the transition from *M. savini* to *A. t. cantiana* occurred during MIS 14 in Britain and that all pre-Anglian assemblages with *A.t. cantiana* faunas must relate to MIS 13. This work also has implications for the ages of sites preserved in the Bytham system that contain pre-Anglian Acheulian archaeology but which previously proved difficult to date due to the limited range of associated biostratigraphical evidence, such as Warren Hill, High Lodge and Feltwell (all in Suffolk) and Brooksby in Leicestershire (Rose et al., 1999; Lee et al., 2004; Stephens et al., 2008; Rose, 2009; Hardaker, 2012). Earlier terrace models for the Bytham sequence in East Anglia placed some of these sites (e.g. Warren Hill, High Lodge and Feltwell) within different terrace units; uncritical correlation of these terraces with separate orbitally-driven 100ka Milankovitch cycles suggested that Mode II assemblages containing handaxes occurred within multiple early Middle Pleistocene interglacials.

However, the revised terrace model for the Bytham system proposed by Westaway (2009a) attributes any altitudinal differences between the aforementioned sites to a complex response of the catchment to the influence of the Anglian ice sheet, similar to that seen within the terrace sequence of the middle Thames (Maddy and Bridgland, 2000). The implication of this reassessment is that all handaxe sites within the Bytham sequence, which occur in the lowest/youngest terraces units, relate to the final climate cycle (i.e. MIS 13 to early MIS 12) before the Anglian glaciation (Westaway, 2009a). This corroborates the earlier suggestion, based on both altitude and lithostratigraphy, that the Bytham deposits west of the Fen Basin represent only the youngest terrace unit of this system and thus the final climate cycle before the Anglian (Rose, 1994; Lee et al., 2004). This younger age within the EMP is supported by the presence of *A. t. cantiana* at Waverley Wood (Shotton et al., 1993; Keen et al., 2006), although such biostratigraphical control is absent at Brooksby; however, an MIS 13 age for the archaeology at this site is strongly implied by its position within the Bytham terrace sequence. With these arguments in mind, it is also worth noting that the AAR values from Waverley Wood and Sidestrand are statistically comparable to one another, implying that they represent the same marine isotopic stage (Preece et al., 2009; Penkman et al., 2013). The deposits at Sidestrand contain the older *A. t. cantiana- M. gregaloides* grouping, providing further evidence that all small mammal assemblages containing *A. t. cantiana* correspond with MIS 13.

Summary

Current understanding of the lithostratigraphy and biostratigraphy of the EMP in Britain suggests that all Acheulian sites that pre-date the Anglian glaciation are of MIS 13 or early MIS 12 age. This is based on identification of one or more of three key attributes: 1) the presence of biostratigraphically diagnostic early Middle Pleistocene small mammal assemblages containing *Arvicola terrestris cantiana* (Boxgrove), 2) the presence of overlying glaciogenic deposits attributed to the Anglian (Happisburgh I, Waverley Wood), and 3) preservation within the youngest terrace deposits of the Bytham system (Brooksby, Feltwell, Warren Hill, High Lodge). This stratigraphic framework can also be applied to sites that are not known to contain archaeology but which preserve important proxy evidence for climates and landscapes during MIS 13 and early MIS 12. These sites provide critical evidence for reconstructions of the palaeoclimatic and palaeoenvironmental context for the earliest Acheulian occupation of Britain and provide evidence for a range of climatic settings, from fully temperate conditions that may be used to infer the environment that existed during the peak of MIS 13 (Sidestrand and the Ostend Freshwater Bed) through to the cold climatic conditions of the early Anglian (the Ostend Arctic Freshwater Bed).

Climates and environments of MIS 13 to 12 in Britain and the North Atlantic

The palaeoclimate of MIS 13 to 12 in Britain

Britain Pleistocene sequences attributed to MIS 13/12 can be divided into four main groups (Table 1; Fig. 4). The first group includes sequences that record fully temperate conditions, indicated by pollen assemblages dominated by deciduous tree species (early temperate interglacial in nature) and the presence of fossils of thermophilous plant and animal species. Sites attributed to this group include the *Unio* Bed at Sidestrand and the lower and upper Freshwater Bed at Ostend (Reid, 1882; West, 1980; Preece et al., 2009). The second group is characterized by post-temperate pollen assemblages, dominated by boreal species and variable amounts of open-ground and which represent either late interglacial or interstadial climatic conditions, following the main interglacial peak. This group includes sites such as Happisburgh I, High Lodge, Waverley Wood and Brooksby (Hunt, 1992; Shotton et al., 1993; Coope, 2006; Ashton et al., 2008a). The third group includes sequences that record the climates of the early glacial period, with evidence for extensive open ground and the presence of cold-adapted arctic/alpine species, such as the Arctic Freshwater Bed at Ostend (Parfitt et al., 2010b) and the Arctic silts at Mundesley, Norfolk (West, 1980). Finally, the fourth group comprises sequences that record the fully glacial conditions of the Anglian (Candy et al., 2011a), including sites with evidence for periglacial soil phenomena, sand wedges and ice wedge casts indicative of widespread and continuous permafrost, and glaciogenic sediments, such as the Lowestoft/Walcott Till and the Corton/Happisburgh Till emplaced by lowland glaciations at this time (Kemp et al., 1993; Whiteman, 2002; Candy et al., 2011a). This final group is not discussed in detail here, since it provides little in the way of detailed palaeoclimatic information, with the exception of ice wedge casts that indicate mean annual temperatures of $<0^{o}$C (Candy et al., 2011a).

Unfortunately, this scheme cannot be applied universally to British MIS 13-12 sequences. The calcareous nature of the sediments preserved at the important early Acheulian site at Boxgrove has resulted in poor pollen preservation (Roberts and Parfitt, 1999), making it difficult to place this site into the vegetation scheme outlined above. This site has also yielded quantified temperature reconstructions through ostracod and herptofaunal assemblage studies, albeit with large ranges that cannot assist in refining palaeotemperature estimates (Holmes et al., 2010). However, the mammalian assemblages from Boxgrove suggest that the landscape was mostly open grassland with some areas of woodland, implying that the fossiliferous silts accumulated after the main interglacial peak (Roberts and Parfitt, 1999; Holmes et al., 2010; Hosfield, 2011). It is important to note, however, that mammals such as *Muscardinus avellanarius* (hazel dormouse), which is closely associated deciduous woodland, occur in association with the earliest archaeology at this site, thereby suggesting that the earliest Acheulian occupation at Boxgrove occurred under fully temperate climatic conditions (Roberts and Parfitt, 1999). Nevertheless, most of the Boxgrove sequence is likely to have been deposited after the interglacial, an interpretation supported by the fact that the sequence accumulated in association with a raised beach landform after sea-level began to fall in the later part of the interglacial-glacial cycle. Consequently, it is assumed that much, but not all, of the Boxgrove palaeoenvironmental sequence records the climate of southern Britain after the interglacial peak has passed.

The Group 1 sequence at Sidestrand, Norfolk, is crucial to understanding the thermal maximum of MIS 13 in Britain, since it contains the most diverse palaeoecological assemblage known from this period and has also yielded the warmest palaeotemperature reconstructions (West, 1980; Preece et al., 2009; Candy et al., 2010). The fragmented nature of the British Quaternary terrestrial record, in which sedimentary units invariably represent relatively short-lived periods of deposition, means that the preservation of deposits representing the absolute thermal peak cannot be assumed. Consequently, the palaeoclimatic data from the *Unio* Bed at Sidestrand can be used to propose the minimum degree of warmth that must have been achieved during the thermal optimum. Mutual climatic range (MCR) reconstructions based on the coleopteran assemblage from Sidestrand have generated rather broad temperature ranges for both the mean warmest (+16 to +24^{o}C) and mean coldest (-9 to +9^{o}C) months (Preece et al., 2009; Coope, 2010). However, these can be further constrained due to the occurrence of a suite of thermophilous plant and animal species in the Sidestrand sequence. These include *Trapa natans* (water chestnut) and *Najas minor* (brittle naiad), both exotic to Britain at the present day and found only in association with the thermal maxima of past interglacials. These plants require mean summer temperatures of ~20^{o}C and ~18^{o}C respectively in order to germinate successfully (Candy et al., 2010), constraining summer temperatures towards the upper end of the MCR warmest month temperature range.

Where present, *Trapa natans* is used to infer summer temperatures of >/=20^{o}C. However, it is important to note that the ecological tolerances of this species are complex and in some settings, particularly at the edges of its range, its distribution may be in response to climatic variables other than temperature (Korhola and Tikkanen, 1997). Nevertheless, temperature thresholds for several key parts of its lifecycle have been recorded: general water temperatures of 12-15°C (Karg, 2006), temperatures above +16°C in order for seed germination (Galanti et al., 1990) and above +20°C for flowering (Jorga et al., 1982) and for fruiting (Meusel et al., 1978). Since these last two are essential for the maintenance of viable populations, we apply the upper threshold of +20^{o}C in this study. Furthermore, although it would be reasonable to assume that the comparison between temperature reconstructions from coleopteran and aquatic plants would be incompatible, as they quantify air and water temperatures respectively, in the sites presented here this is not an issue. A number of modern studies have shown that in lowland Britain, river water temperatures rapidly equilibrate with air temperature, meaning that mean river water temperature are directly comparable with mean air temperature (Waghorne et al., 2012). Although this may not be true for lacustrine systems, since all of the temperature reconstructions presented here are derived from fossil assemblages from fluvial sediments, it is assumed that the temperature values presented here reflect prevailing air temperature.

The presence of species that are intolerant of harsh winters, notably *Hippopotamus* and the water fern *Azolla filiculloides*, also indicate that the mean temperature of the coldest month was unlikely to be <0^{o}C (Candy et al., 2010, although see Janes, 1998 and Szczęśniak et al., 2009). The temperature reconstructions from Sidestrand therefore indicate an environment where warmest month temperatures were at least 3-4^{o}C warmer and winter temperatures broadly comparable to present day climatic conditions.

The Group 2 sequences at High Lodge, Waverley Wood, Brooskby and Happisburgh I record relatively consistent environmental and climatic conditions at the end of the MIS 13 interglacial and the transition into the subsequent MIS 12 glacial stage (Hunt, 1992; Shotton et al., 1993; Coope, 2006; 2010; Ashton et al., 2008a). Vegetational indicators from these sites suggest the development of boreal/coniferous woodland, frequently dominated by *Pinus* (pine) and *Picea* (spruce) with areas of open grassland. These sites have yielded some fully temperate elements, such as the straight-tusked elephant *Palaeoloxodon antiquus* (High Lodge and Waverley Wood) and the Etruscan rhinoceros, *Stephanorhinus etruscus* (High Lodge). However, the MCR temperature reconstructions from these localities provide a fairly uniform picture of cool climates, with mean warmest month reconstructions at least 1-2^{o}C cooler than present (assuming the upper end estimate of the MCR reconstructions) and mean winter temperatures significantly harsher that the present day (below 0^{o}C; Coope, 2006). These temperature estimates are consistent with the boreal nature of some of the species present in the coleopteran assemblages, such as the beetle *Micropeplus hoogendorni*, which is today found in Siberia, at both Waverley Wood and Happisburgh I (Ashton et al., 2008a). It is important to note that the combination of winter and summer temperatures reconstructed for these sites has no analogue in modern day Britain; although comparable summer temperature ranges occur today in northern Scotland, the low winter temperatures have no equivalent in modern lowland Britain.

The Group 3 sequence preserved at Ostend, Norfolk (the Arctic Freshwater Bed) records the climate of the early Anglian and preserves evidence for a continuation of the climatic cooling observed in the post-temperate sequences described above (Parfitt et al., 2010b). Pollen analysis indicates an abundance of herbaceous taxa, suggesting an open landscape with some trees (*Pinus*, *Picea* and, to a lesser degree, *Betula*, *Salix* and *Alnus*). The coleopteran assemblage from the Arctic Freshwater Bed is also indicative of a cold climate, containing a number of species that are currently found in arctic Russia; MCR estimates suggest mean warmest month temperatures of 9 to 11^{o}C and mean coldest month temperatures of -36 to -10^{o}C. The boreal/arctic climate recorded by the flora and invertebrate fauna of the Ostend deposits is supported by elements of the vertebrate fauna, which include *Dicrostonyx* sp. (collared lemming family). The “glacial maximum” of the Anglian is represented in the Ostend sequence by the sub-glacial diamictons that are found across eastern England, but the climate that occurred immediately prior to this event is found in the extensive assemblage of periglacial soil features preserved at a number of sites in East Anglia. These imply mean annual temperatures $<0^{o}$C and represent the end point of the cooling trend described above (Candy et al., 2011a).

The climatic characteristics of the transition from MIS 13 to 12 in Britain summarised above allows two key observations to be made. First, the magnitude of summer warmth experienced in Britain during MIS 13 was as great as any recorded in the Quaternary of the British Isles. Although the suite of thermophilous taxa from the *Unio* Bed at Sidestrand is not as rich as those known from Late Pleistocene MIS 5e sequences, the inferred climatic conditions are indistinguishable from that of the last interglacial in Britain (Candy et al., 2010). This suggests that the thermal maximum of MIS 13 in eastern England was as warm as that of

MIS 5e, which is generally considered to be the warmest interglacial of the last 450 ka in Europe. This contrasts strongly with prevailing global views of MIS 13, which suggest that it was the coldest interglacial of the past 800,000 yrs (Lang and Wolff, 2011). Furthermore, with the exception of the last (Devensian) glaciation, no Pleistocene cold stage has yielded as rich a record of periglacial climate soil features as the Anglian, and no other cold stage prior to the Devensian provides such clear evidence for lowland glaciation in Britain. This is partly due to the poor preservation of late Middle Pleistocene deposits in the region that lies between the Anglian glacial maximum and that of the last cold stage, which has hampered positive identification of post-Anglian, pre-Devensian glacial deposits (White et al., 2010). The extremes of climate that characterized Britain during MIS 13–12 suggest that this was one of the highest-amplitude interglacial/glacial transitions to affect this region. Again, this is in strong contrast to the record of this transition in most marine and ice core sequences, which indicate a relatively subdued and muted glacial inception (Lang and Wolff, 2011)

Second, it is now clear that the earliest Acheulian in Britain appeared during the MIS 13–12 climatic transition, and that these archaeological sites have a consistent palaeoenvironmental signature. Currently, all pre-Anglian Acheulian assemblages, with the exception of the oldest archaeological levels at Boxgrove, are associated with post-temperate interglacial/interstadial climates characterised by boreal landscapes and both winter and summer temperatures colder than the present day. Although the reconstructed warmest month temperatures are consistent with those seen in northern Britain, the severity of the coldest month temperatures has no modern British analogue and implies more continental conditions. These conditions are probably partly due to falling sea levels after the MIS 13 interglacial peak, which resulted in a gradual loss in the maritime character of the British Isles and the occurrence of more progressively continental climates.

The palaeoclimate of MIS 13 to 12 in the North Atlantic and Europe

The North Atlantic has yielded a wide range of SST records (Figs 2 and 5), which have been reconstructed at a range of resolutions using a variety of proxy techniques (Candy and McClymont, 2013). Of particular relevance here are the U1313 (Naafs et al., 2012) and M23414 (Kandiano and Bauch, 2003) records. U1313 is an Alkenone U^{k}_{37} based record of mean annual SST (41^{o}N), which is the highest resolution (0.4ka) SST record anywhere in the world. M23414 contains a Foraminifera transfer function-based record of summer and winter SST (53.5^{o}N), which extends back only 500,000 years and therefore contains only the final phase of MIS 13, but is also of high resolution (1.7ka) and is the closest record to Britain. Examination of these records allows two main observations to be made. First, the climatic characteristics of MIS 13 to 12, as recorded in the British terrestrial record, are consistent with those seen in these two north Atlantic SST records. In the U1313 record, for example, the climatic optimum of MIS 13 (20.2^{o}C) is consistent with those of MIS 5e (19.9^{o}C) and MIS 11 (20.1^{o}C), whilst in the same record, MIS 12 is the coldest glacial of any cold stage of the past 800 ka (Fig. 5). This does not imply that all these interglacials are alike (on the contrary, in terms of duration and structure they are clearly very different), but confirms that the maximum SST temperature values that occurred during MIS 13 are consistent with those of later interglacials. It is likely that in U1313, the duration of peak interglacial conditions in MIS 13 is relatively short-lived (Candy and McClymont, 2013).

In the case of M23414, the summer and winter SST peaks (14.6^{o}C and 10.9^{o}C respectively) are warmer than those of MIS 7 and 9 (14.4/10.6^{o}C and 14.0/10.5^{o}C respectively) but slightly cooler than those of MIS 5e and 11 (15.7/11.5^{o}C and 15.4/11.4^{o}C respectively). Given that the uncertainties associated with the transfer function technique are in the order of at least +/- 1^{o}C, it is reasonable to suggest that there is no statistical difference between the winter and summer temperature peaks of all these interglacials, and certainly between those of MIS 5e, 11 and 13 (Fig. 5). These SST records are therefore consistent with the British terrestrial evidence, suggesting that MIS 13 was an interglacial of strong warmth and that the MIS 13–12 transition was one of the most extreme climatic shifts of the Middle and Late Pleistocene.

Another important feature of the climatic structure of MIS 13 is the uncommon position of its thermal maximum, as observed in U1313, which occurred at the very end of this isotopic stage, ~ 490 ka (Fig. 5); this differs from most other Pleistocene warm stages, in which the interglacial temperature peak occurred during the early onset of the interglacial (Voelker et al., 2010). If it is assumed that the thermal peak of MIS 13 in Britain corresponds to that seen in U1313, then the transition from the interglacial peak to the first stadial of MIS 12 at ~ 470 ka spans ~20,000 years. This would place all of the palaeoecological evidence for climatic change seen in Britain outlined above, from the fully temperate record at Sidestrand to the arctic sediments at Ostend, together with all of the associated Acheulian sites, into an extremely brief window of time. Such a situation is very different to, for example, the transition from MIS 11–10 or 5–4, where a period of ~50,000-60,000 years can be observed between the peak of the interglacial and the first major stadial of the following glacial stage (Lisiecki and Raymo, 2005; Voelker et al., 2010). The M23414 record does not contain a complete record of MIS 13 and therefore cannot be used to corroborate the data from U1313. However, the temperature values from proxies that occur at ~490 ka in M23414 are as warm as the peaks of subsequent interglacials, so it is reasonable to assume that this record is consistent with that of U1313. The late temperature peak during MIS 13 is also seen in a number of global climate records (Lisiecki and Raymo, 2005; Jouzel et al., 2007; Voelker et al., 2010).

Despite the strong agreement between the British terrestrial record and the North Atlantic SST records described above, the climatic structure of MIS 13 recorded elsewhere in the North Atlantic is more complicated. For example, U1314, which has a Foraminifera transfer function-based mean annual SST record spanning MIS 17-11, shows the peak of MIS 13 to be as warm as that of MIS 11, although it also suggests that the interglacial maximum of MIS 13 occurred much earlier in the interglacial at ~525 ka (Alonso-Garcia et al., 2011a and b). In the North Atlantic above the latitude of Britain (>57ºN), SST and ice-rafted detritus records (i.e. ODP 982 (Lawrence et al., 2009), it has been shown that MIS 13 was a relatively cool interglacial (Candy and McClymont, 2013), particularly in records from the Nordic and Labrador Seas (Aksu et al., 1992; Helmke et al., 2003).

More significant are those records from the Iberian margin (MD03-2699, which covers MIS 15-9 (Rodrigues et al., 2011), and MD01-2444/MD01-2443, which covers MIS 11-1 (Martrat et al., 2007)), which allow high resolution SST records to be directly compared with temperature and precipitation reconstructions for a number of Middle Pleistocene temperate episodes present in the terrestrial sequence at Gran Dolina, Atapuerca, Spain (Blain et al., 2012). The scenario in Spain and the Iberian margin is similar to that seen in Britain and the North Atlantic, where terrestrial climate reconstructions for sites with Acheulian archaeology can be resolved to marine isotope stage level and directly compared to a neighbouring SST record. The climatic reconstructions from Gran Dolina are based on herpetofaunas and are chronologically constrained through a combination of U-series and OSL dating, magnetostratigraphy and biostratigraphy (Blain et al., 2012). Although the Gran Dolina sequence does not provide a continuous record through the Middle Pleistocene, MIS 13, 11, 9 and 7 are clearly expressed. Temperature reconstructions indicate that MIS 11 and 9 are the strongest interglacials in terms of warmth, with MIS 13 being substantially cooler (Blain et al., 2012). Significantly, however, the precipitation reconstructions indicate that MIS 13 and other earlier interglacials were not only cooler but were also wetter, by the order of 100 mm/a, than MIS 11-7 (Blain et al., 2012). The temperature signature reported from Gran

Dolina is replicated in MD03-2699 (Rodrigues et al., 2011), which shows the temperature peak of MIS 13, again occurring at ~ 490 ka, being some 2.5^{o}C cooler than that of MIS 9 although only 0.7^{o}C cooler than that of MIS 11 (Fig. 6). As with the record of U1313, however, the peak of MIS 13 in MD03-2699 is relatively short-lived in comparison with both MIS 11 and 9 (Rodrigues et al., 2011). In the nearby composite record of MD01-2444/MD01-2443, the thermal peaks of MIS 9-1 are all warmer by 1-2^{o}C than the peak of MIS 11 and, by inference, must all be several degrees warmer than the peak of MIS 13.

Comparison of the Gran Dolina record with those of MD03-2699 and MD01-2444/MD01-2443 shows, in a similar manner to the British record, good consistency between the Pleistocene terrestrial and marine records for this region. However, in contrast to the British evidence, the MIS 13 records from Iberia and the Iberian margin are not characterized by strong warmth and are more consistent with the cooler MIS 13 interglacial conditions observed in numerous global records. The peak interglacial temperatures for MIS 13 derived from SST records in the North Atlantic therefore provide evidence for a complex climatic setting, with sites such as U1313 and M23414 indicating anomalously warm conditions in this interglacial when compared to the SST patterns of later interglacials such as MIS 11 and 5e.

Discussion

Palaeoclimates of western Europe during MIS 13 and 12 and the climatic context of early human occupation

We began this paper by framing the question as to whether the climate cycles that operated during the EMP were significantly different to those that operated from MIS 11 onwards. With respect to the final interglacial–glacial cycle of the EMP (MIS 13 to 12) in Britain, this appears not to have been the case. The magnitude of warmth experienced during the MIS 13 interglacial (based on evidence from Sidestrand) and the magnitude of cooling that occurred with the onset of MIS 12 (Fig, 4) are similar to those seen in later interglacial/glacial cycles in both the British terrestrial record and North Atlantic records such as M23414 and U1313 (Fig. 5). The arrival of the earliest Acheulian in Britain therefore corresponds with an interglacial/glacial transition that was as extreme as any experienced in the past 500,000 years. However, and perhaps more importantly, the highest resolution North Atlantic SST records from U1313 and MD03-2699 indicate that the MIS 13 interglacial was relatively short-lived, even where it appears to be characterised by significant warmth; furthermore, the transition from fully interglacial to fully glacial conditions was extremely rapid, with a duration of only ~20 ka, in strong contrast to other glacial/interglacial cycles of the past 500,000 yrs. The accelerated transition from MIS 13 to MIS 12 can be primarily attributed to the unusual structure of MIS 13, which was characterised by an interglacial peak late in the warm stage, apparently related to the greenhouse gas peak of this interglacial occurring at the very end of the warm stage (EPICA, 2004; Lisiecki and Raymo, 2005; Loulergue et al., 2008; Voelker et al., 2010).

It is also clear that the pattern outlined above does not apply elsewhere in Europe and the North Atlantic. In Spain and the Iberian margin, the MIS 13 to 12 transition is relatively muted, with MIS 13 appearing not only relatively cool but also significantly more humid, in comparison to interglacials from MIS 11 onwards (Blain et al., 2012). The comparison between the British/North Atlantic record and the Spanish/Iberian margin records is intriguing because it implies that a situation that has no obvious analogue during interglacials of the past 450,000 yrs existed during MIS 13. Temperatures in Britain and the North Atlantic during MIS 13 would have been as warm, or warmer, than most interglacials of MIS 11-1, whereas Spain would have been significantly cooler than these later interglacials. In turn, this would make the glacial inception (around the time of the appearance of the earliest Acheulian in Britain) relatively extreme in northwest Europe but subdued in southwest Europe.

With regards to MIS 13, the implication of these observations is that the latitudinal temperature gradient that existed during this interval would have been weaker than during most interglacial episodes of the late Middle and Late Pleistocene (Fig. 6). In reality, this temperature gradient can only be discussed in a qualitative and speculative manner because the sites that have yielded critical palaeoclimatic data are limited to two marine cores and two terrestrial interglacial localities. Between the latitudes of Britain and Spain, no sites that can be reliably correlated with MIS 13 and which provide quantified temperature reconstructions are yet known; however, given the potential importance for understanding the early human occupation of northern Europe, we highlight the following observations. In order to provide a "rule of thumb" indication of the potential difference in the temperature gradient of MIS 13 and those of later interglacials between these two locations, the mean annual temperature value for interglacial peaks from M23414 and MD03-2699/MD01-2444/MD01-2443 can be subtracted from each other. Using this metric, it is possible to propose a SST difference between Britain and Spain of <ca 4ºC during MIS 13; 2-3ºC less than during later interglacials, which provide values closer to 6.5ºC for MIS 9 and 5e (Fig. 6).

Clearly a number of assumptions and issues accompany such broad quantifications of climatic gradients, particularly because these reflect SST rather than air temperatures and therefore overlook the possibility that these differences were due to changes in ocean circulation patterns rather than regional climatic gradients. However, the fact that similar patterns can be observed in both terrestrial records, from which air temperatures can be estimated, and marine records from which SST reconstructions are derived, suggests that the coarse climate gradient estimates are indeed a function of regional climatic differences rather than local factors. This observation requires further testing as new evidence comes to light. Regardless of the absolute magnitude of the north-south temperature gradients, the fact that the magnitude of the gradient that occurred during MIS 13 appears to have been relatively subdued is critical to understanding the climatic context of the earliest Acheulian occupation of northwest Europe. It is often proposed that one of the reasons for the relatively “late” colonisation of northern Europe, compared to southern Europe, was that the climatic setting north of the Alps offered a new set of ecological/environmental niches, to which hominins needed to adapt (Dennell and Roebroeks, 1996; Roebroeks, 2001; 2005; 2006; Parfitt et al., 2005; Hosfield, 2011). The ideas presented here do not contradict this proposal, but highlight the complexity of the climatic setting in northern Europe during the late EMP, particularly during MIS 13. The evidence outlined above in fact suggests that a *reduced* climatic difference existed between northern and southern Europe, which possibly aided the migration of early humans northwards. This unique climatic setting, corresponding with the arrival of the earliest Acheulian in northern Europe, is a key consideration when discussing the environmental drivers of early human occupation in northern Europe.

Palaeoclimates of the earliest Acheulian in Britain

The above synthesis allows three key observations to be made about the earliest Acheulian sites in Britain. First, that Acheulian sites occur in association with a major climatic transition, from an interglacial climate as warm as MIS 5e through to a glacial stage that was characterised by lowland glaciation in the British Isles. Second, that the marine records from the North Atlantic suggest that this extreme climatic shift potentially occurred over a relatively short time interval of ca 20,000 yrs. Third, that the sites where the most convincing links occur between palaeoclimatic reconstructions and Acheulian technologies indicate that humans consistently occupied a post-temperate interglacial/interstadial landscape dominated by boreal woodland and open grassland under a temperature regime that was cooler and more continental than the present day (Hosfield, 2011; Preece and Parfitt, 2012).

With respect to this final point, this does not preclude the presence of hominins from the climatic optimum of MIS 13. Although a handaxe attributed to the pre-glacial sediments at Sidestrand has been difficult to pin down in terms of its actual context, it nevertheless highlights the possibility of Acheulian archaeology being present during the interglacial peak (Moir, 1923; Wymer, 1985; 1988; Preece et al., 2009). Archaeology at Boxgrove has been found in association with intertidal sediments (the Slindon silts), suggesting human presence in the British landscape in association with a high sea-level stand (Roberts and Parfitt, 1999). The absence of palaeobotanical information, however, prevents it from being definitely established whether hominin occupation occurred in association with deciduous woodland (and therefore warm climate conditions) but the presence of *M. avellanarius* in association with the archaeological levels provides a strong indication that this was so (Roberts and Parfitt, 1999). Finally, at Westbury-sub-Mendip, flint flakes have been found in association with fully temperate vertebrate assemblages (Bishop, 1975). Cutmarked bone also occurs at this site but in association with cool-temperate vertebrate faunas (Andrews and Ghaleb, 1999). The human origin of the flakes has, however, been queried and neither the artefacts nor the cutmarks can prove the existence of Acheulian technology at this site (Cook, 1999).

Consequently, while aspects of the small mammal assemblage from Boxgrove support the presence of Acheulian industries in Britain during warm climate conditions in MIS 13, even at that site, the main archaeological horizons occur in association with a falling sea level, thus post-dating the interglacial peak. The overwhelming majority of sites in MIS 13 clearly post-date the thermal optimum and suggest hominin occupation under post-temperate interglacial/interstadial conditions. These observations are based on a restricted number of sites, however, if it is accepted that there is evidence for some Acheulian occupation during fully temperate (albeit post-optimum) conditions and more abundant evidence for Acheulian occupation during post-temperate interglacial or interstadial conditions, then the British record of hand axe distribution during MIS 13 is similar to that witnessed in MIS 11 (the Hoxnian interglacial). In the British record of MIS 11, Acheulian assemblages are found in association with: 1) fully temperate climates (the Lower Middle Gravel at Barnfield Pit), 2) late interglacial climates (the Upper Middle Gravel and Upper Gravel at Barnfield Pit) and 3) interstadial conditions that occur after the main interglacial, MIS 11a (?) (Hoxne)(Bridgland, 1994; White and Schreve, 2000; Schreve, 2001b; Ashton et al., 2008b).

The number of pre-Anglian Acheulian sites in Britain is too small to make confident statements about the environmental preferences of these early hominin groups, although the traditional view of avoidance of dense forests with restricted hunting opportunities still holds true (Gamble 1987). However, a number of sites apparently record Acheulian activity not only in association with cool temperate climates but specifically with harsh winters, for example Happisburgh I, which has yielded strong evidence for mean coldest month temperatures of <-3^{o}C. As highlighted earlier, these MCR temperature reconstructions have, on the basis of the extreme cold recorded for the winter months, no analogue in modern day Britain and require an increase in continentality to occur. In this respect, the key question related to environmental controls on the earliest Acheulian in Britain concerns the "overwintering problem" (Roebroeks, 2006; Hosfield, 2011). How did the earliest humans cope with the extremely low winter temperatures that the Acheulian inhabitants apparently encountered? This is a question not simply associated with the earliest British Acheulian but with almost all human occupation (Mode I and II sites) in the British EMP (Parfitt et al., 2010a). With the exception of Pakefield, which appears to be increasingly anomalous in its evidence for early hominin activity in association with interglacial climates of extreme warmth, all other sites where lithic assemblages can be associated with robust palaeoenvironmental and temperature reconstructions consistently indicate hominin occupation in association with cool or post-temperate climates, boreal landscapes and/or climates that are cooler than the present, notably with winter temperatures that were at least ≤0^{o}C. The ability to cope with extreme cold in winter may relate closely to long range migration behaviour, fire use or other subsistence/adaptation strategies. However, the nature of these adaptations would increasingly appear to be the crucial question that needs to be addressed in order to understand both the climatic context of the earliest Acheulian occupation and indeed the earliest hominin occupation of any kind in Britain and northern Europe.

Conclusions

There is increasing evidence to suggest that the earliest Acheulian in Britain occurred during MIS 13, potentially extending into early MIS 12. A review of the stratigraphic and climatic evidence for this interval in Britain and the North Atlantic allows the following conclusions to be drawn concerning the climatic context of the earliest Acheulian in Britain.

- The earliest Acheulian in Britain occurred in association with one of the most extreme interglacial to glacial transitions of the past 500,000 years, with MIS 13 to 12 in Britain being characterised by a shift from climates that were as warm as those of MIS 5e through to a glacial stage that was characterised by widespread periglaciation and lowland glaciation. This pattern is consistent with records of SST variability in the North Atlantic at comparable latitudes to the British Isles.
- Although there is good evidence to support the presence of Acheulian industries in Britain during temperate climate conditions in MIS 13, the majority of Mode II archaeological sites, when found in association with robust multiproxy palaeoenvironmental data, suggest that early humans were existing largely under cool to post-temperate climates, boreal landscapes and/or under climatic regimes that are cooler than the present, notably with winter temperatures at or below freezing. The coleopteran-based MCR temperature reconstructions from the "cool temperate" Acheulian sites suggest that the climate and environments of these early colonists have no analogue in modern day Britain, primarily because of the extreme winter cold envisaged. This implies that human occupation occurred during episodes of enhanced continentality, most probably in association with the falling sea levels that occurred after the main interglacial peak. The ability of early human populations to adapt to these relatively 'extreme'" winter conditions would appear to be the key factor when considering the nature of the earliest Acheulian (and indeed pre-Acheulian) occupation of Britain.
- The record of MIS 13 seen in Britain and the North Atlantic of enhanced warmth contrasts sharply with that seen in terrestrial records of mainland Spain and SST records from the Iberian margin, which indicate that this interglacial was significantly cooler in those southerly regions than most interglacials of the past 450,000 yrs.
- It is likely that this strong contrast between the records of MIS 13 in northwest and southwest Europe would have produced weaker north-south temperature gradients during this interglacial than in later interglacial episodes, something that may have facilitated the spread of Acheulian populations. The climatic setting of Europe during MIS 13 was therefore significantly different from that seen in later

interglacials, a disparity that needs to be carefully considered when discussing the climatic context of early hominin occupation in northern Europe.

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Figure 1 – Long-term patterns of interglacial/glacial climate cycles as expressed in the EPICA Dome C deuterium record, top (Jouzel et al., 2007), and a sea surface temperature record from the southern ocean, middle (Martinez-Garcia et al., 2009). Note the shift in peak interglacial and glacial magnitude after MIS 13 which is clearly expressed in both records. The bottom curve is the SST record from U1313 in the North Atlantic (Naafs et al., 2012), which shows a similar climatic stratigraphy but a less clear shift in interglacial intensity post-MIS13. The Stratigraphic nomenclature of the British terrestrial sequence (centre) is compared with these long continuous climate records. The estimated age of pre-Anglian (pre-MIS 12) archaeology is shown. Parfitt et al., (2005) have proposed that Mode I archaeology at Pakefield could relate to either MIS 17 or 19 (with the Mode I archaeology at Happisburgh III being pre-MIS 19 and, therefore, not shown in this figure). Westaway (2009a; 2009b and 2010) has suggested that all Mode II archaeology (Pakefield and Happisburgh III) should be correlated with MIS 15. Most authors suggest a correlation of pre-Anglian Acheulian sites with MIS 13 and possibly the very end of MIS 15.

Figure 2 – Maps of the key sites discussed in this study; a) Europe and the North Atlantic, and b) the British Isles. All records in 2a contain key important records of MIS 13, mostly with quantified temperature estimates: MD03-2699 (Rodrigues et al., 2011), Atapuerca (Blain et al., 2012), U1313 (Naafs et al., 2012), M23414 (Kandiano and Bauch, 2003), 982 (Lawrence et al., 2009), MD-992277 (Helmke et al., 2003). Labels for 2B; Bx – Boxgrove, W-S-M - Westbury-sub-Mendip, WW- Waverley Wood, Br – Brooksby, Fl – Feltwell, WH – Warren Hill, HL - High Lodge, Pk – Pakefield, Hp – Happisburgh, Os – Ostend, Si – Sidestrand, WR – West Runton.

Figure 3 – $\delta^{18}O$ stratigraphy of the early Middle Pleistocene as shown in LR04 (top). The records from DSDP 607 (middle) and ODP 1123 (bottom) is the estimated $\delta^{18}O$ of sea water calculated using benthic $\delta^{18}O$ values and quantified bottom water temperature estimates. These studies give a clearer indication of global ice volume as they remove past variations in fractionation that are inherent to any benthic signal. These studies show a clear pattern of

MIS 13, 17 and 19 having a single "interglacial/temperate" interval, whilst MIS 15 appears to have two relatively clear but separate fully interglacial/temperate episodes.

Figure 4 – Climatic and environmental data from sites that correspond to MIS 13 through to MIS 12 in Britain. Most temperature estimates are from coleopteran mutual climate range (MCR) estimates (see discussion in Coope, 2006; 2010; Candy et al., 2010; Parfitt et al., 2010). The exceptions to this are; Boxgrove and the Ostend Arctic Bed, where temperature estimates are based on ostracod assemblages using the MOTR technique (Holmes et al., 2009; Horne et al., 2012). In the Ostend 'Freshwater Bed' minimum summer temperatures are based on the presence of *Trapa natans* (West, 1980). Both Boxgrove and the Ostend 'Freshwater Bed' are suggested to occur late in the interglacial; Ostend on the basis of the associated pollen assemblage (post temperate IVa) and Boxgrove on the basis of the open nature of many of the mammal species. The Sidestrand *Unio* bed represents the early temperate (pollen zone II (West, 1980; Preece et al., 2009) and Tmax is constrained by the plant macrofossil evidence and the coleopteran based MCR. The sites within the "Late MIS 13" category are all characterised by more "boreal" landscapes (Hunt, 1992; Ashton et al., 2008; Shotton et al., 1993) although little is known about the vegetation from Brooksby (Coope, 2006). Note that coleopteran assemblages from Waverley Wood record oscillations in both Tmax and Tmin, the estimates quoted here are from the base of the channel in the main section (Shotton et al., 1993). MIS 12 conditions are indicated by the Ostend 'Arctic Bed' (Parfitt et al., 2010) and the periglacial phenomena of the Anglian glacial (Candy et al., 2010) the evidence of open-ground species during the Anglian comes from plant macro-fossils assemblages from sites such as Corton (West and Wilson, 1968).

Figure 5 – The temperature record of MIS 13 as shown from three different North Atlantic records (see figure 2 for site location) and the EPICA Dome C (EDC) deuterium based temperature anomaly record for reference (Jouzel et al., 2007). In all cases that dashed horizontal line represents the mean temperature maximum of MIS 11 to 5 in the same record, or in neighbouring records, MD01-2444/MD01-2443 (Martrat et al., 2007) in the case of MD03-2699. Crucially these records show that in U1313 and M23414 the temperature peak of MIS 13 is as warm as those of later interglacial, consistent with the British terrestrial record which is at the same latitude as M23414. The record from the Iberian margin shows a temperature signal that more closely equates to the EDC record which shows that the peak of MIS 13 is significantly colder than that of later interglacials. The Iberian margin record of MD03-2699 is consistent with the terrestrial temperature record from Atapuerca that also shows MIS 13 being cooler than post MIS 12 interglacials. The vertical red lines represent the timing, in the north Atlantic, of the interglacial peak of MIS 13 and the first stadial of MIS12, highlighting the rapidity (20,000 yrs) of the transition from fully interglacial to fully glacial conditions.

Figure 6 – Temperature differences between the interglacial peak of; a) MIS 13 (490,000 yrs BP) and b) MIS 5e (125,000 yrs BP). The temperature difference between southwestern and northwestern Europe during MIS 13 is effectively two thirds of that which occurred in later interglacials such as MIS 5e. SST data from MD03-2699 (Rodrigues et al., 2011) and MD01-2444/MD01-2443 (Martrat et al., 2007), SST data from M23414 is based on foram data from Kandiano and Bauch (2003) but recalculated to yield mean annual rather than summer and

winter SST (mean annual data calculated using ANN and the MARGO dataset, data calculated by and used with permission of Dr M. Alonso-Garcia).

Table 1 – A summary of the key sites of MIS 13 and 12 age in the British Quaternary. The table summarises the key chronological data, proposed age, palaeoenvironmental data and presence/absence of archaeology.

	Chronological evidence							Key palaeoclimatic proxies							
		Vertebrates								Thermophiles					
SITE:	Pollen	*Arvicola terrestris cantiana*	*Microtus gregaloides*	*Microtus gregalis*	Dating	Stratigraphy	**Proposed age**	Coleopteran MCR	MOTR	*Najas minor*	*Trapa natans*	*Azolla filiculoides*	*Hippopotamus* sp.	**Inferred climate**	**Archaeology**
Sidestrand (*Unio* Bed) West (1980) Preece *et al*. (2009)	Zone IIa	+	+		AAR	Overlain by Anglian deposits	MIS 13 (15?)	Tmax +16 to +24 °C Tmin -9 to +9 °C		+	+	+	+	Temperate	Acheulian?*
Ostend (freshwater bed) West (1980)	Zone IV	+				Overlain by Anglian deposits	MIS 13				+	+		Late temperate	n/a
Boxgrove (Slindon silts and continental facies) Roberts and Parfitt (1999) Holmes *et al*. (2009)		+		+			MIS 13		Tmax +14 to +20 °C Tmin -4 to +4 °C					Temperate – post temperate	Acheulian
Brooksby (Bytham sands and gravels) Coope (2006, 2010)							MIS 13	Tmax +15 to +16 °C Tmin -10 to +2 °C						Post temperate?	Acheulian
Waverley Wood Shotton *et al*. (1993) Coope (2006)		+			AAR	Overlain by Anglian deposits	MIS 13	Tmax +15 °C to +18 °C † Tmin -13 to +1 °C						Late temperate / post temperate	Acheulian
High Lodge Hunt *et al*. (1991) Hunt (1992) Coope (2006)						Overlain by Anglian deposits	MIS 13	Tmax +15 to +16 °C Tmin -4 to +1 °C						Late temperate	Acheulian
Happisburgh I Ashton *et al*. (2008) Coope (2006)		+				Overlain by Anglian deposits	MIS 13	Tmax +12 to +15 °C Tmin -11 to -3 °C						Post temperate	Acheulian
Ostend (Arctic bed) (Parfitt *et al*. (2010b), Horne et al. (2012))				+		Overlain by Anglian deposits	early MIS 12	Tmax +9 to +11°C Tmin -36 to -10 °C	Tmax +10 to +13°C Tmin -21 to -20 °C					Early glacial	n/a

† sequence contains evidence for climatic variability, values from the base of the sequence shown here

* see Moir (1923)

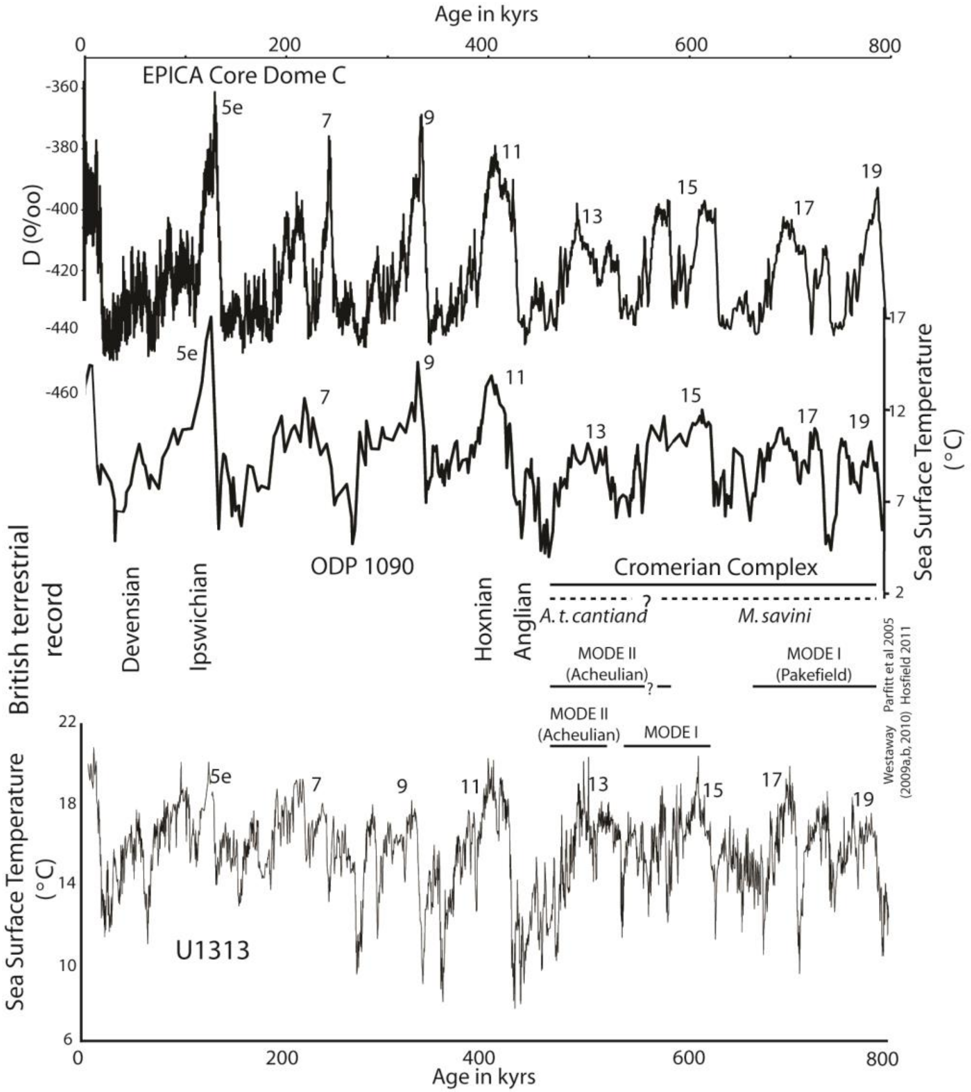

Age in kyrs
0
200
400
600
800
EPICA Core Dome C
D (0/oo)
-360
-380
-400
-420
-440
-460
5e
7
9
11
13
15
17
19
ODP 1090
Sea Surface Temperature (°C)
17
12
7
2
Cromerian Complex
?
A. t. cantiana
M. savini
British terrestrial record
Devensian
Ipswichian
Hoxnian
Anglian
MODE II (Acheulian)
MODE I (Pakefield)
Parfitt et al 2005 Hosfield 2011
MODE II (Acheulian)
MODE I
Westaway (2009a,b, 2010)
Sea Surface Temperature (°C)
22
18
14
10
6
U1313
Age in kyrs

Figure 1

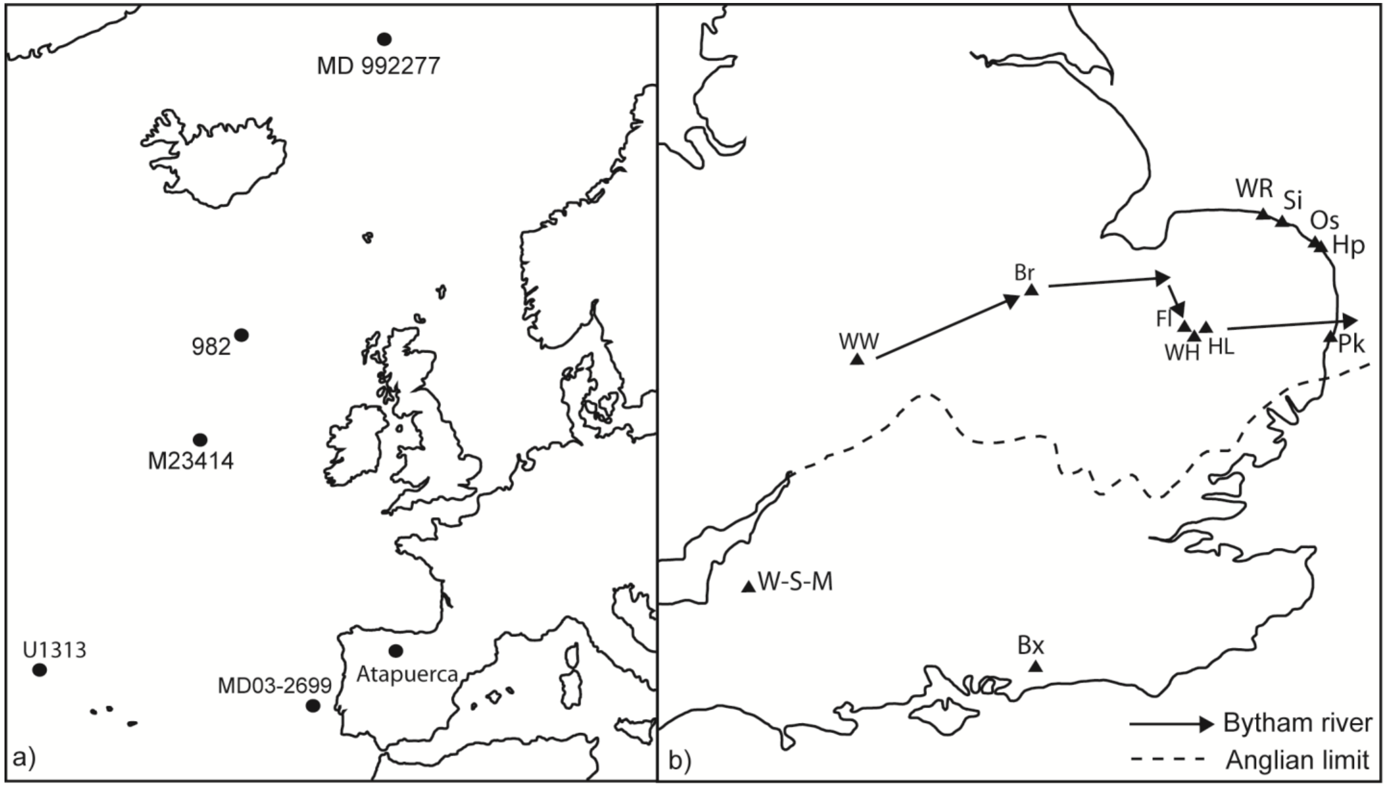

MD 992277
982
M23414
U1313
MD03-2699
Atapuerca
a)
WR
Si
Os
Hp
Br
WW
Fl
WH
HL
Pk
W-S-M
Bx
Bytham river
Anglian limit
b)

Figure 2

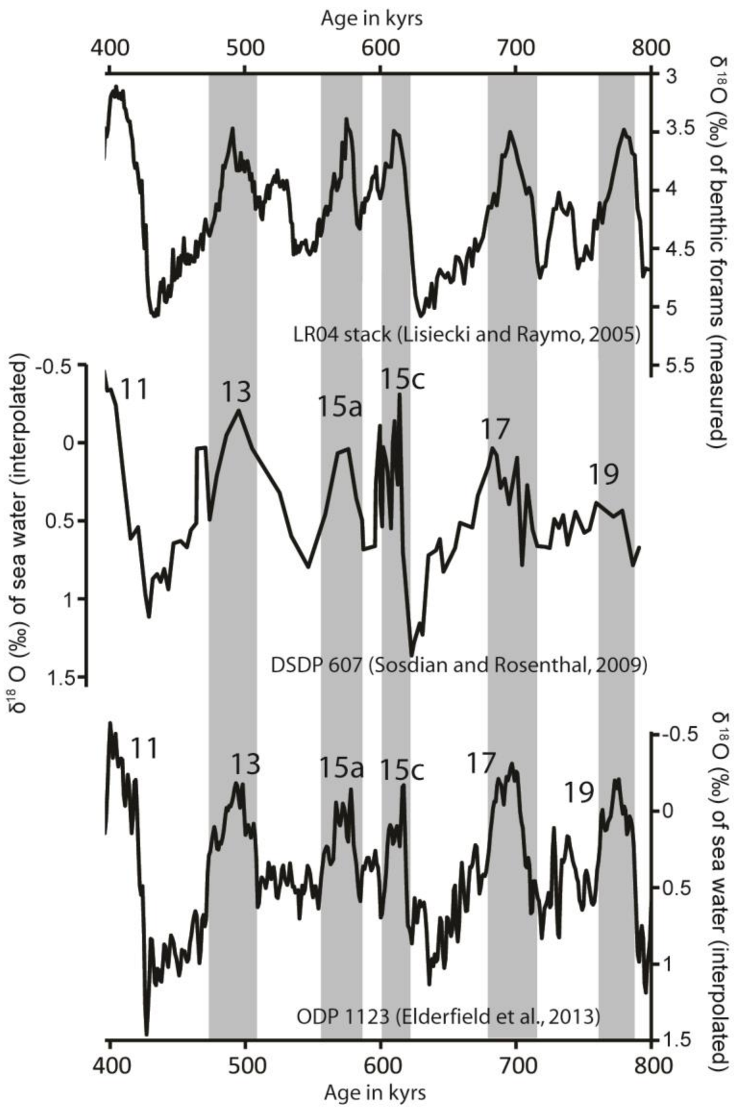

Age in kyrs
400
500
600
700
800
3
3.5
4
4.5
5
5.5
δ18O (‰) of benthic forams (measured)
LR04 stack (Lisiecki and Raymo, 2005)
-0.5
0
0.5
1
1.5
δ18 O (‰) of sea water (interpolated)
11
13
15a
15c
17
19
DSDP 607 (Sosdian and Rosenthal, 2009)
11
13
15a
15c
17
19
-0.5
0
0.5
1
1.5
δ18O (‰) of sea water (interpolated)
ODP 1123 (Elderfield et al., 2013)
400
500
600
700
800
Age in kyrs

Figure 3

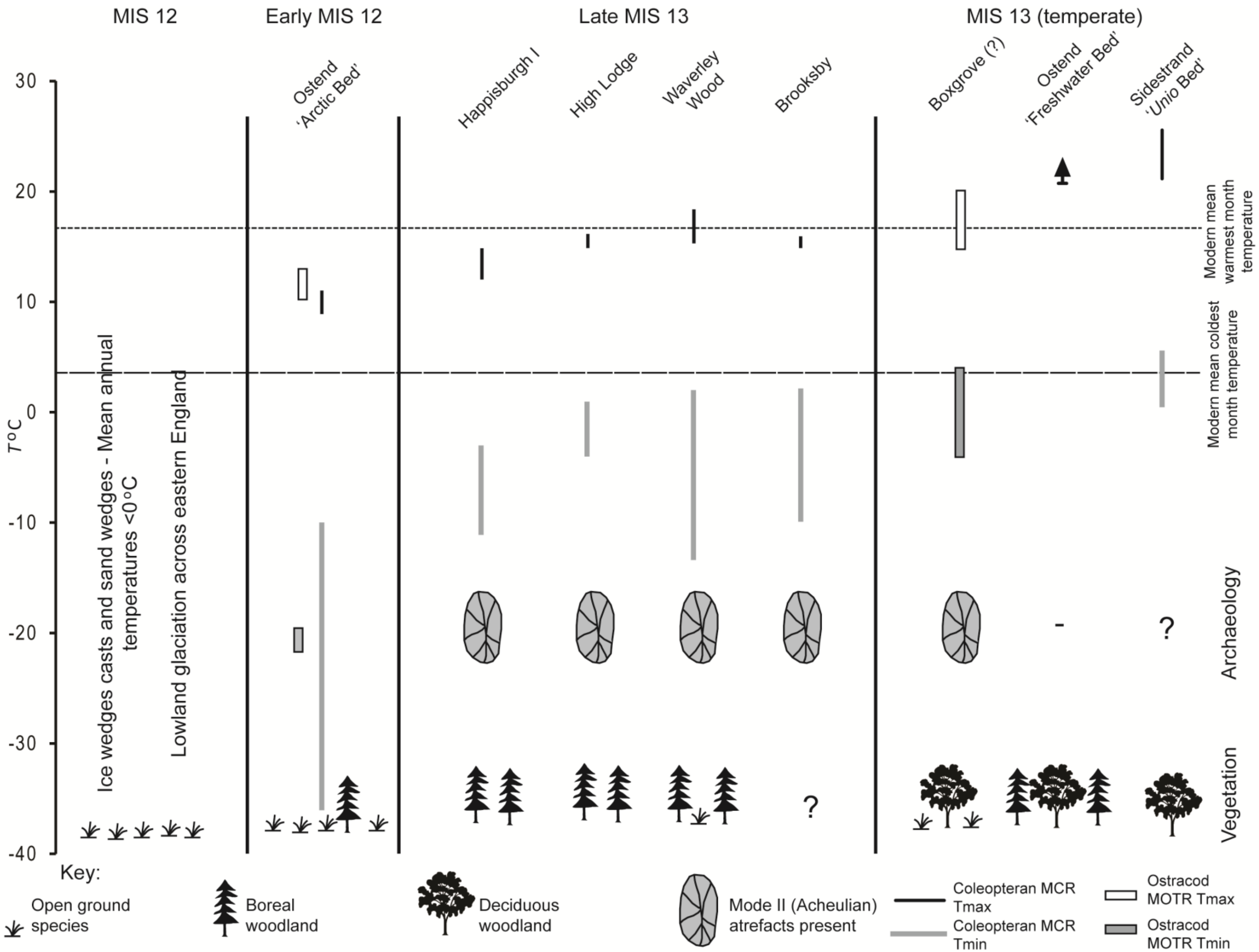

MIS 12
Early MIS 12
Late MIS 13
MIS 13 (temperate)
Ostend 'Arctic Bed'
Happisburgh I
High Lodge
Waverley Wood
Brooksby
Boxgrove (?)
Ostend 'Freshwater Bed'
Sidestrand 'Unio Bed'
T °C
30
20
10
0
-10
-20
-30
-40
Ice wedges casts and sand wedges - Mean annual temperatures <0 °C
Lowland glaciation across eastern England
Modern mean warmest month temperature
Modern mean coldest month temperature
Archaeology
Vegetation
-
?
?
Key:
Open ground species
Boreal woodland
Deciduous woodland
Mode II (Acheulian) atrefacts present
Coleopteran MCR Tmax
Coleopteran MCR Tmin
Ostracod MOTR Tmax
Ostracod MOTR Tmin

Figure 4

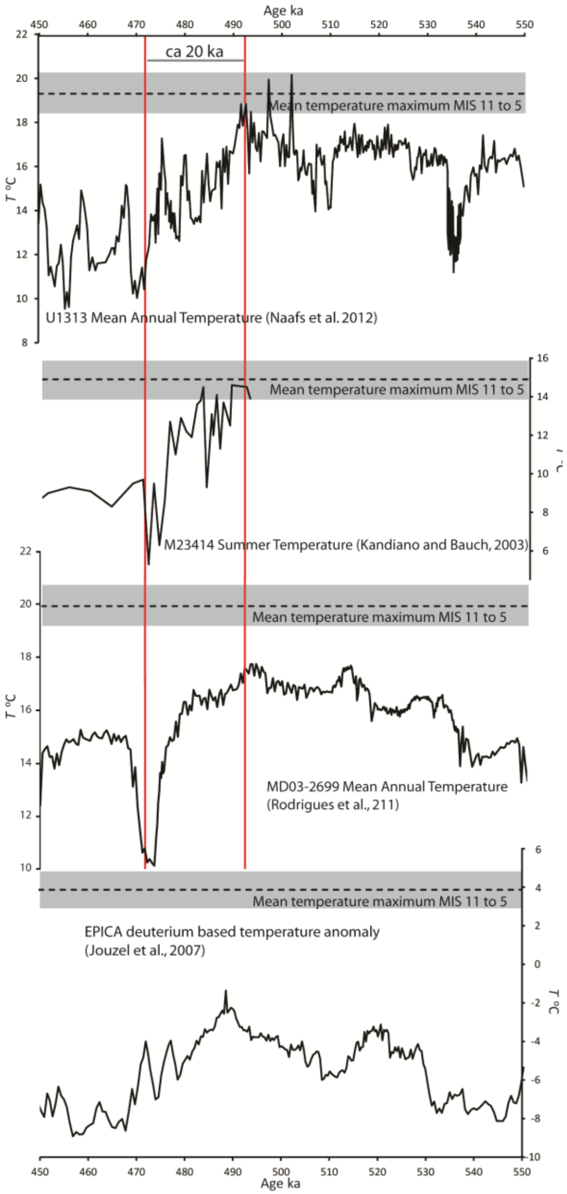
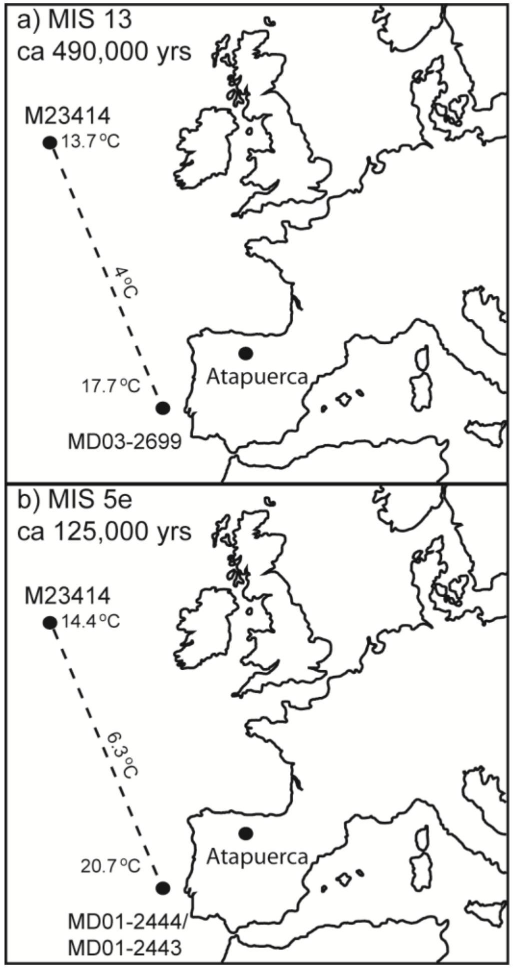

Age ka
ca 20 ka
Mean temperature maximum MIS 11 to 5
T °C
U1313 Mean Annual Temperature (Naafs et al. 2012)
Mean temperature maximum MIS 11 to 5
M23414 Summer Temperature (Kandiano and Bauch, 2003)
Mean temperature maximum MIS 11 to 5
MD03-2699 Mean Annual Temperature
(Rodrigues et al., 211)
Mean temperature maximum MIS 11 to 5
EPICA deuterium based temperature anomaly
(Jouzel et al., 2007)
Age ka

Figure 5


a) MIS 13
ca 490,000 yrs
M23414
13.7 ºC
4ºC
17.7 ºC
Atapuerca
MD03-2699
b) MIS 5e
ca 125,000 yrs
M23414
14.4 ºC
6.3ºC
20.7 ºC
Atapuerca
MD01-2444/
MD01-2443
Figure 6

onbehalfof+d.r.bridgland+durham.ac.uk@manuscriptcentral.com; on behalf of; d.r.bridgland@durham.ac.uk

Journal of Quaternary Science - Decision on Manuscript ID JQS-15-0085.R1

01-Oct-2015

Dear Dr Candy,

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Thank you for your fine contribution.

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