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The chronology of abrupt climate change and Late Upper Palaeolithic human adaptation in Europe

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ABSTRACT: This paper addresses the possible connections between the onset of human expansion in Europe following the Last Glacial Maximum, and the timing of abrupt climate warming at the onset of the Lateglacial (Bölling/Allerød) Interstadial. There are opposing views as to whether or not human populations and activities were directly 'forced' by climate change, based on different comparisons between archaeological and environmental data. We review the geochronological assumptions and approaches on which data comparisons have been attempted in the past, and argue that the uncertainties presently associated with age models based on calibrated radiocarbon dates preclude robust testing of the competing models, particularly when comparing the data to non-radiocarbon-based timescales such as the Greenland ice core records. The paper concludes with some suggestions as to the steps that will be necessary if more robust tests of the models are to be developed in the future.

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KEYWORDS: Lateglacial; radiocarbon calibration; IntCal04; Lake Suigetsu; palaeotemperature reconstruction; human adaptation; tephrochronology.

Introduction

The extent to which human evolution and adaptations have been influenced by climatic change during the late Quaternary is a key question in archaeology. The possible causal relationships between millennial-scale climate change and long-term hominid evolution has long been debated (e.g. Ruff, 1994; Holliday and Falsetti, 1995; Holliday, 1997, 1999; Sherratt, 1997; Housley *et al.*,1997; Blockley *et al.*, 2000a,b), but the idea that extremely abrupt climate shifts, decadal in scale, could be implicated as initiators of human dispersal and development has only recently emerged. It was not until the publication of the Greenland ice-core records in the early 1990s that the sheer rapidity with which the global climate system was capable of change became better appreciated (e.g. Alley *et al.*, 1993; Johnsen *et al.*, 1997). Prior to this development, assessments of rates of climate change, which were based on records obtained from other archives such as lake and ocean sediment sequences, were constrained by limitations affecting the dating methods employed; the latter were often not capable of resolving events with the temporal resolution required.

With the new perspective that the ice-core records have provided, there has been growing speculation about a possible causal link between, for example, the dramatic increase in temperatures that are assumed to have affected Europe around 14 700 Ice Core Years (ICY) ago, and the sudden dispersal of humans into northern and western parts of Europe, which appear to have roughly coincided with widespread cultural changes. Is it possible that abrupt climate change triggered an equally abrupt and widespread response in human development at that time? Some researchers have concluded that this was probably the case (e.g. Blockley *et al.*, 2000a,b; Terberger and Street, 2002; Blackwell and Buck, 2003), while others have argued instead for the greater importance of social and cultural influences, which need not have been driven by climate (e.g. Housley *et al.*, 1997). Here we examine the potential for resolving these opposing views. Success in this endeavour is important for archaeology, in terms of clarifying not only the history of events during the Late Upper Palaeolithic, but also the wider debate about how hunter-gatherer societies coped with repeated episodes of rapid environmental change during the late Quaternary.

The period with which we are concerned more-or-less equates with the Last Termination, the important transition between the end of the last cold stage and the start of the Holocene (ca. 23 to 11.5 k Ice Core Years (ICY) BP; ca. 20 to 10

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^{14}C kyr BP). This period witnessed a sequence of abrupt climatic changes which are clearly reflected in Greenland ice-core records, as well as in numerous North Atlantic and European palaeoenvironmental records (Lowe, 2001). In summary, the most important events, which are best represented in the Greenland ice-core records (proposed as palaeoclimate stratotypes for this period; see Björck *et al.*, 1998; Walker *et al.*, 1999, 2001), are: (i) an episode of severe cold during the Last Glacial Maximum (LGM), ca. 23–22 k ICY BP or ca. 20–18 k ^{14}C yr BP; (ii) subdued warming between ca. 18–13 k ^{14}C yr BP, during Greenland Stadial 2 (GS-2); (iii) significant climatic amelioration at ca. 14.7 k ICY BP, at the start of a period of comparative warmth that persisted until ca. 12.8 k ICY BP (13 to 11 k ^{14}C yr BP), termed Greenland Interstadial 1 (GI-1), or the Bölling–Allerød period; (iv) a return to severe cold during GS-1 (the 'Younger Dryas'), between 12.8 and 11.5 k ICY BP (11 to 10 k ^{14}C yr BP), and (v) marked climatic amelioration at the start of the Holocene (11.5 k ICY BP; 10 k ^{14}C yr BP). The GI-1 ('Bölling–Allerød') episode also experienced at least two minor (and/or very short-lived) periods of colder conditions, defined as events GI-1d and GI-1b in the GRIP stratotype record (Walker *et al.*, 1999). In this paper we are mainly concerned with the transition from the relatively cool conditions after the Last Glacial Maximum to the abrupt warming at the start of GI-1 at around 14 700 ICY BP. These events appear to have had major impacts in Europe, recorded in numerous environmental sequences, and since there are also extensive archaeological records for the Last Termination, it should in theory be possible to test hypotheses concerning the degree to which human development and climate change were causally connected during this interval. Indeed, the Last Termination is perhaps the best available period in which to examine this issue, because the climate shifts were very pronounced (ca. 7°C or more, based on some temperature reconstructions), the archaeological evidence is reasonably abundant, and of a relatively good level of preservation, and the period lies within the range of radiocarbon dating and calibration (although not the highest precision of calibration, as given by tree-rings). Despite these advantages, however, it has proved difficult to construct robust tests of the competing models. This paper outlines the chronological weaknesses that have undermined testing of the models presented so far, and ends with proposals that may lead to more robust approaches in the future.

The 'abandonment and re-immigration' debate

It is not disputed that human occupation of northwest and north-central Europe increased dramatically during the early 'Lateglacial' period (i.e. about or just before 13 k ^{14}C yr BP), for there is a significant increase in the number of records of human occupancy that date to around that time. What is debated are two main issues: (a) whether northern Europe was wholly abandoned, or alternatively was occupied only seasonally or sporadically, during the LGM, and (b) whether re-immigration into northwest Europe, some time after the LGM, coincided precisely with abrupt climate amelioration. With respect to the second issue, if the evidence suggests that human population growth preceded climate warming, then this would falsify one of the contending hypotheses, in which case, social or cultural explanations might seem more likely. On the other hand, if the two were synchronous, or if human population growth post-dated climatic warming by only a short period, then, although this does not prove a causal relationship, it would certainly strengthen the case for climate as a forcing factor on human mobility and adaptation.

Housley (1991; Housley *et al.*, 1997) collated the best available evidence for the timing of human expansion in Europe from ca. 14.0 k ^{14}C yr BP onwards, based predominantly on uncalibrated AMS radiocarbon dates obtained from human and humanly modified material using strict quality assurance protocols. The results were compared with uncalibrated radiocarbon dates for the onset of the rise in tree pollen at the start of the Lateglacial (Bölling–Allerød), which was regarded as the main indicator of regional climate warming. Housley *et al.* (1997) concluded that the data supported a model of widespread abandonment of northwest Europe by humans during the LGM, but that the first wave of re-immigration into the region occurred slightly *before* the onset of climatic warming (the start of the 'Bölling–Allerød'), as indicated by tree pollen increases. They therefore concluded that humans were driven from northwest Europe by climatic severity, but that non-climatic factors, most probably social developments, enabled humans to adapt better to the prevailing cold conditions, and hence to re-migrate into the region prior to any significant improvement in climate. The argument, however, rests on the possibility of determining the precise order of archaeological and climatic events, an objective which is constrained by the following:

1 The immigration of some plants, and especially of trees, usually lags behind climatic warming, sometimes by considerable intervals. Fossil insect records (e.g. Coope, 2002) and stable isotope measures (Hoek and Bohncke, 2001; Jones *et al.*, 2002) record responses to shifts in climate during the Last Termination that pre-date (often significantly) the responses inferred from palaeobotanical data, and hence the former proxies would perhaps provide more reliable indicators of the timing of significant climate change.
2 Blockley *et al.* (2000a) have questioned the validity of the abandonment model (during the LGM) on the grounds of sampling uncertainties. Recent research in north-central Europe raises further doubt, for there is now radiocarbon-dated evidence for human occupation of areas previously considered to have been abandoned during the LGM (Terberger and Street, 2002).
3 Comparisons based on uncalibrated radiocarbon dates are questionable, since radiocarbon time is not linear, and the true order of samples or events cannot therefore be ascertained until all radiocarbon dates have been reliably calibrated (Taylor *et al.*, 1996).

In an attempt to base comparisons on a common timescale, Blockley *et al.* (2000a,b) and Terberger and Street (2002) compared the calibrated ^{14}C timescale for human expansion into Europe after the LGM with climate reconstructions based on the Greenland ice-core records. Both studies concluded that there was general synchroneity between climate warming and human expansion into Europe. Indeed, Terberger and Street (2002) tentatively suggest a close correspondence between the first evidence for human re-migration into Europe after the LGM, and the onset of Greenland Interstadial 2 (GI-2), the period of subdued warmth that succeeded the LGM (see also Barton *et al.*, 2003). However, as explained below, these interpretations are also problematic.

Comparisons between radiocarbon based datasets

Housley *et al*. (1997) based their interpretations on analysis of 127 AMS and 14 conventional radiocarbon dates obtained from stratigraphical records with direct evidence for human occupation during the Last Termination. The records were obtained from eight countries, and treated as regional datasets. Only those dates that had been subject to rigorous sample selection and pretreatment quality assurance measures were included in the compilation, in an effort to reduce any bias introduced by sample contamination or laboratory imprecision. The earliest uncalibrated date in each regional dataset was effectively selected to denote the age of the onset of human expansion in each respective region (see Blockley *et al*., 2000a). This approach has been questioned because (i) uncalibrated dates cannot be compared directly, for the reasons given above, and (ii) the selection of one end member of a dataset as being representative of that dataset can be criticised on statistical grounds (Blockley *et al*., 2000a; Blackwell and Buck, 2003).

An alternative procedure is to treat subsets of the radiocarbon dates as multiple estimates of a single event, and to combine the probabilities of the individual age estimates, applying Central Limit Theorem, to derive the highest likelihood estimate for that event. When this approach is adopted, a significantly younger age than those obtained by Housley *et al*. (1997) for the expansion of humans in each region is suggested (Blockley *et al*., 2000a,b). This approach has been criticised in turn, however, for there are too few dates to justify the application of Central Limit Theorem in the analysis of some of the regional datasets, owing to the non-normality of the individual date distributions, while the overall spread of the radiocarbon data also renders these combination procedures inappropriate (Blackwell and Buck, 2003).

Yet another and perhaps more appropriate alternative is to treat each regional subset as representing a *phase* during which a particular event or process has occurred (Bronk Ramsey, pers. comm.; Blackwell and Buck, 2003) and to employ Bayesian probability procedures to both calibrate the radiocarbon dates and to estimate the ages of the boundaries of the phase (i.e. beginning and end of each phase) (Buck *et al*., 1991, 1992; Bronk Ramsey, 1999). While the precise age of any point or horizon within the phase may not be capable of precise definition, the probability that the true calibrated age of the onset of an event lies within the phase boundaries can be estimated with specified statistical confidence. Blackwell and Buck (2003) used this approach in an attempt to clarify the age of the onset of re-immigration of humans into Europe at the end of the last cold stage. We have repeated this methodological approach using the new IntCal04 calibration curve in order to compare these data to radiocarbon-dated terrestrial palaeoclimate data also calibrated with IntCal04 (see below).

Defining index points for significant palaeoclimatic and archaeological change

In order to test hypotheses concerning the possible link between human development and climate shifts, definitions are crucial. In this paper we will focus on the problems of defining (a) the evidence for the onset of climate change; (b) the evidence for significant change in human development or behaviour (e.g. migration; expansion in numbers; social adaptation); and (c) establishing the precise age of climatic or archaeological 'events'.

Onset of climate change

In order to establish the precise stratigraphical horizon at which a significant shift in climate is judged to be evidenced in the proxy record, three principal problems must first be resolved. First, not all physical processes or organisms will respond to climate impact at the same rate (Lowe *et al*., 1999; Mayle *et al*., 1999). As mentioned earlier, there is abundant evidence to suggest that certain kinds of insects, for example, respond much more quickly than some plants, particularly trees (e.g. Coope, 2002), and this is most clearly apparent where fossil insect records can be compared directly with tree-pollen data extracted from the same core (e.g. Walker *et al*., 1993, 2003; van Geel *et al*., 1989; Jones *et al*., 2002). In many archaeological studies, however, pollen-stratigraphical evidence is frequently the sole proxy indicator available for reconstructing the palaeoenvironmental (including palaeoclimatic) context. This evidence can therefore be misleading, particularly in assessments of the sequence of events during Lateglacial times, when colonisation by trees and some other plants lagged considerably behind insect invasions during episodes of rapid warming. In general, comparatively little is known about the signal–response lags of many proxy environmental indicators.

Secondly, there were important regional contrasts in the timing and magnitude of climate change in northwest Europe during the Last Termination. Some, if not all, of the major climate responses were time-transgressive (i.e. spatio-temporal phenomena that require far more subtle modelling) in nature (Coope *et al*., 1998), while it appears that some parts of the North Atlantic region may have been experiencing climatic warming at the same time as other parts were undergoing cooling (Lowe, 2001). Thirdly, little is known about key climate variables during Lateglacial times, so that interpretations are currently extremely general. It is, for example, generally assumed that palaeo-proxy fluctuations reflect changes in annual temperature, whereas differences in moisture supply or in seasonality and/or length of growing season may have been equally or more vital for some organisms.

Clearly, therefore, care is required when defining 'climate change'; account needs to be taken of regional contrasts in climate response, of the specific proxy indicators employed, and of the limited information on the attributes of the climatic regime that are being inferred. The uncertainties involved should perhaps be expressed statistically.

Definition of significant archaeological events

The question of the definition of the timing of cultural phases and change is also significant. The relationship between established classification systems of tool typologies and radiocarbon dating of associated material is particularly important. In the case of the 'new' sites, i.e. those ascribed to a period following any hypothesised abandonment, typological re-classification has taken place in a number of cases. Wiesbaden-Igstadt, for example, was considered to belong to the Aurignacian technocomplex, often dated to the first half of the European Upper Palaeolithic; however, the radiocarbon dates suggested this site was significantly younger than any other well-dated Aurignacian site (Terberger and Street, 2002). This led to a reinvestigation of the lithic material in question, with the result that they were re-classed as Badegoulian. Other sites (Breitenbach in Thuringia, Kastelhole Nord in Switzerland, Stranska Skala in the Czech Republic, Mittlere-Klaus in Bavaria and Langsmannerdorf in Austria) have also been re-classified under similar circumstances. All show similar typology and are chronologically comparable.

Although it has been shown unequivocally that these tools do not fall into typical Aurignacian forms (Terberger and Street, 2002), being composed largely of flakes (some without blade technology; others with no backed tools, or no abrupt re-touch), this reappraisal took place *in the light of the radiocarbon estimations*. Thus, the arguments tend towards the circular; the radiocarbon date causes the reappraisal of the technology, which then confirms the date. A related issue is raised by work concerned with the dating of human and anthropogenically modified osteokerodontic (bone, hair and tooth) material. In some cases, cultural horizons considered to be relatively early, are subsequently dated to later than was assumed, and vice versa. For example, at the British site of Kent's Cavern, a date of 17 490–16 440 cal. yr BP (14 140 ± 110 ^{14}C yr BP, OxA-2845), was rejected on typological grounds. The date was on a bone pin, which had been interpreted as belonging to the Aurignacian (see Jacobi in Hedges *et al.*, 1994: 342). This was because it had some stylistic similarities with pins from French Aurignacian contexts and had been found in levels with 'Aurignacian-like' material. Although there is no chemical evidence presented in the Oxford laboratory date-lists for contamination, nevertheless contamination of the sample was assumed on archaeological grounds.

Thus, modern archaeologists can easily find themselves in the invidious position of redefining cultural phases purely on the basis of radiocarbon estimations, and indeed, conversely, rejecting dates which appear chemically sound on cultural grounds. These issues must be resolved if the science is to progress in a meaningful manner. This problem has been recognised and strenuous efforts have been made to deal with it by the archaeological community. Extensive quality assurance protocols have been established to address the utilisation of radiocarbon dates in Palaeolithic archaeology (see Housley *et al.*, 1997; Pettitt *et al.*, 2003). Nevertheless, archaeological interpretations are heavily dependent on radiocarbon dates and on the quality of available calibration.

Establishing the precise age of climatic or archaeological transitions

Once the key stratigraphical horizons indicating important climatic or archaeological changes have been identified, precise ages for these horizons need to be estimated. As outlined above, by far the most widely employed method for dating events of Last Termination age is radiocarbon dating. This method is subject to a number of uncertainties, however, which reflect such factors as laboratory measurement precision, low stratigraphic (temporal) resolution (Lowe and Walker, 2000; Walker *et al.*, 2001), possible recycling of older material (e.g. Turney *et al.*, 2000) and calibration errors (Blockley *et al.*, 2004). The cumulative effect of these limitations can give rise to uncertainty ranges that are frequently of the order of 500–1000 years at 2σ in both archaeological and environmental records (Blockley *et al.*, 2004). Here we enlarge on the reduced precision introduced by calibration.

The internationally accepted standard radiocarbon calibration curve until recently has been IntCal98, now superseded by IntCal04, which contains new calibration data and improved statistical methodologies for integrating calibration datasets (Buck and Blackwell, 2004). The Lateglacial part of both of these calibration datasets is, however, based largely on radiocarbon-dated marine samples from paired U-Th/^{14}C dated corals (Bard *et al.*, 2004, Cutler *et al.*, 2004; Burr *et al.*, 2004) and laminated sediments from the Cariaco Basin (tropical Atlantic; Hughen *et al.*, 2004), because dendrochronology records do not yet extend as a continuous series to much before the start of the Holocene. The Cariaco laminated marine sediment calibration extends through the period 14 700 to 12 400 cal. yr BP (Hughen *et al.*, 1998a,b; Stuiver *et al.*,1998), the earlier date corresponding to 12 959 ± 98 is based on paired ^{14}C/U-series dates obtained from corals, enabling the calibration dataset to be extended back to 26 000 cal. yr BP. The IntCal04 Lateglacial dataset, as with IntCal 98 is, therefore, based predominantly on marine samples which are by definition affected by marine reservoir uncertainties (see, for example, Goslar *et al.*, 2000, 2001). Calibrating radiocarbon dates using these curves, therefore, introduces an additional uncertainty, the magnitude of which is difficult to assess at present with constant reservoir offset being assumed in most cases (Stuiver *et al.*, 1998, Hughen *et al.*, 1998a, 2004). Although this situation might be improved in the future if the dendro-based calibration series can be extended back into the Lateglacial period, the current level of uncertainty will remain for some time yet.

An alternative calibration model that extends back beyond ca.15 000 cal. yr BP is that based on radiocarbon-dated, varved lake sediments from Lake Suigetsu in Japan (Kitagawa and van der Plicht, 1998, 2000). Although this dataset does not suffer from marine reservoir problems (Litt *et al.*, 2003), nevertheless there are uncertainties associated with the varve chronology from this site (Nakagawa *et al.*, 2003).

For the reasons outlined above we believe, therefore, that during the onset of the Lateglacial interstadial questions remain over how well we can compare radiocarbon-based chronologies with other records.

The timing of human expansion in northwest Europe and of abrupt climate warming at the start of the Lateglacial

In this section we attempt to compare the timing of the onset of human expansion in northwest Europe and of abrupt climate warming at the start of the Lateglacial, using an approach which takes into account the uncertainties outlined in earlier sections of this paper. For this analysis, all of the radiocarbon dates have been calibrated using IntCal04 and the Suigetsu calibration models, on the assumption that increased confidence can be attached to the outcomes if both calibrations yield similar results. The climate signal for northern Europe used here is variations in the mean temperature of the warmest month inferred from fossil coleopteran records, with the record obtained from Llanilid, Wales (Walker *et al.*, 2003), used as an illustration (Fig. 1). It is assumed that these data are less prone to the lag effects which complicate the use of palaeobotanical records. The chronology for the beetle temperature reconstruction from Llanilid is taken from Walker *et al.* (2003), and Blockley *et al.* (2004) (but re-calibrated with IntCal 04), where different age modelling approaches were attempted, including

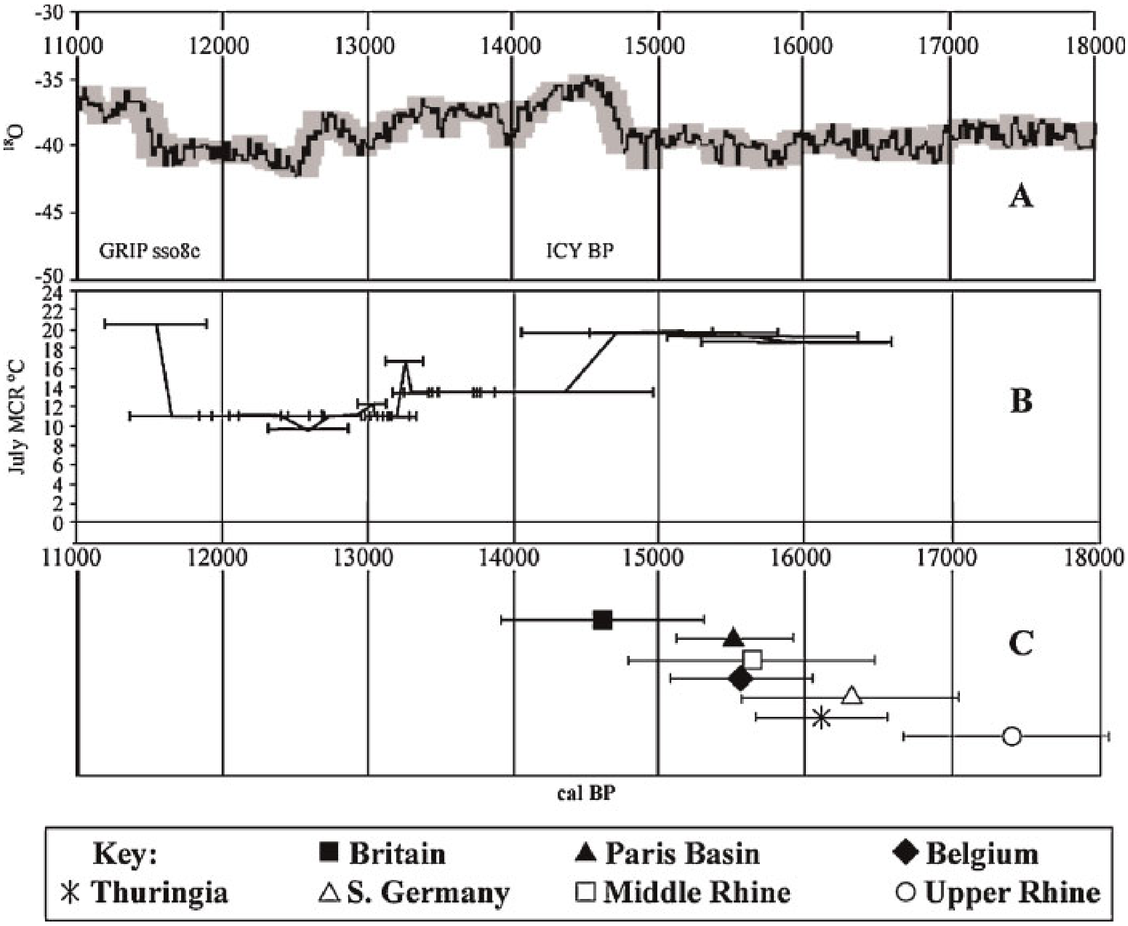

Figure 1 (A) GRIP (ss08c) δ^{18}O proxy temperature reconstruction in Ice Core Years before 1950; (B) The Llanilid Lateglacial beetle MCR temperature reconstruction from Walker *et al.* (2003) and Blockley *et al.* (2004), recalibrated using IntCal04; and (C) estimates for the onset of human expansion in northwest Europe using the approach of Blackwell and Buck (2003), recalibrated using IntCal04, both on a calibrated timescale. Error ranges for the ice core chronology are based on Johnsen *et al.* (1997) and Bayesian model calibrated radiocarbon highest posterior density intervals are all displayed at 95% confidence

the more traditional regression-based age model and the application of a Bayesian bounded sequence algorithm with a uniform prior (see Buck *et al.*, 1991; Bronk Ramsey, 1999, 2000; Steier and Rom, 2000). The latter is the approach adopted here, but both methodologies yield virtually identical results for a calibrated timing of the onset of British Lateglacial warming. We have estimated the age for the onset of human expansion in each of several different regions of Europe using the data from Housley *et al.* (1997) and the approach of Blackwell and Buck (2003).

The beetle records, when analysed using both calibration models, suggest that Lateglacial warming in Britain had already begun by ca. 16 500–15 000 cal. yr BP. This conclusion is supported by two other beetle-based palaeotemperature records from northwest Europe, from Gransmoor in Yorkshire (Walker *et al.*, 1993; Blockley *et al.*, 2004), and Usselo in the Netherlands (van Geel *et al.*, 1989), both of which also suggest that warming occurred around about 13 000 radiocarbon yr BP (15 000–16 000 cal. yr BP). This compares with the 'conventional' GRIP ice-core date of ca. 14 700 ICY BP for the onset of Lateglacial warming in Greenland (the onset of Greenland Interstadial 1). If the difference in timing of warming between Greenland and Britain is real, then it underlines the need to compare European archaeological records with palaeoclimate records obtained from Europe, and not with the Greenland ice-core records, when comparing the timing of the onset of human expansion and of climatic warming.

Figure 1 displays the results of Bayesian model output for the chronologies of human demographic shifts and environmental change from terrestrial sites compared to the Greenland ice-core GRIP timescale for Lateglacial climate change. These currently represent the application of some of the most sophisticated approaches applied to some of the best available data and taken at face value they suggests that there may well have been a regional gradient in the timing of the onset of human expansion in Europe, for the calibrated age ranges obtained for central European datasets tend to pre-date those obtained for western regions. Furthermore, it is tempting to conclude, on the basis of the dated archaeological records, that human expansion across most of Europe either postdated, or was broadly synchronous with, abrupt climate warming in Europe at ca. 16 000 cal. yr BP (or, to be more precise, with the abrupt warming event that is reflected in the Llanilid, and also the Gransmoor and Usselo records (see Blockley *et al.*, 2004), for only the upper Rhine dataset provides a calibrated age range that pre-dates the onset of this warming event. It also appears on the basis of these data that both the warming trend indicated in the beetle temperature reconstruction and the archaeological evidence for abrupt human expansion pre-date the evidence for warming in the Greenland ice-core record. These conclusions also hold true if this exercise is repeated using either IntCal98 or the Suigetsu calibration models, and also when the timescale for human demographic change is estimated by plotting raw calibrated radiocarbon dates as opposed to estimating the onset of each archaeological phase using the approach of Blackwell and Buck (2003).

The above conclusions are, however, very tentative at this stage. Figures illustrate the large uncertainties inherent in age models that are based on calibrated radiocarbon dates. While a large part of the uncertainty is caused by imprecision in the calibration models, the approach we have attempted may be further undermined because of (a) the limited number of dates based on human or humanly modified material that is presently available for most of the regions considered, (b) the possibility that major climate changes during the Lateglacial were time-transgressive across Europe, and (c) the added complication that human expansion across Europe may also have been time-transgressive (Housley *et al.*, 1997; Blackwell and Buck, 2003).

The sequence of events that unfolded in Europe during the Last Termination may have been much more complex than is generally assumed. Recent work on Badegoulian sites in Germany (Street and Terberger, 1999; Terberger and Street, 2002) indicate that at around the time of the LGM, sites were occupied for very short periods, whereas those dating to the younger period of the early Magdalenian are characterised by evidence of longer-term occupation. Taken together with the radiocarbon datasets outlined above, a plausible explanation of human demographics during the transition from the last cold stage to the beginning of the Holocene is that there was a substantial decline in population, with temporary (possibly seasonal) occupation (but not abandonment) of northern Europe during the LGM, followed by rapid expansion into northern zones, with more long-term occupation of sites, as soon as, or very shortly after, the climate had warmed sufficiently. The task ahead is to test this general speculation, as well as the other theories referred to earlier, employing more robust geochronological methods than are currently at our disposal.

The need for more robust procedures for testing models of archaeological change during the last glacial–interglacial transition

A key research priority for the future is to develop improved geochronological methods whereby the timing of human expansion and of climate warming in Europe following the LGM can be much better constrained. Building on existing work directed to this end (see, for examples Blackwell and Buck, 2003, Pettitt *et al.*, 2003) the following steps, developed in parallel, would seem the most likely to deliver more robust approaches for testing the hypotheses outlined in earlier sections of this paper:

1 a significant increase in the number of radiocarbon dates obtained from human and humanly modified material for each of the regions of interest;
2 identification of key stratigraphic sequences wherein any evidence for an increase in the number of human remains and/or of humanly modified artefacts can be dated within a continuous stratigraphic and (ideally) palaeoclimatic context;
3 quantification of the uncertainties in published age models, this is a particular problem with many published age models for palaeoclimate sequences;
4 comparison of the regional archaeological records with palaeoclimate reconstructions based on those climate proxies that are least susceptible to lag effects;
5 comparison of regional archaeological models with quantified palaeoclimatic reconstructions developed for each corresponding region, in order to minimise the complications caused by spatio-temporal uncertainties;
6 the identification of time parallel marker horizons in both archaeological and environmental sequences that can be used to constrain chronologies and test hypotheses of synchroneity or otherwise between climatic and archaeological events;
7 the development of appropriate statistical models for the generation and integration of chronological, spatial, and environmental data, through close collaboration between statisticians and the palaeo-community. Although this process is under way, we are as yet not nearly integrated enough within the various communities.

These steps are required as current methodologies are inadequate to deal properly with the spatio-temporal problem of understanding fully the relationship between abrupt climate change and human demographic expansion. This problem relates not only to our chronometric tools but, as highlighted by Blackwell and Buck (2003), our statistical methodologies as well. The models presented in Fig. 1, although among the best available, are from geographically disparate sites with no available integration of the different datasets though a single model. Partly this is due to the lack of suitable statistical tools but also because very few environmental records have enough radiocarbon dates for reliable and precise age modelling as discussed above, therefore, when sites with sufficient numbers of radiocarbon dates are used to study chronologies of change the analyses of spatio-temporal questions is limited to the study of only a few geographically limited locations.

Clearly this approach would involve extensive collaboration between archaeologists, palaeoclimatologists and geochronologists, with a view to synthesising data at a continental scale. We would welcome such a multiproxy and multi-institutional collaborative initiative. An existing project which illustrates how such an initiative can be managed, and how informal collaboration can yield significant scientific benefits, is the INTIMATE project ('INTegrating Ice-core, Marine and Terrestrial records for the Last Termination') of the INQUA Palaeoclimate Commission. This initiative has run for about a decade, and has the overall aim of synthesising high-resolution palaeoclimate records for the North Atlantic region and is open to all interested scientists. It holds annual workshops, devoted to solving problems of high-precision chronology and correlation, and occasionally publishes the outcomes of the project workshops, which are considered to have moved the science forward (e.g. Björck *et al.*, 1998; Walker *et al.*, 1999; Lowe *et al.*, 2001). The advantages of this form of informal collaborative group have been recognised within the Palaeolithic archaeological community and we believe that shortly a similar group will be organised to address exactly the questions outlined in this paper, along with related geochronological problems further back in the Palaeolithic.

One of the key proposals to emerge from the work of INTIMATE has been the recognition of the importance of tephrochronology for improving the chronology of the European Lateglacial by providing time parallel marker horizons within sequences (e.g. Davies *et al.*, 2002). The reason for this is that the recent expansion of 'microtephra' research (identification of tephras that are not visible to the naked eye, also termed cryptotephra) has revolutionised the way in which tephrochronology can be employed to support Lateglacial palaeoenvironmental research (see Davies *et al.*, 2002). The search for 'microtephra' layers in Lateglacial sediments has extended the known distribution of tephras into regions in which tephras had not previously been detected, and has led to the discovery of new tephras, not previously represented in the visible tephra record. This has greatly extended the areas in Europe in which tephrochronology can be applied, and provided additional 'tielines' for the correlation of Lateglacial sequences. Indeed, members of the INTIMATE project have gone as far as to suggest that tephrochronology might provide a more robust framework for the chronology and correlation of Lateglacial sequences and events, for much of Europe (e.g. Lowe *et al.*, 2001; Turney *et al.*, 2004). Tephra layers provide an independent basis for testing age models based on radiocarbon dating and, because some Lateglacial tephras have been detected in Greenland ice-core records, they also potentially provide a basis for direct correlation between ice-core, marine and terrestrial records. The advantages that tephrochronology might bring to some archaeological studies, which depend upon improved geochronological procedures, such as the topic addressed in this paper, ought also to be explored. We are actively involved in extending the use of 'microtephras' as a chronological tool in palaeoclimate research and have begun to expand the search for microtephras into archaeological sites in regions where visible tephra horizons are not present. The potential for microtephrochronology to become an essential chronological and stratigraphical tool for the study of archaeological and environmental problems is highlighted by Fig. 2, which shows the distribution of tephras covering the late Upper Palaeolithic and the Mesolithic of Europe. For most eruptions little work has been done so far in searching for microtephra deposits and, therefore, the eruptive fallout ranges are based on visible horizons only. However, the Icelandic system has been particularly well studied as a Lateglacial and Early Holocene source of isochronous deposits for Britain and Scandinavia, and the significant extension of the range of Icelandic tephrochronology is clear, as is the potential for the Laacher See tephra as a late Upper Palaeolithic marker horizon (12 880 varve yr BP; e.g. Litt *et al.*, 2001). Several new studies by groups around Europe will shortly extend the reported presence of Icelandic tephras much further south in Europe. This will in time apply also to the other eruptive centres.

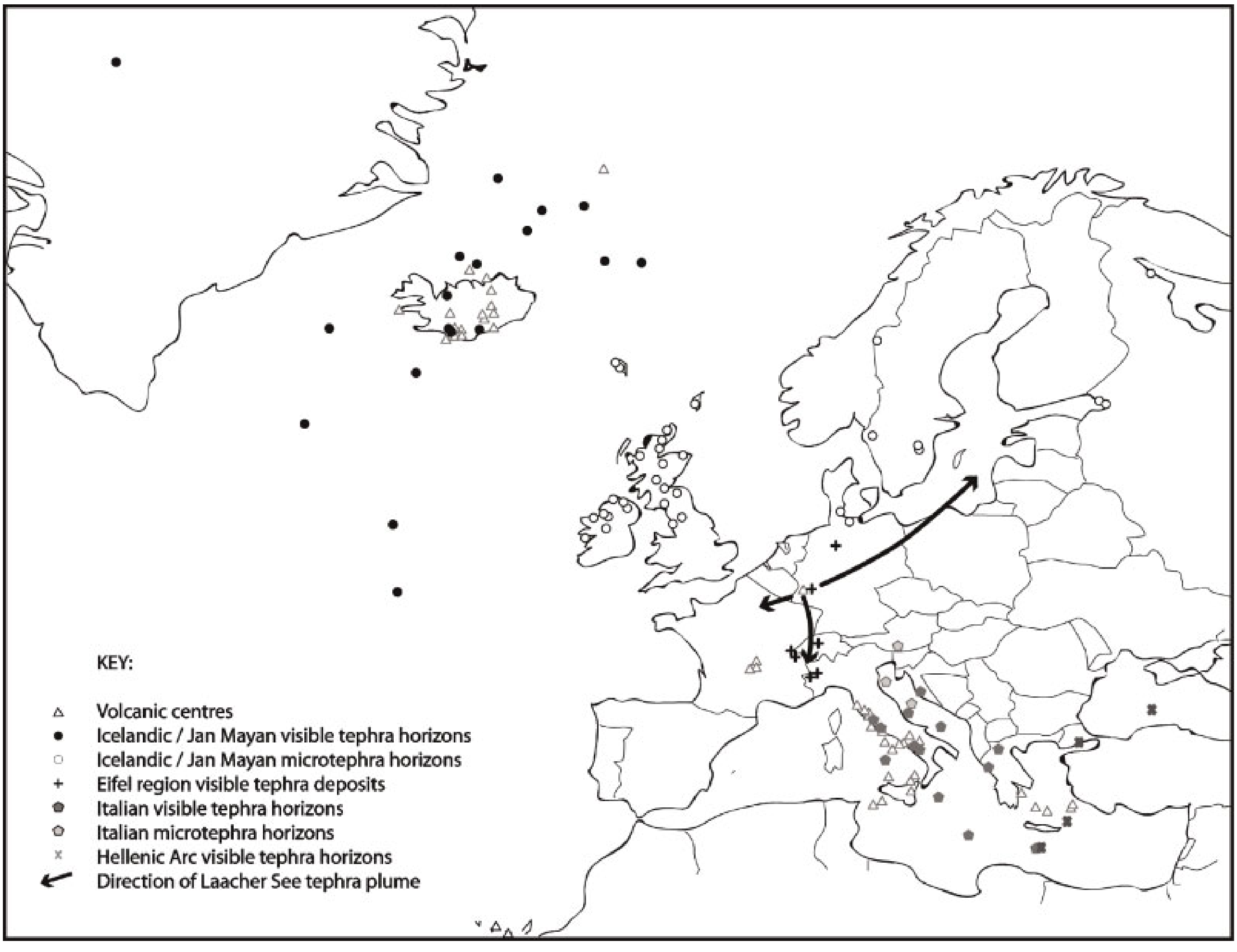

Figure 2 Distribution of visible and microtephra deposits in Europe and the North Atlantic of later Upper Palaeolithic and Mesolithic age expanded from Davies *et al.* (2002). Volcanic centres and tephra deposits from Icelandic, Jan Mayan, Eifel, Italian and Hellenic Arc volcanic regions shown. Sites plotted are not exhaustive, but illustrate the extent of, ash plume fallout for the various volcanic centres. Icelandic data from: Bergman *et al.*, 2004; Björck and Wastegard, 1999; Boygle, 1994; Caseldine *et al.*, 1998; Chambers *et al.*, 2004; Dugmore and Newton, 1997; Dugmore *et al.*, 1995; Dugmore *et al.*, 1992; Eiriksson *et al.*, 2000; Haflidason *et al.*, 2000; Hall and Pilcher, 2002; Hunt, 2004; Langdon *et al.*, 2003; Langdon and Barber, 2001; Litt *et al.*, 2001; Mortensen *et al.*, 2005; Pilcher and Hall, 1996; Pilcher *et al.*, 1996; Pilcher *et al.*, 1995; Plunckett et al., 2004; Turney *et al.*, 1997; van den Bogaard and Schmincke, 2002; Wastegard *et al.*, 2000, 2001. Eifel data from: Litt *et al.*, 2001; Moscariello and Costa, 1997; van den Bogaard and Schmincke, 1985; Vanniere *et al.*, 2004. Italian data from: Calanchi *et al.*, 1996; Jahns and van den Bogaard, 1998; Keller *et al.*, 1978; Schmidt *et al.*, 2002; Wulf *et al.*, 2004. Hellenic Arc data from: Wulf *et al.*, 2002

We are now beginning to apply this approach to archaeological questions and have recently identified microtephra layers in several archaeological sequences covering the Late Bronze Age through to the Early Upper Palaeolithic (publications forthcoming) including sites in southern and eastern England, a region from which tephras of these ages had not previously been detected (Matthews *et al.*, in preparation). These preliminary investigations indicate the potential for applying tephrochronology more widely in archaeological investigations, to help resolve questions of chronology and correlation.

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