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New chronological data (ESR and ESR/U-series) for the earliest Acheulean sites of northwestern Europe

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Abstract

Increasing evidence suggests that bifacial technology, Mode II, arrived in Europe during the early Middle Pleistocene, i.e. significantly earlier than previously proposed. In northern France and Britain, much of the age attribution for these assemblages has been based on biostratigraphy and lithostratigraphy rather than absolute dates. This study presents a systematic application of ESR dating of sedimentary quartz and ESR/U-series dating of fossil tooth enamel to key Acheulean sites of this area. Although the age estimates have large associated uncertainties, the majority of the derived dates are consistent with existing age estimates. The new chronologies and the problems associated with dating material of early Middle Pleistocene age are discussed. In Britain the earliest archaeology, Mode I, is older than MIS 15, whereas localities containing Acheulean technologies span late MIS 15/MIS 13 through to MIS 9. A similar pattern is seen in northern France although age estimates from sites such as la Noira suggest the possible appearance of the Acheulean in central France as early as MIS 17. The dates presented here support the suggestion that the earliest Acheulean appeared in NW Europe during the early Middle Pleistocene, significantly after its appearance in the southern parts of the continent.

Key-words

Acheulean, Lower Palaeolithic, early Middle Pleistocene, geochronology, archaeology

Introduction

Evidence of bifacial technology in Europe is much more recent than in Africa, where it appears around 1.8 Ma (Lepre et al., 2011; Beyene et al., 2013). Recent discoveries in Spain, France and England have, however, enriched our vision of human colonization in both the southern and the northern parts of the continent and attest to the onset of this technology before 500 ka, for example at Notarchirico (600 ka) in Italy (Piperno ed., 1999; Lefevre et al., 2010), Arago (older than 550 ka, levels P and Q) in the south of France and la Noira (700 ka, lower unit, stratum a) in central France (Barsky and Lumley, 2010; Barsky, 2013; Moncel et al., 2013; Falguères et al., in press). Moreover, the recent discovery of the site of la Boella in Spain with bifacial tools dated to 1 Ma – 900 ka (Mosquera et al., this volume) has shed new light on the starting-point of European bifacial technology. This site, and its associated artefacts, has raised questions as to the origin of this technology (local or introduced) and has reduced the chronological gap for the appearance of this technology between Africa and Europe (Vallverdu et al., 2014). In Western Europe as a whole, assemblages with bifacial technology are present in both the south and the north of this region by at least 500ka. Here, the emergence of the Middle Palaeolithic, and hence the disappearance of the Acheulean, is observed between MIS 11 and 9 (i.e. Moncel et al., 2012; Adler et al., 2014).

The archaeological evidence between 800 and 500 ka allows for a closer interrogation of these assemblages, for example whether they represent episodic arrivals of new hominin groups bearing this technology, an influx of new ideas, or alternatively reflect a local origin or innovation of this technology (Roberts and Parfitt 1999 ; Hublin, 2009 ; Premo and Hublin, 2009; Bridgland and White, 2014; Ashton et al., 2011; Despriée et al., 2011; Ashton and Lewis 2012; Stringer, 2012; Moncel et al., 2013 ; Meyer et al., 2014). The scarcity of sites over such a long period of time suggests short-lived dispersal events and probably a source-sink dynamic from the south with phases of depopulation and recolonization. Northern Europe would have been occupied predominantly during favourable climatic periods, although this does not necessarily entail temperatures as warm or warmer than the present day (Candy et al., this volume). Lithic series from both before and after Marine Oxygen Isotope Stage (MIS) 12 display a wide diversity of features due to various activities, raw materials and traditions. As regards the raw materials, flint is mainly used in the north whereas a wider range of lithologies (siliceous stones, quartz, quartzite, volcanic stones) were exploited in the south. The low number of well-dated sites before 500 ka and the (as yet) uncertain origin of this new bifacial technology may possibly also explain the diversity of strategies and assemblage composition, since each site has individual variations. Between MIS 11 and 9, the range of bifacial forms tends to decrease but some inter-site variability persists. It is thus now appropriate to refer to several European "Acheuleans", rather than a single Acheulean, and to consider them as discontinuous phenomena. In this paper, where we later refer to Acheulean, this is taken to reflect the diversity apparent within this tradition.

The establishment of a chronological framework for Acheulean sites in this region encounters certain difficulties. The period is far beyond the application range of radiocarbon, whilst other geochronological methods, such as ^{39}Ar/^{40}Ar or U-series cannot be routinely applied, due to the widespread lack of suitable materials such as volcanic minerals and speleothems. The present-day framework is hence largely based on relative dating methods, mainly biostratigraphy from mammals (e.g. Schreve et al, 2007, Auguste, 2009) and malacofauna (e.g. Preece et al. 2007, Limondin-Lozouet et al, this issue), lithostratigraphical evidence, such as the record in Britain of glacial tills (Rose, 2009) and the discovery of numerous archaeological sites in northern France and southern England in fluvial terrace staircases (Antoine et al., 2007; Bridgland and Westaway, 2014). Geochronological methods have also been applied but differ significantly on both sides of the English Channel. In England, Amino Acid Racemization (AAR) (Penkman et al., 2013), palaeomagnetism (Parfitt et al., 2010) and luminescence methods (OSL and TL) (e.g. Pawley et al., 2010) have been employed, whereas in France, the chronology has been for a long time based on the use of Electron Spin Resonance (ESR) and coupled ESR/U-series methods respectively on quartz grains extracted from sediments (Laurent et al., 1994; Voinchet et al., 2010) and mammal teeth (Bahain et al., 2007).

This paper presents new chronological data from an Anglo-French collaborative project “Emergence of Acheulean in North-West Europe: chronology, environment, technologies” (2010-2014) devoted to understanding the timing, nature and palaeoenvironments of the onset of bifacial technology in North-West Europe. The new dating analyses presented here have focused on two types of sequences. First, sediment sequences that contain *in situ* Acheulean artefacts and second, sediment sequences that contain either older (Mode 1) archaeology or which contain no archaeology but are important stratigraphic localities for the time interval under consideration. This approach was applied to sites from both France and England, allowing the earliest Acheulean to be placed into an overarching regional chronological framework. The main advantage of this approach is that the same dating techniques were used to calculate age-estimates for the key sequences in north-west Europe. ESR dating of sedimentary quartz and ESR/U-series dating of large mammal tooth enamel were consequently applied to several sites of early Middle and late Middle Pleistocene age. At all of these sites some independent chronological control (through lithostratigraphy, biostratigraphy or geochronology) was available with which the derived ESR and ESR/U-series age estimates could be compared. Where possible, both large mammal teeth and sediments were sampled from the sequence in order to compare results. The paper concludes by discussing the implications of this combined approach for understanding the timing of the appearance of the Acheulean in north-west Europe.

Materials and methods

Electron Spin Resonance (ESR) dating is a palaeodosimetric method, i.e. the sample is used as a dosimeter having recorded the total dose of radiation that it received since the event of interest for dating, namely the time of sediment deposition for quartz grains or the death of the animal in the case of teeth (Grün 1989; Ikeya, 1993). The age calculation necessitates determination of the total dose, also referred to as the archaeological dose or equivalent dose D_e, and to estimate the annual dose rate D_a received by the sample.

The total dose is assessed through the quantification of paramagnetic electrons trapped in the mineral lattice of the sample according to its specific sensitivity to radiation. The dose rate is calculated taking into account the cosmic rays and α, β and γ radiations emitted by the radionuclides contained in the sample and in its environment. For palaeontological remains, the annual dose varies throughout the history of the sample in relation to the uptake of uranium during fossilization. It is therefore necessary to couple the ESR study with U-series analyses in order to model this phenomenon for each sample. In the case of teeth, these models allow, for each part of the dental tissue, the determination of an uptake parameter calculated from both ESR and U-series data. This parameter may indicate post-depositional uptake (p-value) but also partial posterior U-leaching (n-value) according to the current model (US model (Grün et al., 1988) and AU model (Shao et al., 2012) respectively). This parameter is then used to determine the corresponding dose rate contribution of each dental tissue to the total dose and is therefore crucial for the age determination.

For sediment, as the dated event does not correspond with the crystallization of the mineral but with a younger geological event, ESR dating of quartz grains is based on a completely different characteristic, namely quartz sensitivity to sunlight. Exposure of the quartz grains to sunlight leads to a release of trapped electrons and to the zeroing of the corresponding ESR signal (known as bleaching). Unfortunately, this bleaching is always incomplete for the ESR Aluminium (Al) centre used in the present work and it is therefore necessary to determine the specific maximal bleaching intensity of each studied sample in order to determine the ’real’ total dose of radiation received after deposition. This residual dose is then subtracted from the total dose to obtain D_e values used for the age calculation.

Sampling

Several regions were selected for the study (Fig. 1). Most sites lie within the catchments of well-studied fluvial systems (Somme, Seine, Cher, Thames, Bytham), or within shallow marine basins (Sussex, East Anglia), with a particular focus on archaeological levels located below till and outwash deposits that have been attributed to the Anglian glaciation (MIS 12). Where possible, sites younger than the Anglian were also sampled in the same regions for methodological comparison and age control. Two late Middle Pleistocene sites (Tourville-la-Rivière and Abbeville-Route-de-Paris) were also sampled for methodological comparisons. In addition, a site containing Mode 1 archaeology (Pakefield) and one without archaeology (but with regionally-important biostratigraphical assemblages), namely the stratotype of the Cromerian Interglacial at West Runton, were also sampled, for age comparison with other early Middle Pleistocene sites containing abundant Acheulean assemblages. A total of 46 sediment samples and 14 teeth was therefore sampled from 17 sites with geological ages ranging from an estimated MIS 19 to MIS 7 inclusive (Table 1).

Figure 1 –Location of the studied sites

Table 1 –List of the samples analyzed in the present work

At each site, sediment samples of around 1 kg weight were sampled from freshly-cleaned sections readily relatable to the archaeological horizons. Systematic *in situ* gamma-ray measurements were provided for each sediment sample using a mobile gamma spectrometer (Canberra Inspector 1000), in order to evaluate the γ dose rate.

For ESR/U-series analyses, similar *in situ* studies and sediment sampling were also performed in order to date large mammal teeth. When the teeth were directly sampled at the site (Saint-Pierre-lès-Elbeuf, Abbeville Carpentier), gamma spectrometry was performed as close as possible to the discovery location. When the teeth were selected from museum collections, dose rate measurements and sediment sampling were undertaken within the beds from which the teeth were known to have come (Purfleet, Pakefield, Beeches Pit, Tourville-la-Rivière).

Analytical protocols

ESR dating of quartz grains

The extraction and preparation protocol of quartz grains is described in Voinchet et al. (2004).

After extraction, each sample was split into eleven aliquots. Nine of these were irradiated at different doses ranging from 200 to 16000 with a gamma ^{60}Co source (CEN (CEA) Saclay, France). One aliquot was conserved as natural reference and the eleventh aliquot was exposed during 1000h to light in a Dr Honhle SOL2 solar simulator in order to determine the unbleachable part of the ESR-Al signal. Each series of eleven aliquots was measured at least three times by ESR at 107K using an Bruker EMX spectrometer and each aliquot was measured three times after an approximatively 60° rotation of the tube in the ESR cavity. D_e were then determined from the obtained ESR intensities versus dose growth curve using an exponential+linear function (Voinchet al., 2013) with Microcal OriginPro 8 software with $1/I^2$ weighting. In the age calculation, D_a were calculated from the radionuclide content of the sediments, taking into account the *in situ* gamma-ray data and the location of the samples in the stratigraphical sequence.

ESR/U-series dating of teeth

Details of the analytical methodology and age calculations for ESR/U- series dating approach are available in Bahain et al (2012) and Shao et al (2014) respectively. After separation and cleaning of the different dental tissues, the enamel of each tooth was powdered, sieved and the 100-200 µm fraction split into aliquots for D_e determination from irradiated and natural ESR intensities. U-series analyses were then performed on each dental tissue though α and γ spectrometry. Coupled ESR/U-series ages were then calculated from the whole data set (including the same environmental dose rate estimations as for the sediments) using US-ESR or AU-ESR models according to the obtained isotopic data.

Chronological Results

The results obtained by ESR and ESR/U-series dating methods are shown in Tables 2 and 3 respectively and in figures 2 and 3 (Additional data are given in supplementary tables S1 to S3). The main part of the ESR/U-series ages (except for the Tourville-la-Rivière and Pakefield samples) was calculated using the AU model, indicating complex U-uptake/leaching histories for these samples.

Table 2 –ESR results obtained on quartz extracted from sediments of Acheulean sites in England and north-west France. Analytical uncertainties are given with ±1σ.

Table 3 - ESR/U-series results obtained on mammal teeth from Acheulean sites of England and northern France. Analytical uncertainties are given with ±1σ. Italics indicate AU model results.

For the French sites, the results obtained by ESR and ESR/U-series at Abbeville Carpentier and Saint-Pierre-lès-Elbeuf, MIS16/15 and MIS12/11 respectively, are broadly consistent with previous age-estimates for these sites (Lautridou *et al.*, 1999; Antoine *et al.*, 2007; Bahain *et al.*, 2007). The age of the Saint-Pierre-lès-Elbeuf lower fluvial sands (yellow sands) seems, however, to be seriously over-estimated as these are generally considered to be MIS 12/11 in age but generate an estimate of ca. MIS 16. The ages obtained at Tourville-la-Rivière (teeth, MIS7), La Celle-sur-Seine (MIS12/11), Brinay la-Noira, Amiens Rue-du-Manège and Abbeville Route-de-Paris (quartz) are in agreement with the expected ages based on the position of the deposits in their respective fluvial systems and previous ESR or ESR/U-series results (Laurent et al., 1994; Antoine, 1994; Antoine et al., 2007 ; Despriée et al., 2010; Limondin-Lozouet et al., 2006).

Figure 2–Age density plots obtained from ESR and ESR/U-series results for the studied sites of England and Northern France

Figure 3 –ESR and ESR/U-series ages obtained for the studied sites of England and Northern France

For the English localities, even where the results generated in this study are in agreement with the accepted ages for these sites, the ESR and ESR/U-series data differ greatly at the two sites for which a comparison was attempted. For example, at Purfleet, the ESR/U-series age obtained on a molar of *Dama dama* is entirely consistent with the geological and biostratigraphical age estimates for MIS 9 at this site (eg. Bridgland, 1994; Schreve et al., 2002; Penkman et al., 2011). However, one of the ESR dates on sediment is substantially over-estimated, perhaps as a result of incomplete initial bleaching of some quartz grains in the fluvial sediments. Indeed, several thousands of grains are involved in ESR measurements and the presence of a few unbleached grains within the sample (for example reworked from the bedrock or river bank) will lead to such over-estimation. Single grain OSL studies may potentially furnish additional data on the possible bleaching heterogeneity of the sediment quartz grains and such work should be considered for the future. This over-estimated age is clearly erroneous as it would imply depositions during the early Middle Pleistocene age, at a time when the Thames was not flowing in the Purfleet area (Bridgland, 1994). The other ESR age estimate on sediment, in contrast, is consistent with an MIS 9 age when the analytical uncertainties are taken into consideration. For Pakefield, the quartz extracted from the shallow marine sands and gravel that overlie the Cromer Forest bed Formation provides an age estimate of MIS16/15, again consistent (within uncertainties) with the date for the Rootlet Bed proposed by Parfitt et al. (2005). The uppermost age in the sequence (Q4) suggests correlation with MIS 12 for the Corton Sands, again consistent with this bed being deposited during the Anglian glaciation (Lee et al., 2004). In contrast, the U-series date on a horse tooth from the Pakefield Rootlet Bed is severely under-estimated, potentially due to poor environmental dose rate reconstruction. It should also be noted that the ages of shallow marine sediments at Valdoe seem to be systematically under-estimated when compared with the accepted age of MIS 13 for the Slindon Sands, also preserved at Boxgrove (Roberts and Parfitt, 1999). This under-estimation may be due to a bad estimation of the residual dose, by under-estimating the initial bleaching rate in shallow marine environments similar to the phenomenon observed by Liu and Grün (2011). With the exception of the aforementioned samples, the ESR results obtained for pre- and post-MIS 12 sites are in broad agreement with other age estimates and these first results are promising.

Discussion

ESR and ESR/U-series age estimates for British early and late Middle Pleistocene sites

The sampled British sites all have pre-existing age estimates, some of which are more robust than others. For example, the site of Beeches Pit is very well constrained to MIS 11 on the basis of lithostratigraphy and biostratigraphy, supported by AAR data, U-series and OSL dating (Preece et al., 2007; Penkman et al., 2011). Equally, there is strong lithostratigraphic, biostratigraphic and AAR evidence to suggest that Purfleet and Barnham are of MIS 9 and 11 ages respectively, also supported by OSL age estimates for the former (Schreve et al., 2002; Bridgland et al., 2013; Ashton et al., 1998). Consequently, these sites offer ideal opportunities for testing the ESR and ESR/U-series age estimates that have been generated in this study. For both Beeches Pit and Barnham, the ESR and ESR/U-series analysis generate age-estimates that are consistent, within uncertainties, with an MIS 11 age (Beeches Pit = 397 ±45ka, Barnham 393 ±83ka and 448±55ka). The age estimates for Purfleet are far more variable. Whilst the dating of the teeth from Purfleet has yielded an age that is consistent with MIS 9 (319 ±26ka), the sediment ESR analyses yield dates that indicate either a MIS 9 age, but with very large associated uncertainties (392 ±211ka), or unrealistically old ages (699 ±73ka) when the biostratigraphy of the site and fluvial history of the Thames is considered. Despite this issue, however, the consistency between the existing age estimates for these sites and those generated in this study suggests that these techniques can provide substantial age information to be derived from older sites. Furthermore, as the MIS 9 and 11 sites described above contain some of the youngest Acheulean artefacts in Britain, the results presented here are consistent with the youngest Acheulean occurring during this time span supporting a lower to middle Palaeolithic transition in the middle part of the late Middle Pleistocene.

The remaining British sites that have been dated all contain lithostratigraphic and/or biostratigraphic evidence to suggest a pre-Anglian, or pre-MIS 12, age. This is supported, in many cases, by AAR analysis (Penkman et al., 2011). Deposits at Maidcross Hill, Brooksby, Pakefield and West Runton occur below Anglian glaciogenic deposits and are, therefore, definitively pre-Anglian in age. At both Warren Hill and Maidcross Hill, the deposits bearing Acheulean artefacts occur within deposits of the Bytham river, a west-east draining river system that was overridden by, and therefore destroyed by, the Anglian ice sheet. Archaeological finds associated with Bytham river deposits are therefore automatically of pre-MIS 12 age. The deposits at Valdoe, the Slindon Sands, are beyond the Anglian ice limits and cannot, therefore, be correlated with this glaciation on a lithostratigraphic basis. However, at Boxgrove, which also contains the Slindon Sands, the mammalian assemblages from the overlying Slindon Silts indicate a pre-Anglian and an early Middle Pleistocene age for these sites (Roberts and Parfitt, 1999).

More precise age attributions have been proposed for some of these pre-Anglian sites. However, they are more speculative than those proposed for the MIS 11 and 9 sites described above. The deposits at Boxgrove, and by association those at Valdoe, have been correlated on the basis of their small mammal assemblages to the youngest of Preece and Parfitt's (2012) early Middle Pleistocene biostratigraphic groups. This attribution is based on, among other indicators, the presence of *Arvicola terrestris cantiana* and *Microtus gregalis*. This would suggest correlation of these deposits with the youngest temperate episode in the early Middle Pleistocene, i.e. MIS 13. It is also argued that deposits of the Bytham River at Brooksby can, on the basis of altitude, be correlated with the lowest terrace, and, therefore, represent the youngest sediments associated with the Bytham sequence. This would suggest that the pre-Anglian deposits at this site are either MIS 13 or early MIS 12 in age.

The context of both Warren Hill and Maidcross Hill is more complicated. Westaway (2009a & b; 2010) has argued that these deposits represent the final phase of sedimentation for the Bytham system, and are therefore, as at Brooksby, of MIS13/12 age. The Bytham terrace stratigraphy of Lee et al. (2004) would imply an older age for these two sites. Within their proposed terrace stratigraphy, Lee et al. (2004) have suggested that the deposits at Warren Hill correspond with the second terrace of the Bytham river and have argued an age of MIS 14 or late MIS 15 for these deposits.

In all existing stratigraphic models, the Cromer forest-Bed (CfB) deposits at Pakefield and West Runton represent the oldest sediments analyzed in this study. Both deposits contain *Mimomys savini*, the extinct water vole species that is replaced on the continent by *A. terrestris cantiana* during MIS 15 (Preece and Parfitt, 2012). Furthermore, both sites have yielded AAR ratios that imply an age of MIS 15 or earlier (Penkman et al., 2011). At both sites it is likely that MIS 15 is a minimum age for the CfB deposits, whilst at Pakefield, it has been argued that these sediments could be of MIS 15, 17 or even 19 in age (Parfitt et al., 2005). At both West Runton and Pakefield, the CfB deposits are separated from the overlying Anglian sediments by a series of sand and gravel units representing a range of depositional environments, including shallow marine, fluviatile and glaciofluvial outwash. Age-estimates for these deposits are varied and highly debated (Lee et al., 2004).

In this context, many of the ESR and ESR/U-series age estimates are highly consistent with existing chronological models. For example, the ESR estimates from both Warren Hill (544 ±53ka and 539 ±38ka) and Maidcross Hill (529 ±55ka and 631 ±56ka) are consistent with the sediments being deposited during the latter part of the early Middle Pleistocene. The two Warren Hill age estimates are consistent with those proposed by Lee et al. (2004), with the absolute dates lying within MIS 14, although the associated uncertainties imply that the true age of these deposits could be late MIS 15 or early MIS 13, the latter also being consistent with the age proposed by Westaway (2009a & b; 2010). Superficially the ESR age estimates from the Slindon Sands at Valdoe appear problematic as the mid-point estimates of all three ages imply deposition during MIS 11/10. The uncertainties associated with these dates are, however, large and, in the case of two of the three ages, overlap with the latter part of MIS 13, the age for the Slindon Sands inferred from the regional biostratigraphy.

At both Pakefield and West Runton the ESR quartz age estimates shown in Table 2 are consistent with current age models for both sites. The ESR quartz ages are all derived from sediments that overlie the CfB at both sites. At West Runton, tidal sands were sampled that directly overlie the CfB deposits; these yielded ages of MIS 13 age (487 ±56ka and 516 ±156ka), implying that the CfB at this site must be older than MIS 13. This is consistent with current suggestions that the CfB at West Runton is MIS 15 or older (Penkman et al., 2011; Preece and Parfitt, 2012), although it does imply that there is a significant hiatus between the CfB and the overlying tidal sediments. At Pakefield, the three ESR quartz ages that are taken from sediments units that directly overlie the CfB have yielded estimates of MIS 15 (581 ±61ka, 595 ±73ka and 619 ±67ka). This would again imply that the CfB at this site must be MIS 15 or older. At Pakefield, the sands that directly underlie the Lowestoft till and which are glaciofluvial in origin, date, within uncertainties, to MIS 12 (409 ±108ka). It is worth noting that the ESR/U-series age from tooth enamel recovered from the CfB at Pakefield is unrealistically young, yielding an age of 232 ±16ka. At most of the British late Middle and early Middle Pleistocene sites that have been dated as part of this study, the derived ages are relatively consistent, with some caveats, with existing age models. The one exception to this is the site of Brooksby, where samples from the same pre-Anglian stratigraphic unit yield age estimates ranging between MIS 18 (710 ±64ka) and 8 (294 ±36ka). Currently it is unclear why this scatter in derived ages exists. Despite the stratigraphic consistency of the derived ages, the size of the uncertainties is frequently so great that it is impossible to correlate deposition with a single isotopic stage. Consequently, absolute ages that correlate with cold-climate isotopic stages do not necessarily imply hominin occupation in Britain during cold-climate conditions as the uncertainties could also place occupation within either the preceding or succeeding warm stage.

ESR and ESR/U-series age estimates for French early and late Middle Pleistocene sites

The French sites are located in several river catchments within northern France. The chronology of the terrace system of the Somme River is particularly well understood. A series of ten stepped alluvial formations has been recognized here from between + 5/6 m and + 55 m above the maximum incision of the present day valley (Antoine, 1994, Antoine et al., 2007). The summary of the data derived from both fluvial and slope deposits (sedimentology, bio-indicators, geochronology) shows that each alluvial formation corresponds to the morphosedimentary budget of a single glacial-interglacial cycle (Antoine, 1994) and the geochronological data obtained by different methods (amongst them radiocarbon, U-series, OSL, ESR, ESR/U-series, palaeomagnetism) result in this system having one of the best chronostratigraphical models in this region (Bahain et al., 2007). The ESR and ESR/U-series ages obtained at Abbeville Carpentier and Amiens Rue du Manège are consistent with this chronological framework, placing the deposition of Formations VI and V of the system in MIS16/15 and MIS 14/13 respectively. The age estimate for Abbeville Carpentier is consistent with the biostratigraphical record, which includes a number of early Middle Pleistocene species, such as the main part of the palaeontological assemblage from Carpentier and the mollusc *Tanousia* found at the site of Moulin-Quignon in the same alluvial formation (Auguste, 2009; Locht et al., 2013 ; Antoine et al., 2015). The ESR dates obtained at Abbeville Route de Paris seem, in contrast, over-estimated in comparison with the site elevation within the valley system. However, independent age control is missing for this site and the geological attribution to a particular terrace level is complicated by urbanisation.

The Seine River valley also contains a well-defined terrace sequence but this is mainly restricted to the Middle Pleistocene (Lautridou et al., 1999, Antoine et al., 2007). From a malacological point of view, Saint Acheul (Formation IV of the Somme system, Antoine et al., 2007), Saint-Pierre-lès Elbeuf and La Celle-sur-Seine are two localities that contain the well-defined MIS 11 *Lyrodiscus* assemblage (Limondin-Lozouet and Antoine, 2006). This is also in England at Beeches Pit and Hitchin (Limondin-Lozouet et al., this issue). The ESR/U-series and ESR dates obtained on teeth and sediments from the White Sands at Saint-Pierre-lès-Elbeuf are in agreement with the MIS11 attribution of this malacological assemblage, whereas ESR dates on the underlying fluvial Yellow Sands seem over-estimated in comparison (Lautridou et al., 1999, Antoine et al., 2007).

At La-Celle-sur-Seine, the ESR age obtained on the fluvial sands underlying the thick tufa formation places its deposition during MIS12, in good agreement with the other available geochronological data (U-series, ESR/U-series) and the malacological record derived from the overlying tufa (Limondin-Lozouet et al., 2006, 2010, this volume) The inferred MIS 7 age of the Tourville-la-Rivière D2 archaeological layer derived from new ESR/U-series analyses is also consistent with the terrace elevation in the system and both IRSL and independent ESR/U-series ages (Balescu et al., 1997; Faivre et al., 2014) and biostratigraphy (Auguste, 2009).

By contrast, the lack of faunal remains and the complex geological history of the Cher River system, which has led to alternating phases of aggradation and incision, has limited the development of a chronostratigraphical framework for this valley. Indeed, the chronology of the Cher system is exclusively based on ESR ages (Despriée et al., 2011; Moncel et al., 2014). The new ages obtained at la Noira are in agreement with previous results obtained from the site and equivalent localities within the same terrace unit, but also with the regional evolution of several other river systems within the Middle Loire Basin (Voinchet et al., 2010).

Significance of chronological investigations for the earliest Acheulean in North-western Europe

The new age estimates support existing chronological frameworks of early hominin occupation and archaeology in north-western Europe. They also provide new age estimates for sequences that have been previously poorly-constrained.

With respect to British sites, the following conclusions can be drawn. Firstly, the new dates support the widely held view that Beeches Pit and Barnham are MIS 11 in age and that Purfleet is MIS 9 in age. This supports the existing model of the British Palaeolithic, within which the youngest Acheulean sites are found in late Middle Pleistocene deposits and are dated to MIS 11 and 9. Secondly, sites containing Mode 1 archaeology (excepting the Clactonian) are dated to MIS 15 or older (see Candy et al., this volume, for discussion). For example, the CfBF at Pakefield, which contains only a small assemblage of cores and flakes, is overlain by sands and gravels dated to MIS 15. Finally, these new age estimates suggest that pre-Anglian Acheulean sites date to the latest part of the early Middle Pleistocene. At both Warren Hill and Maidcross Hill, these age estimates suggest a potential age that ranges from MIS 15 at the oldest, to MIS 13 at the youngest. Although the ages calculated for Valdoe have relatively large uncertainties, they are consistent with previous age estimates of MIS 13. In summary, these new dates suggest that core and flake industries in Britain are of MIS 15 age or older, whereas sites with bifacial technology span a range of ages from MIS 15 to MIS 9 inclusive. It is important to note that this chronological model is consistent with the biostratigraphical model proposed by Preece and Parfitt (2012); that is to say that Acheulean technologies, when found in levels containing small mammal assemblages, always are found with *A. t. cantiana* and never with *M. savini*. This is a critical point since in parts of eastern and southern Europe the transition from *M. savini* to *A. t. cantiana* appears to occur at the earliest during MIS 15 (Preece and Parfitt, 2012) or MIS16 (Pereira et al., this volume). This does not discount the possibility that, locally, *A. t. cantiana* may appear prior to this age but supports the general suggestion, that any deposits that contain this biostratigraphically-significant indicator species must be in North-western Europe of MIS 15 age or younger (Candy et al., this volume).

With respect to French sites, for North-west France, new dates obtained on sites with bifaces located along the Loire tributaries, the Seine and Somme Valleys span a range of time from MIS 17 to MIS 9. New dates from the lower level at la Noira confirm previous results, indicating some of the earliest evidence of bifacial technology in Europe. At this site, hominins were therefore present after the period of river incision that occurred at the beginning of MIS 16 (Despriée et al. 2011 ; Moncel et al. 2013). Further north, the sites of Carrière Carpentier (Abbeville) and Rue du Manège (Amiens) on the Somme Valley system attest to younger occupation dated to MIS 14 at the very latest (the ancient discoveries from Moulin-Quignon could be oldest but their stratigraphic positions are too uncertain to be used as chronological evidence). *In situ* Early Acheulean settlements in this region were dated to early MIS 12 in the 1990s (Cagny-la-Garenne, Antoine et al., 2007 ; Bahain et al., 2007), but new field discoveries have significantly increased the age of the oldest human occupation at these sites. Rue du Manège is dated to around 550 ka using both ESR and the terrace stratigraphy (early MIS 13) (Locht et al., 2013; Antoine et al., 2015) but the lithic assemblage lacks bifacial tools. The most recent discoveries of bifaces at Carrière Carpentier were recovered from above the Cromerian “white marls”, at the very base of the slope deposits directly overlying the fluvial sequence (hillwashed sands and gravels). On the basis of ESR (quartz) these bifaces correlated with MIS 14/13, i.e. contemporaneous with the “Rue du Manège” artefacts. Nevertheless they could be also slightly older (MIS 15) if we consider that they have been preserved in hillwashed sands and gravely lenses deposited immediately after the Interglacial of the White Marl (see Antoine et al., 2015) At La-Celle-sur-Seine, in the Seine Valley, a new ESR date is consistent with previous age estimates, the vertebrate faunal assemblage (*Cervus* sp., *Equus* sp., *Macaca sylvanus*, *Hippopotamus amphibius)* and a molluscan assemblage containing the *Lyrodiscus* fauna that characterizes MIS 11 tufas in north-west Europe (Limondin-Lozouet et al., 2010). Finally the new dates obtained at Saint-Pierre-lès-Elbeuf, Seine Valley, are consistent with the IRSL ages and pedostratigraphic record of this site, which comprises four loess layers interspersed with four interglacial soils, suggesting four full glacial-interglacial cycles: Elbeuf I (Eemian) to Elbeuf IV (Holsteinian) (Cliquet et al. 2009). The oldest soil (Elbeuf IV) is immediately overlain by white alluvial sands with faunal and lithic remains. It is also covered by a limestone tufa that has yielded vertebrate remains, occasional flint artefacts and an interglacial molluscan fauna with *Lyrodiscus*. This fauna indicates both oceanic and continental climate, together with Lusitanian (Iberian seaboard) species (Cliquet et al. 2009; Limondin-Lozouet et al. 2010). This tufa has been attributed to MIS 11, an age confirmed by the new dates. The recent fieldwork has investigated the white sands and tufa overlying the paleosol Elbeuf IV yielding *in situ* Acheulean artefacts and faunal remains.

Conclusion

The ESR and U-Th series dating techniques applied in this study to sedimentary quartz and fossil teeth provides a chronological framework within which the Acheulean sites of northern France and Britain may be placed. Whilst this study has generated an independent chronology for the Lower Palaeolithic of this region, the dates that are presented here are, for the most part, entirely consistent with those suggested by the existing bio- and litho-stratigraphies and former geochronological data. These dates suggest that core-and-flake industries (Mode I archaeology) in Britain is >MIS 15 in age, whilst the oldest assemblages with the bifacial technology (Acheulean, Mode II) sites date to late MIS 15/MIS 13. The youngest Acheulean assemblages are dated to MIS 11/9. Undoubtedly the oldest ESR ages for an Acheulean site come from La Noira (most probably MIS 17 in age), making this the earliest hand axe locality in northwest Europe. In Britain no Acheulean site has yielded ages older than MIS 15/13. With the exception of La Noira most Acheulean sites in both Britain and northern France date to the interval MIS 15-9. There is, therefore, some regional consistency in the time interval over which Acheulean industries occur in both Britain and France with the exception of an earlier appearance in the south of this area. This study, therefore, provides the first radiometric dating evidence that supports the arrival of Acheulean technology in northern Europe prior to MIS 12 and shows a diverse record of bifacial industries across the late part of the early Middle Pleistocene. Although this dating study reduces the age gap between the arrival of bifacial technology in southern versus northern Europe, it is important to note that the oldest Acheulean artefacts in southern Europe are still significantly older than their counterparts in Britain and France.

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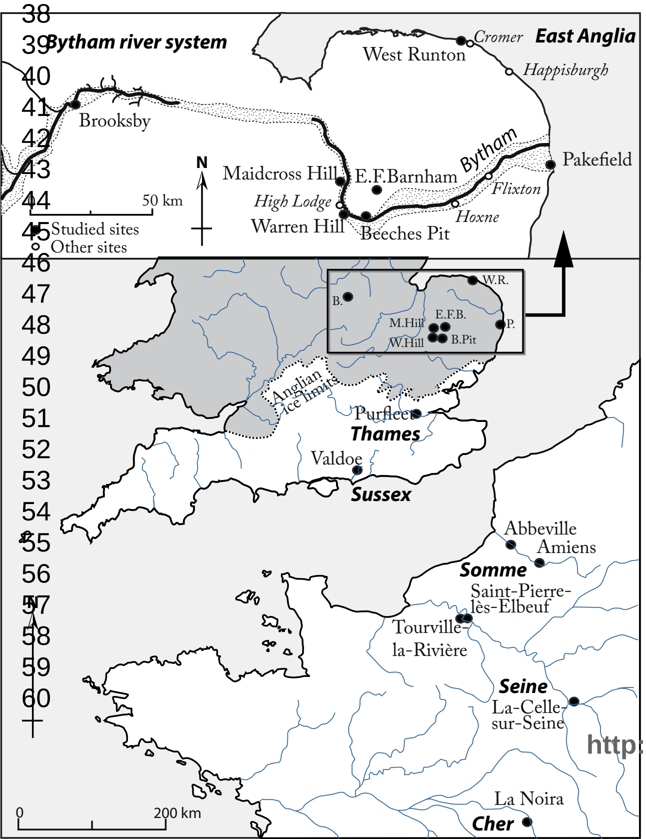
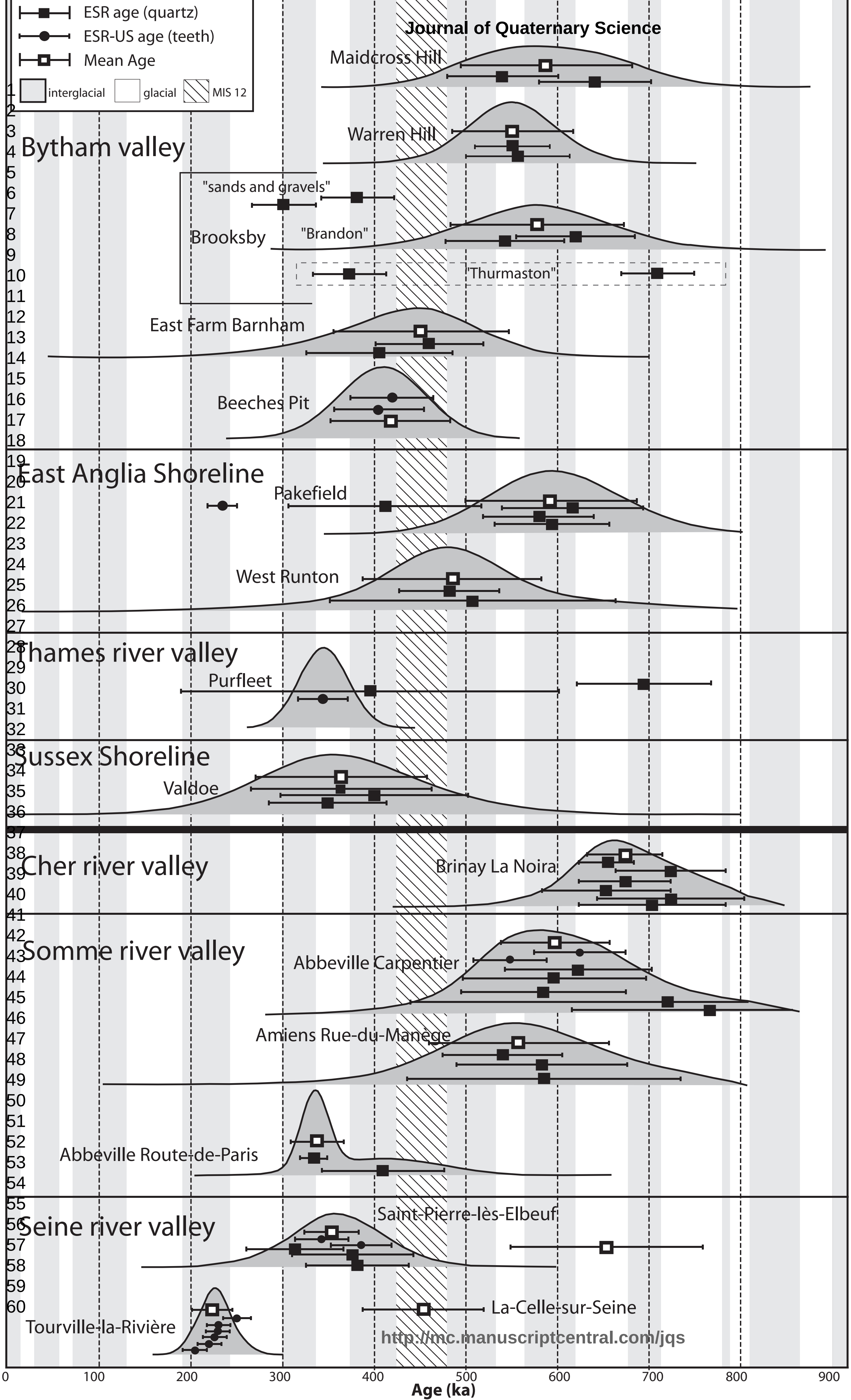

Bytham river system
East Anglia
West Runton
Cromer
Happisburgh
Brooksby
Bytham
Pakefield
N
Maidcross Hill
E.F.Barnham
Flixton
50 km
High Lodge
Hoxne
Warren Hill
Beeches Pit
Studied sites
Other sites
W.R.
B.
E.F.B.
M.Hill
P.
W.Hill
B.Pit
Anglian ice limits
Purfleet
Thames
Valdoe
Sussex
Abbeville
Amiens
Somme
Saint-Pierre-lès-Elbeuf
Tourville-la-Rivière
Seine
La-Celle-sur-Seine
La Noira
Cher
0
200 km


ESR age (quartz)
ESR-US age (teeth)
Mean Age
interglacial
glacial
MIS 12
Bytham valley
Maidcross Hill
Warren Hill
"sands and gravels"
Brooksby
"Brandon"
"Thurmaston"
East Farm Barnham
Beeches Pit
East Anglia Shoreline
Pakefield
West Runton
Thames river valley
Purfleet
Sussex Shoreline
Valdoe
Cher river valley
Brinay La Noira
Somme river valley
Abbeville Carpentier
Amiens Rue-du-Manège
Abbeville Route-de-Paris
Seine river valley
Saint-Pierre-lès-Elbeuf
La-Celle-sur-Seine
Tourville-la-Rivière
0
100
200
300
400
500
600
700
800
900
Age (ka)

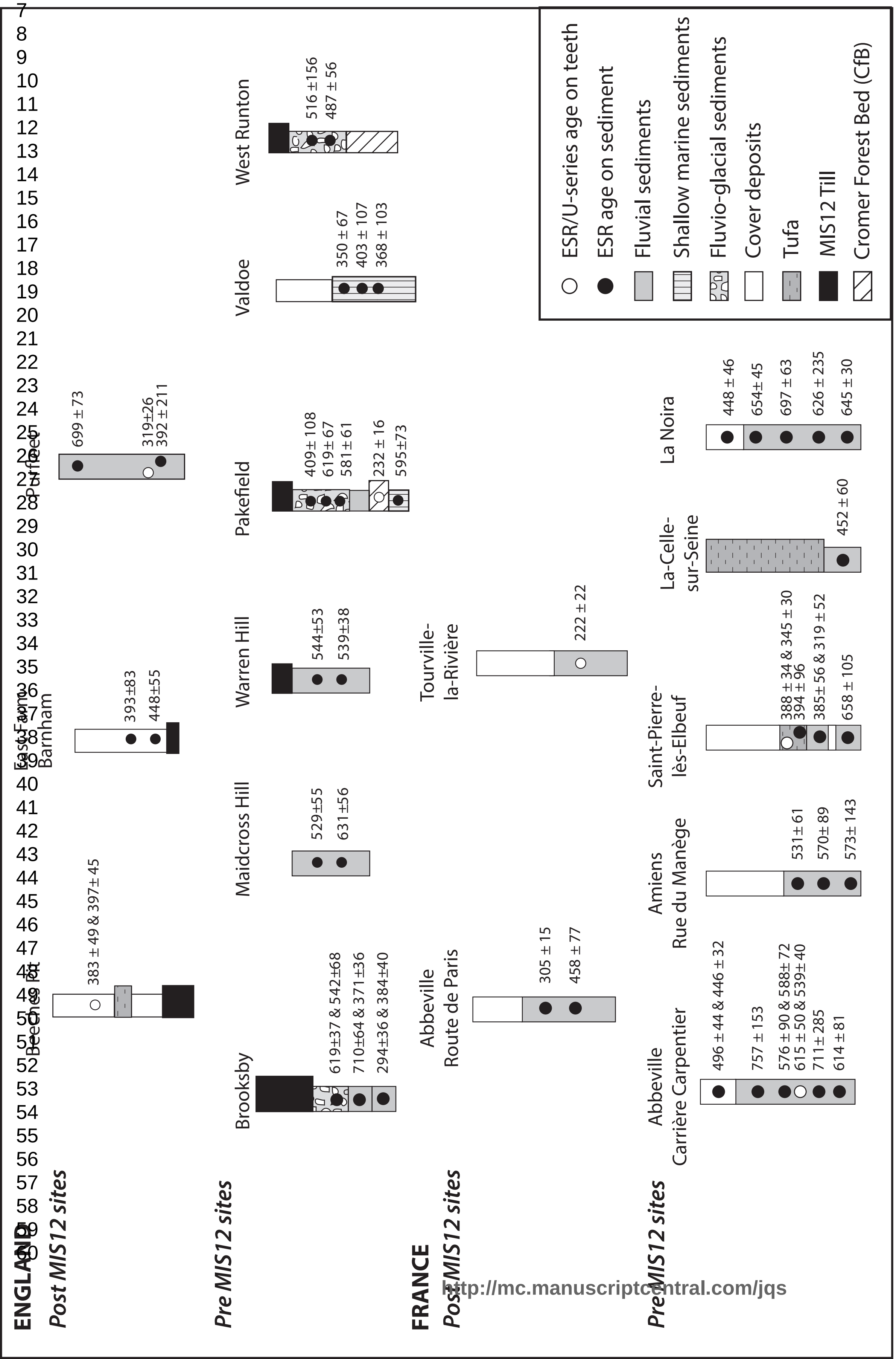

ENGLAND
Post MIS12 sites
Purfleet
699 ± 73
319±26
392 ± 211
East Farm
Barnham
393±83
448±55
Beeches Pit
383 ± 49 & 397± 45
Pre MIS12 sites
West Runton
516 ±156
487 ± 56
Valdoe
350 ± 67
403 ± 107
368 ± 103
Pakefield
409± 108
619± 67
581± 61
232 ± 16
595±73
Warren Hill
544±53
539±38
Maidcross Hill
529±55
631±56
Brooksby
619±37 & 542±68
710±64 & 371±36
294±36 & 384±40
FRANCE
Post MIS12 sites
Tourville-
la-Rivière
222 ± 22
Abbeville
Route de Paris
305 ± 15
458 ± 77
Pre MIS12 sites
La Noira
448 ± 46
654± 45
697 ± 63
626 ± 235
645 ± 30
La-Celle-
sur-Seine
452 ± 60
Saint-Pierre-
lès-Elbeuf
388 ± 34 & 345 ± 30
394 ± 96
385± 56 & 319 ± 52
658 ± 105
Amiens
Rue du Manège
531± 61
570± 89
573± 143
Abbeville
Carrière Carpentier
496 ± 44 & 446 ± 32
757 ± 153
576 ± 90 & 588± 72
615 ± 50 & 539± 40
711± 285
614 ± 81
○ ESR/U-series age on teeth
● ESR age on sediment
Fluvial sediments
Shallow marine sediments
Fluvio-glacial sediments
Cover deposits
Tufa
MIS12 Till
Cromer Forest Bed (CfB)

Table 1. List of the samples analyzed in the present work

Sector	Site	Geological age (MIS)	Methods used	References	Sampled sediments				Sampled Teeth
					Fluvial	Fluvio-glacial	Shallow-marine	Cover sequence	
Bytham Valley	*Maidscross Hill*	*MIS15 ?*			2	-	-	-	-
	Brooksby	MIS15 to MIS13-?			4	2	-	-	-
	Warren Hill	MIS13 ?			2	-	-	-	-
Central East Anglia, post-Anglian	East Farm Barnham	MIS11			2	-	-	-	-
	Beeches Pit	MIS11			-	-	-	-	2 (cover sequence)
East Anglia Coast	Pakefield	MIS19 to MIS13 ?			-	3	1	-	1 (CFB??)
	West Runton	MIS19 to MIS13 ?			-	2	-	-	-
Thames Valley	Purfleet	MIS9			2	-	-	-	1 (fluvial sequence)
Sussex Coast	Valdoe	MIS13			-	-	3	-	-
Somme Valley	Abbeville Carpentier	MIS16/15 to MIS 12 ?	Location into the fluvial system, stratigraphy of the cover sequence, biostratigraphy, various dating methods	Antoine et al. (2007, 2014) Bahain et al. (2007)	5	-	-	2	2 (fluvial sequence)
	Amiens Rue du Manège	MIS14/13			3	-	-	-	-
	Abbeville Route de Paris	MIS 7 ?			2	-	-	-	-
Seine Valley	Saint-Pierre-lès-Elbeuf	MIS14 to MIS11	Location into the fluvial system, stratigraphy of the cover sequence, biostratigraphy, various dating methods	Antoine et al. (2007) Cliquet et al. (2009) Limondin-Lozouet et al. (2010)	4	-	-	-	2 (fluvial sequence)
	La Celle	MIS12/11			1	-	-	-	-
	Tourville-la-Rivière	MIS7			-	-	-	-	6 (fluvial sequence)
Cher Valley	Brinay La Noira	MIS16/15	Location into the fluvial system, ESR dating of the whole system	Despriée et al. (2011) Moncel et al. (2014)	4	-	-	1	-

Table 2. ESR results obtained on quartz extracted from sediments of Acheulean sites in England and north-west France. Analytical uncertainties are given with ±1σ.

Water contents (%) were estimated by the difference in mass between the natural sample and the same sample dried for a week in an oven at 50°C. Dose rates were determined taking into account alpha and beta attenuations estimated for the selected grain sizes from the tables of Brennan (2003); k-value of 0.15 (Yokoyama et al., 1985), cosmic dose rate calculated from the equations of Prescott & Hutton (1994). The bleaching rate δ_{bl} (%) is determined by comparison of the ESR intensities of the natural and bleached aliquotes (δbl= ((Inat-Ibl)/Inat)x100).

Sector	Site	Sample and Unit	D_a (µGy/a)	δ_{Bl} (%)	D_e (Gy)	Ages (ka)
Bytham Valley	**Maidscross Hill**	Sands and gravels 1	1282±32	42	678±70	**529±55**
		Sands and gravels 2	985±33	48	621±55	**631±56**
	Warren Hill	Sands and gravels 1	966±25	46	526±51	**544±53**
		Sands and gravels 2	1054±33	43	568±40	**539±38**
	Brooksby	Q1 - Sands and gravels	1648±29	42	485±60	294±36
		Q2 - Sands and gravels	2010±56	54	772±80	**384±40**
		Q3 - Thurmaston Formation	1033±28	52	733±65	**710±64**
		Q4 - Thurmaston Formation	1658±36	51	615±60	**371±36**
		Q5 - Brandon Formation	1802±32	55	1115±120	**619±37**
		Q6 - Brandon Formation	1656±28	49	898±112	**542±68**
Central East Anglia, post-Anglian	**East Farm Barnham**	Sands and gravels 1	1652±44	39	740±90	**448±55**
		Sands and gravels 2	2774±71	38	1091±230	**393±83**
East Anglia Coast	**Pakefield**	Q1 - Marine sands	1586±35	41	944±116	**595±73**
		Q2 - Sands and gravels	584±25	47	339±35	**581±61**
		Q3 - Sands and gravels	746±25	42	462±50	**619±67**
		Q4 - Sands and gravels	836±28	46	342±90	**409±108**
	West Runton	Q1 - Estuarine and Freshwater sands	525±20	39	271±82	**516±156**
		Q2 - Estuarine and Freshwater sands	714±24	41	348±40	**487±56**
Thames Valley	**Purfleet**	Q1 - Shelly Gravels	497±21	46	195±105	**392±211**
		Q2 - Greenlands Shell Bed	428±19	40	299±31	**699±73**
Sussex Coast	**Valdoe**	Q1 - Slindon sands	1042±26	49	365±70	**350±67**
		Q2 - Slindon sands	1268±37	51	511±135	**403±107**
		Q3 - Slindon sands	1259±26	50	463±130	**368±103**
Somme Valley	**Abbeville Carpentier**	Q12-1 - Sheet VII - Layer 3 (slope)	582±17	38	289±24	**496±44**
		Q12-2 - Sheet VII - Layer 3 (slope)	487±15	36	217±14	**446±32**
		Q1 -Sheet VII - Layer 4b (fluvial)	688 ± 13	49	521±105	**757 ± 153**
		Q3 -Sheet VII - Layer 4c (fluvial)	483 ± 11	43	278±43	**576 ± 90**
		Q5 -Sheet VII - Layer 4c (fluvial)	401 ± 10	42	236±28	**588 ± 72**
		Q4 -Sheet VII - Layer 4d (fluvial)	433 ± 9	41	308±123	**711 ± 285**
		Q6 -Sheet VII - Layer 5b (fluvial)	476 ± 14	41	292±38	**614 ± 81**
	Amiens Rue du Manège	Q1 -Sheet VI - Fluvial sands	1114±25	52	638±159	**573±143**
		Q3 -Sheet VI - Fluvial sands	915±22	46	522±81	**570±89**
		Q4 -Sheet VI - Fluvial sands	1327±61	47	704±77	**531±61**
	Abbeville Route de Paris	Q1 -Sheet III ? - Fluvial sands	894±23	42	429±20	**305±15**
		Q2 -Sheet III ? - Fluvial sands	760±44	38	551±90	**458±77**
Seine Valley	**Saint.Pierre-lès-Elbeuf**	Q1 -Elbeuf sheet - Yellow sands	957±20	51	629±100	**658±105**
		Q2 -Elbeuf sheet - White sands	1076±22	39	414±60	**385±56**
		Q3 -Elbeuf sheet - White sands	1243±36	41	396±65	**319±52**
		Q4 -Elbeuf sheet - Sandy tufa	908±27	38	358±87	**394±96**
	La Celle	La Celle sheet -Fluvial sands	981±22	40	644±85	**452±60**
Cher Valley	**Brinay La Noira**	Sheet D - niv III-1	2907±40	42	1875±87	**645±30**
		Sheet D- niv III-2	3323±45	48	2079±780	**626±235**
		Sheet D - niv IV-1	2811±44	42	1960±177	**697±63**
		Sheet D niv IV-2	3398±62	40	2221±153	**654±45**
		Sheet D VI (slope ?) niv VI	2529±92	48	1132±115	**448±46**

Table 3. ESR/U-series results obtained on mammal teeth from Acheulean sites of England and northern France. Analytical uncertainties are given with ±1σ. Italics indicate AU model results.

Sector	**Site**	**Unit**	**Sample**	**Tissue**	**U content (ppm)**	**D_e (Gy)**	**Uptake parameter p (US) or *n (AU)***	**D_a (µGy/a)**	**US or *AU* Age (ka)**
Thames Valley	**Purfleet**	Layer 3	PFT 1201	enamel	0.564 ± 0.034	244.93 ± 7.55	*-0.0041 ± 0.0004*	768 ± 67	*319 ± 26*
				dentine	39.165 ± 0.803		*-0.0042 ± 0.0004*		
Central East Anglia, post-Anglian	**Beeches Pit**	Layer 5	BP 1201	enamel	2.326 ± 0.056	645.43 ± 76.04	*-0.0037 ± 0.0004*	1685 ± 291	*383 ± 49*
				dentine	19.303 ± 0.429		*-0.0038 ± 0.0004*		
			BP 1202	enamel	1.386 ± 0.034	671.79 ± 77.40	*-0.0034 ± 0.0005*	1691 ± 57	*397 ± 45*
				dentine	26.930 ± 0.605		*-0.0039 ± 0.0007*		
				cement	20.763 ± 0.999		*-0.0043 ± 0.0004*		
East Anglia Coast	**Pakefield**	Rootled Bed	PKF 1201	enamel	2.215 ± 0.077	191.95 ± 2.72	2.8283 ± 0.3157	936 ± 76	232 ± 16
				dentine	1.058 ± 0.040		0.4842 ± 0.1467		
Seine Valley	**Tourville-la-Rivière**	D2	TVL 157	enamel	0.594 ± 0.024	220.08 ± 2.33	-0.8300 ± 0.0368	961 ± 58	229 ± 13
				dentine	25.342 ± 0.580		-0.7151 ± 0.0450		
			TVL 160	enamel	0.402 ± 0.016	207.72 ± 2.72	-0.9128 ± 0.0319	911 ± 56	228 ± 13
				dentine	22.504 ± 0.486		-0.8797 ± 0.0340		
			TVL 219	enamel	0.671 ± 0.022	204.54 ± 2.49	-0.8188 ± 0.0456	1008 ± 61	203 ± 13
				dentine	31.541 ± 0.636		-0.7257 ± 0.0526		
			TVL 923	enamel	0.490 ± 0.018	220.08 ± 2.33	-0.8849 ± 0.0360	934 ± 59	219 ± 13
				dentine	29.026 ± 0.741		-0.7814 ± 0.0436		
			TVL 928	enamel	0.296 ± 0.014	191.33 ± 5.82	-0.9317 ± 0.0302	768 ± 55	249 ± 15
				dentine	19.976 ± 0.348		-0.6885 ± 0.0479		
			TVL 929(a)	enamel	0.374 ± 0.013	191.95 ± 2.73	-0.7420 ± 0.0447	853 ± 54	225 ± 13
				dentine	3.046 ± 0.067		-0.7269 ± 0.0456		
	Saint-Pierre-lès-Elbeuf	White sands	SPLE 01	enamel	0.193 ± 0.011	290.35 ± 14.06	*-0.0033 ± 0.0004*	748 ± 75	*388 ± 34*
				dentine	23.151 ± 0.501		*-0.0033 ± 0.0004*		
			SPLE 02	enamel	0.175 ± 0.009	245.97 ± 11.44	*-0.0037 ± 0.0004*	713 ± 70	*345 ± 30*
				dentine	22.097 ± 0.469		*-0.0041 ± 0.0004*		
Somme Valley	**Abbeville Carpentier**	4c	CC 5	enamel	0.432 ± 0.022	314.97 ± 17.39	*-0.0022 ± 0.0002*	512 ± 50	*615 ± 50*
				dentine	10.544 ±0.273		*-0.0022 ± 0.0002*		
			CC10	enamel	0.256 ± 0.016	245.97 ± 11.44	*-0.0026 ± 0.0002*	452 ± 40	*539 ± 40*
				dentine	12.432 ± 0.298		*-0.0025 ± 0.0002*		

Table S1 Radionuclide content and associated dose rates for analyzed sediments of Acheulian sites of England and North-western France. Analytical uncertainties are given with ±1σ.

Sector	Site	Unit	U (ppm)	Th (ppm)	K (%)	H_2O (%)	D_α (µGy/a)	D_β (µGy/a)	D_γ (µGy/a)	D_{cosmic} (µGy/a)
Bytham Valley	Maidscross Hill 1	M. Hill Sands and gravels	0.65±0.07	2.26±0.10	0.93±0.01	7,6	19±1	740±20	407±20	116±6
	Maidscross Hill 2	M. Hill Sands and gravels	0.36±0.06	1.29±0.08	0.67±0.01	4,1	11±1	540±17	314±25	120±6
	Warren Hill 1	W. Hill Sands and gravels	0.63±0.06	2.09±0.09	0.70±0.01	11,2	17±1	557±16	297±15	95±5
	Warren Hill 2	W. Hill Sands and gravels	0.46±0.07	1.83±0.09	0.80±0.01	6,3	15±1	639±18	301±24	100±5
	Brooksby Q1	Brooksby Sands and gravels	0.99±0.06	3.60±0.09	1.21±0.01	12	27±1	940±15	529±22	151±8
	Brooksby Q2	Brooksby Sands and gravels	1.00±0.14	4.17±0.21	1.47±0.03	12	30±1	1116±38	713±30	151±8
	Brooksby Q3	Thurmaston Formation	0.59±0.06	1.30±0.08	0.62±0.01	12	13±1	482±15	374±20	164±8
	Brooksby Q4	Thurmaston Formation	1.23±0.07	3.38±0.12	1.16±0.02	12	29±2	927±23	538±21	164±8
	Brooksby Q5	Brandon Formation	0.78±0.07	2.30±0.09	1.48±0.02	12	19±1	1061±19	543±22	179±9
	Brooksby Q6	Brandon Formation	0.72±0.05	1.70±0.07	1.34±0.01	12	16±1	951±15	510±21	179±9
Central East Anglia, post-Anglian	EastFarm Barnharm 1	Sands and gravels	1.63±0.10	4.86±0.15	0.87±0.02	4,5	46±2	905±27	561±28	140±7
	EastFarm Barnharm 2	Sands and gravels	2.87±0.13	8.31±0.21	1.48±0.02	10	72±3	1442±33	1140±57	120±6
East Anglia Coast	Pakefield Q1	Marine sands	0.99±0.09	2.93±0.13	1.31±0.01	15	23±2	949±18	573±26	41±2
	Pakefield Q2	Sands and gravels	0.36±0.06	1.04±0.08	0.42±0.01	15	8±1	310±14	220±18	45±2
	Pakefield Q3	Sands and gravels	0.49±0.06	1.06±0.07	0.61±0.01	15	10±1	436±13	255±19	45±2
	Pakefield Q4	Sands and gravels	0.52±0.07	1.43±0.09	0.63±0.01	15	12±1	460±16	281±19	83±4
	West Runton Q1	Estuarine and Freshwater sands	0.47±0.04	1.13±0.06	0.33±0.01	15	10±1	270±9	205±16	41±2
	West Runton Q2	Estuarine and Freshwater sands	0.55±0.05	1.94±0.07	0.50±0.01	15	14±1	394±12	265±18	41±2
Thames Valley	Purfleet Q1	Shelly Gravels	0.37±0.05	0.98±0.07	0.18±0.01	12	9±1	173±11	195±16	120±6
	Purfleet Q2	Greenlands Shell Bed (?)	0.55±0.05	0.76±0.06	0.15±0.01	12	10±1	172±10	163±14	83±4
Sussex Coast	Valdoe Q1	Slindon sands	0.88±0.07	2.61±0.09	0.70±0.01	15	21±1	562±15	386±18	73±4
	Valdoe Q2	Slindon sands	1.04±0.10	3.21±0.15	0.85±0.02	15	25±2	679±25	480±19	83±4
	Valdoe Q3	Slindon sands	0.99±0.05	3.19±0.07	0.74±0.01	15	24±1	608±11	516±21	111±6
Somme Valley	Abbeville Carpentier 2012-1	Sheet VII - Layer 3 (slope)	0.75±0.07	1.19±0.08	0.2±0.01	15	14±1	223±13	159±11	186±9
	Abbeville Carpentier 2012-2	Sheet VII - Layer 3 (slope)	0.52±0.06	1.01±0.07	0.16±0.01	15	10±1	169±10	121±10	186±9
	Abbeville Carpentier1	Sheet VII - Layer 4b (fluvial)	0.74±0.05	1.25±0.06	0.21±0.01	15	13±1	226±10	279±12	140±7
	Abbeville Carpentier3	Sheet VII - Layer 4c (fluvial)	0.48±0.05	0.79±0.06	0.06±0.01	15	9±1	101±8	209±16	136±7
	Abbeville Carpentier5	Sheet VII - Layer 4c (fluvial)	0.38±0.05	0.77±0.06	0.12±0.01	15	7±1	80±8	156±8	131±7
	Abbeville Carpentier4	Sheet VII - Layer 4d (fluvial)	0.36±0.04	0.65±0.05	0.05±0.01	15	7±1	128±6	150±8	122±6
	Abbeville Carpentier6	Sheet VII - Layer 5b (fluvial)	0.50±0.05	1.09±0.07	0.19±0.01	15	10±1	189±11	140±7	113±6
	Amiens Manège 1	Sheet VI - Fluvial sands	0.97±0.07	2.19±0.09	0.70±0.01	10	11±1	593±16	356±15	154±8
	Amiens Manège 3	Sheet VI - Fluvial sands	0.88±0.07	1.74±0.09	0.51±0.1	10	9±1	453±16	299±10	154±8
	Amiens Manège 4	Sheet VI - Fluvial sands	1.03±0.06	2.78±0.07	0.87±0.07	10	13±1	717±52	443±21	154±8
	Abbeville Rte Paris 1	Sheet III ? - Fluvial sands	1.65±0.08	4.58±0.11	0.72±0.01	10	20±1	720±17	513±15	154±8
	Abbeville Rte Paris 2	Sheet III ? - Fluvial sands	1.38±0.21	4.14±0.14	0.61±0.01	10	18±2	611±33	443±29	131±7
Seine Valley	Saint-Pierre 2011-1	Elbeuf sheet - Yellow sands	0.69±0.05	2.49±0.07	0.57±0.01	15	18±1	462±10	435±15	42±2
	Saint-Pierre 2011-2	Elbeuf sheet - White sands	1.09±0.06	3.05±0.07	0.62±0.01	15	25±1	544±12	466±15	42±2
	Saint-Pierre 2011-3	Elbeuf sheet - White sands	1.37±0.11	3.33±0.15	0.66±0.02	15	29±2	601±24	571±19	42±2
	Saint-Pierre 2011-4	Elbeuf sheet - Sandy tufa	0.84±0.07	2.04±0.09	0.32±0.01	10	19±1	343±15	508±19	38±2
	La Celle 4	Elbeuf sheet -Fluvial sands	0.79±0.07	2.49±0.09	1.19±0.01	10	21±1	909±17	442±13	51±3
Cher Valley	Noira niv III-1	Sheet D III	1.26±0.06	4.9±0.12	2.51±0.01	10	38±1	1862±13	920±36	88±4
	Noira niv III-2	Sheet D III	1.18±0.06	4.84±0.13	2.98±0.01	10	36±1	2156±12	1040±42	91±5
	Noira niv IV-1	Sheet D IV	1.21±0.07	4.80±0.35	2.35±0.01	10	36±2	1747±15	920±35	108±5
	Noira niv IV-2	Sheet D IV	2.17±0.13	10.89±0.41	2.20±0.01	10	76±3	1881±25	1290±48	152±8
	Noira niv VI	Sheet D VI (slope ?)	0.95±0.03	3.67±0.33	2.03±0.06	10	28±4	1493±70	810±35	198±10

Table S2 U-series and ESR preparation data for analyzed teeth of Acheulian sites of England and North-western France. Analytical uncertainties are given with ±1σ.

Sector	Site	Unit	Samples	Tissue	U content (ppm)	^{230}Th/^{232}Th	^{234}U/^{238}U	^{230}Th/^{234}U	^{222}Rn/^{230}Th	Initial thickness (µm)	Removed thickness Internal side (µm)	Removed thickness External side (µm)
Thames Valley	Purfleet	Layer 3	PFT1201	enamel	0.56 ± 0.03	12	1.611 ± 0.100	1.075 ± 0.082	0.982	872 ± 109	178 ± 22	46 ± 6
				dentine	39.17 ± 0.80	339	1.404 ± 0.027	1.058 ± 0.030	0.256			
Central East Anglia, post-Anglian	Beeches Pit	Layer 5	BP1201	enamel	2.33 ± 0.06	12	1.099 ± 0.027	1.096 ± 0.036	0.596	1285 ± 161	58 ± 7	119 ±15
				dentine	19.30 ± 0.43	43	1.049 ± 0.017	1.106 ± 0.036	0.487			
		Layer 5	BP1202	enamel	1.39 ± 0.03	35	1.211 ± 0.029	1.110 ± 0.039	0.896	1247 ± 156	173 ± 22	174 ± 22
				dentine	26.93 ± 0.61	92	0.967 ± 0.014	1.209 ± 0.039	0.322			
				cement	20.76 ± 1.00	11	0.980 ± 0.037	1.524 ± 0.0129	0.416			
East Anglia Coast	Pakefield	Rootled Bed	PKF1201	enamel	2.22 ± 0.08	22	1.339 ± 0.043	0.320 ± 0.020	1,000	1636 ± 205	210 ± 26	252 ± 31
				dentine	1.06 ± 0.04	18	1.247 ± 0.046	0.514 ± 0.031	1,000			
Seine Valley	Tourville-la-Rivière	D2	TVL 157	enamel	0.59 ± 0.02	169	1.441 ± 0.069	0.848 ± 0.045	0,334	959 ± 17	21 ± 3	74 ± 9
				dentine	25.34 ± 0.58	> 500	1.306 ± 0.026	0.787 ± 0.025	0,366			
			TVL 160	enamel	0.40 ± 0.02	52	1.313 ± 0.060	0.879 ± 0.049	1,000	1050 ± 131	28 ± 3	160 ± 20
				dentine	22.50 ± 0.49	200	1.333 ± 0.026	0.865 ± 0.025	0,340			
			TVL 219	enamel	0.67 ± 0.02	75	1.259 ± 0.043	0.789 ± 0.037	0,405	1027 ± 128	14 ± 2	167 ± 21
				dentine	31.54 ± 0.64	> 500	1.274 ± 0.022	0.750 ± 0.023	0,378			
			TRV 923	enamel	0.49 ± 0.01	42	1.301 ± 0.054	0.850 ± 0.045	0259	958 ± 120	68 ± 9	76 ± 9
				dentine	29.03 ± 0.74	152	1.261 ± 0.028	0.797 ± 0.029	0,293			
			TRV 928	enamel	0.30 ± 0.01	48	1.409 ± 0.076	0.927 ± 0.058	0,258	1268 ± 159	200 ± 25	148 ± 18
				dentine	19.98 ± 0.35	172	1.311 ± 0.021	0.803 ± 0.021	0,523			
			TVL 929(a)	enamel	0.37 ± 0.01	37	1.236 ± 0.047	0.787 ± 0.038	0,247	1200 ± 150	112 ± 14	60 ± 8
				dentine	3.05 ± 0.07	> 500	1.263 ± 0.025	0.783 ± 0.027	1,000			
	Saint-Pierre-lès-Elbeuf	White Sands	SPLE01	enamel	0.19 ± 0.01	7	1.393 ± 0.093	1.056 ± 0.077	1,000	926 ± 120	14 ± 2	37 ± 5
				dentine	23.15 ± 0.50	> 500	1.433 ± 0.028	1.081 ± 0.032	0.273			
			SPLE02	enamel	0.18 ± 0.01	10	1.485 ± 0.089	1.040 ± 0.082	1,000	987 ± 120	53 ± 7	27 ± 3
				dentine	22.10 ± 0.47	444	1.424 ± 0.015	1.168 ± 0.035	0.219			
Somme Valley	Abbeville Carrière Carpentier	4c	CC5	enamel	0.43 ± 0.02	29	1.157 ± 0.070	1.172 ± 0.078	1,000	1059 ± 132	123 ± 15	79 ± 10
				dentine	10.54 ± 0.27	238	1.236 ± 0.024	1.234 ± 0.045	0.497			
			CC10	enamel	0.26 ± 0.07	20	1.342 ± 0.099	1.345 ± 0.106	1,000	1185 ± 148	78 ± 10	7 ± 1
				dentine	12.43 ± 0.30	331	1.265 ± 0.025	1.227 ± 0.043	0.352			

Table S3. Radionuclide contents of sediments associated to analyzed teeth from Acheulian sites of England and North-western France.

Sector	Site	Unit	Samples	^{238}U (ppm)	^{230}Th (ppm)	^{40}K (%)
Thames Valley	Purfleet	Layer 3	Sed1201	0.509 ± 0.050	0.709 ± 0.053	0.154 ± 0.053
Central East Anglia, post-Anglian	Beeches Pit	Layer 5	Sed1201	2.335 ± 0.129	8.511 ± 0.197	0.906 ± 0.018
East Anglia Coast	Pakefield	Rootled bed	Sed1201	1.578 ± 0.131	4.588 ± 0.111	1.377 ± 0.015
Seine Valley	Tourville-la-Rivière	D2	sed157	1,072 ± 0,086	4,005 ± 0,114	0,894 ± 0,014
			sed160	1,252 ± 0,074	4,341 ± 0,099	0,902 ± 0,011
			sed219c	1,293 ± 0,076	3,807 ± 0,102	0,853 ± 0,012
			sed923	1,065 ± 0,063	3,716 ± 0,084	0,837 ± 0,010
			sed928	1,120 ± 0,078	3,735 ± 0,103	0,799 ± 0,012
			sed929	1,151 ± 0,086	3,678 ± 0,114	0,807 ± 0,014
	Saint-Pierre-lès-Elbeuf	White Sands	Sed1201	0.834 ± 0.065	1.904 ± 0.083	0.323 ± 0.009
Somme Valley	Abbeville Carrière Carpentier	4c	sedCC5	0.635 ± 0.052	1.519 ± 0.064	0.310 ± 0.068
			sedCC10	0.484 ± 0.047	0.749 ± 0.054	0.061 ± 0.004