JOURNAL OF QUATERNARY SCIENCE (2015) **30**(7) 610–622 ISSN 0267-8179. DOI: 10.1002/jqs.2814

New chronological data (ESR and ESR/U-series) for the earliest Acheulian sites of north-western Europe

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Received 29 June 2015; Revised 2 October 2015; Accepted 2 October 2015

ABSTRACT: Increasing evidence suggests that bifacial technology (Acheulian, Mode 2) 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 electron spin resonance (ESR) dating of sedimentary quartz and ESR/U-series dating of fossil tooth enamel to key Acheulian sites of this area. Although the age estimates have large associated uncertainties, most 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 (cores and flakes, Mode 1) is older than Marine Isotope Stage (MIS) 15, whereas localities containing Acheulian 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 Acheulian in central France as early as MIS 17. The dates presented here support the suggestion that the earliest Acheulian appeared in NW Europe during the early Middle Pleistocene, significantly after its appearance in the southern parts of the continent. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS: Acheulian; archaeology; early Middle Pleistocene; ESR; geochronology; Lower Palaeolithic; quartz; U-series.

Introduction

Evidence of bifacial technology in Europe (also termed Mode 2 or Acheulian) 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, 1999; Lefèvre *et al.*, 2010; Pereira *et al.*, 2015), 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 to 900 ka (Mosquera *et al.*, 2015) has shed new light on the starting-point of European bifacial technology. This site, and its associated artefacts, have raised questions as to the origin of this technology (local or introduced) and have reduced the chronological gap for the appearance of this technology between Africa and Europe (Vallverdú *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 500 ka. Here, the emergence of the Middle Palaeolithic, and the subsequent fading of the 'classic Acheulian', is observed between Marine Isotope Stage (MIS) 11 and 9 (i.e. Moncel *et al.*, 2012; Adler *et al.*, 2014), although handaxes continue to be made until the replacement of Neanderthals by modern humans in the Late Pleistocene.

The archaeological evidence between 800 and 500 ka allows 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; Ashton *et al.*, 2011; Despriée *et al.*, 2011; Ashton and Lewis, 2012; Stringer, 2012; Moncel *et al.*, 2013; Bridgland and White, 2014; Meyer *et al.*, 2014). The scarcity of sites over such a long period 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 high or higher than the present-day (Candy *et al.*, this volume). Lithic series from both before and after MIS 12 display a wide diversity of features due to various activities, raw materials and traditions. As regards the raw

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materials, in Europe, flint is mainly used in the north (northern France, England), whereas a wider range of lithologies (siliceous stones, quartz, quartzite, volcanic stones) were exploited in the south (southern France, Italy, Spain). 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, as 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 referto several European 'Acheulians', rather than a single Acheulian, and to consider them as discontinuous phenomena. In this paper, when we later refer to Acheulian (with evidence of bifaces), this is taken to reflect the diversity apparent within this tradition.

The establishment of a chronological framework for Acheulian sites in this region encounters certain difficulties. The period is far beyond the application range of radiocarbon, while 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. It includes biostratigraphy mainly from mammals (e.g. Schreve *et al.*, 2007; Auguste, 2009) and malacofauna (e.g. Preece *et al.*, 2007; Limondin-Lozouet *et al.*, 2015), 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 [optically stimulated luminescence (OSL) and thermoluminescence (TL)] (e.g. Pawley *et al.*, 2010) have been employed, whereas in France, the chronology is mainly 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.*, 1998; 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 Acheulian in North-West Europe: chronology, environment, technologies' (2010–2014), devoted to understanding the timing, nature and palaeoenvironments of the onset of bifacial technology in NW Europe. The new dating analyses presented here have focused on two types of sequences: first, sediment sequences that contain *in situ* Acheulian artefacts; and second, sediment sequences that contain either older (Mode 1 or core and flake industries without bifaces, considered as technologically less elaborate) 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 Acheulian to be placed within 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 NW 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 to compare results. The paper concludes by discussing the implications of this combined approach for understanding the timing of the appearance of the Acheulian in NW Europe.

Materials and methods

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 for 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 dose rate D_a received by the sample.

The total dose is assessed through the quantification of unpaired 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 to model this phenomenon for each sample. In the case of teeth, these models allow, for each 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 employed model [US model (Grün *et al.*, 1988); 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 rate 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 optical bleaching). With reference to the signal used in this study, which is related to the aluminium paramagnetic centre (the Al-centre) in the quartz structure, there remains a part of the Al-centre that is not fully bleached during exposure to sunlight. This part is responsible for the presence of 'residual' ESR signal at the time of deposition of the quartz grains after their transportation. It is therefore necessary to determine the intensity of this residual signal or the specific maximal bleaching intensity of each studied sample to determine the 'real' total dose of radiation received after deposition. This residual intensity is then subtracted from the total dose to obtain D_e values used for the age calculation.

Recent experiments have shown that the residual dose due to insufficient bleaching of Al signal was a few grays after transport of a quartz grain by a river in mid-latitudes. These few grays are integrated into the selected error range (Voinchet *et al.*, in press). Recent comparison between $^{39}Ar/^{40}Ar$ dates and ESR Al age estimates shows a good agreement for early Middle Pleistocene fluvial sediments, without overestimation or evidence for incomplete bleaching (Pereira *et al.*, 2015).

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

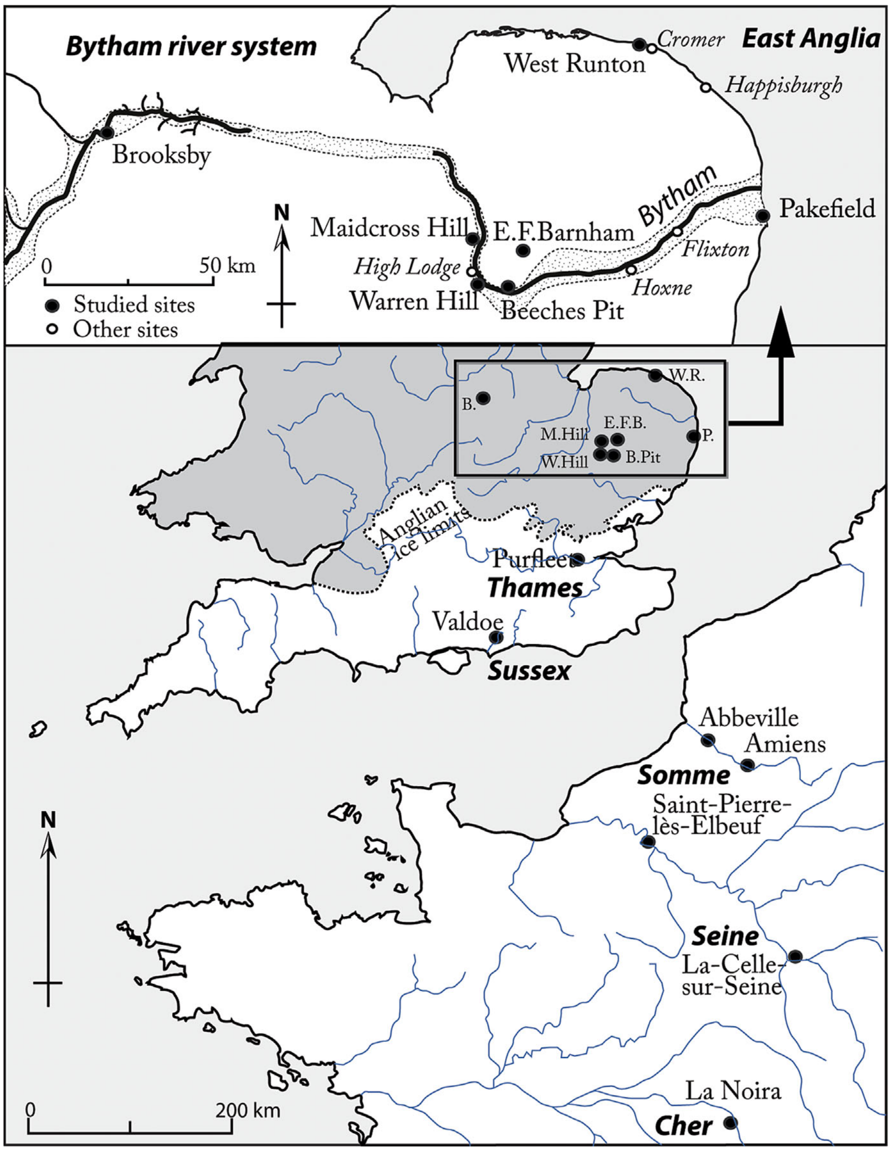

Figure 1. Location of the studied sites.

(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. 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 Acheulian assemblages. A total of 46 sediment samples and 14 teeth were therefore sampled from 17 sites with geological ages ranging from an estimated MIS 19 to MIS 7 inclusive (Table 1).

At each site, sediment samples of around 1 kg 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 portable gamma spectrometer (Canberra Inspector 1000), to evaluate the γ dose rate.

For ESR/U-series analyses, similar *in situ* studies and sediment sampling were also performed 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).

Analytical protocols

ESR dating of quartz grains

The ESR dating method was applied on 100–200-μm quartz grains (the best grain size for ESR studies; Voinchet *et al.*, 2015). The extraction and preparation protocol of these quartz grains is described by Voinchet *et al.* (2004). The D_e is determined using an additive protocol. This protocol was first described by Yokoyama *et al.* (1985) and modified first by Laurent *et al.* (1998) and later by Voinchet *et al.* (2004). After extraction, each sample was split into 11 aliquots. Nine of these were irradiated at different doses ranging from 200 to 16 000 Gy with a gamma ^{60}Co source (CEN (CEA) Saclay, France). One aliquot was conserved as natural reference and the eleventh aliquot was exposed for 1000 h to light in a Dr Honhle SOL2 solar simulator to determine the unbleachable part of the ESR-Al signal. The equivalent dose (D_e) is then determined by subtraction of the residual intensity evaluated from the maximum bleaching value from the total dose which is obtained by an exponential + linear function.

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

Sector	Site	Geological age (MIS)	Methods used	References	Sampled sediments: Fluvial	Fluvio glacial	Shallow marine	Cover sequence	Sampled teeth
Bytham Valley	Maidscross Hill	MIS 15 or 13	Terrace stratigraphy of Bytham River	Ashton and Lewis (2005)	2	–	–	–	–
	Brooksby	MIS 15 to MIS 13	Terrace stratigraphy of Bytham River, biostratigraphy		4	2	–	–	–
	Warren Hill	MIS 13	Terrace stratigraphy of Bytham River	Bridgland *et al.* (1995)	2	–	–	–	–
Central East Anglia, post-Anglian	East Farm Barnham	MIS 11	Stratigraphy, amino acid geochronology, biostratigraphy	Ashton *et al.* (1998), Penkman *et al.* (2013)	2	–	–	–	–
	Beeches Pit	MIS 11	Stratigraphy, amino acid geochronology, TL dates, biostratigraphy	Preece *et al.* (2007)	–	–	–	–	2 (cover sequence)
East Anglia Coast	Pakefield	MIS 19 to MIS 13	Stratigraphy, biostratigraphy,	Parfitt *et al.* (2005)	–	3	1	–	1 (CFB??)
	West Runton	MIS 19 to MIS 13	Amino acid geochronology	Penkman *et al.* (2013)	–	2	–	–	–
Thames Valley	Purfleet	MIS 9	Thames terrace stratigraphy, amino acid geochronology, biostratigraphy	Schreve *et al.* (2002), Penkman *et al.* (2013)	2	–	–	–	1 (fluvial sequence)
Sussex Coast	Valdoe	MIS 13	Stratigraphy of Sussex raised beaches, biostratigraphy	Pope *et al.* (2009)	–	–	3	–	–
Somme Valley	Abbeville CarpentierAmiens Rue du Manège	MIS 16/15 to MIS 12 MIS 14/13	Location into the fluvial system, stratigraphy of the cover sequence, biostratigraphy, various dating methods	Antoine *et al.* (2007, 2015) Bahain *et al.* (2007)	5 3	– –	– –	2 –	2 (fluvial sequence) –
Seine Valley	Saint-Pierre-lès-Elbeuf La Celle sur Seine	MIS 14 to MIS 11 MIS 12/11	Location into the fluvial system, stratigraphy of the cover sequence, biostratigraphy, various dating methods	Cliquet *et al.* (2009) Antoine *et al.* (2007) Limondin-Lozouet *et al.* (2010)	4 1	– –	– –	– –	2 (fluvial sequence) –
Cher Valley	Brinay La Noira	MIS 16/15	Location into the fluvial system, ESR dating of the whole system	Despriée *et al.* (2011) Moncel *et al.* (2015)	4	–	–	1	–

Each series of 11 aliquots was measured at least three times by ESR at 107 K using a Bruker EMX spectrometer and each aliquot was measured three times after a 60° rotation of the tube in the ESR cavity. This rotation allows us to take into account the angular dependence related to the sample heterogeneity (more or less sensitive grain mixture) and to the grain orientation distribution. D_e values were then determined from the obtained ESR intensities versus dose growth curve, using an exponential+linear function (Voinchet *et al.*, 2013) with Microcal OriginPro 8 software, weighted by the inverse of the squared ESR intensities ($1/I^2$). In the age calculation, D_a values were calculated from the radionuclide content of the sediments, taking into account the *in situ* and laboratory gamma-ray data and the location of the samples in the stratigraphic sequence.

ESR/U-series dating of teeth

Details of the analytical methodology and age calculations for the 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 through 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 Figs 2 and 3 (additional data are given in Supplementary Tables S1–S3). The main part of the ESR/U-series ages (except for the Pakefield samples) was calculated using the AU model, indicating complex U-uptake/leaching histories for these samples.

For the French sites, the results obtained by ESR and ESR/U-series at Abbeville Carpentier and Saint-Pierre-lès-Elbeuf, MIS 16/15 and MIS 12/11, 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 lower fluvial sands (yellow sands) seems, however, to be seriously over-estimated as these are generally considered MIS 12/11 in age but generate an estimate of ca. MIS 16. The ages obtained from La Celle-sur-Seine (MIS 12/11), Brinay-la-Noira and Amiens Rue-du-Manège (quartz) agree 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.*, 1998; Limondin-Lozouet *et al.*, 2006, 2010; Antoine *et al.*, 2007; Despriée *et al.*, 2010).

For the English localities, even where the results generated in this study agree with the estimated 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 (e.g. Bridgland, 1994; Schreve *et al.*, 2002; Penkman *et al.*, 2013). However, one of the ESR dates on sediment is substantially over-estimated, perhaps because of incomplete initial optical 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 (e.g. reworked from the bedrock or river bank) will lead to such over-estimation (Voinchet *et al.*, 2015). 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 deposition during the early Middle Pleistocene, 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 considered. For Pakefield, the quartz extracted from the shallow marine sands and gravel that overlie the Cromer Forest-bed Formation (CFbF) provides an age estimate of MIS 16/15, 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 consistentwith 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. This is because *in situ* gamma spectrometry at the site demonstrated considerable variation in dose rate between the various deposits. Furthermore, the tooth used came from museum collections and although provenanced to the Rootlet Bed, its precise position was not established, meaning that potential variation in the external dose rate will have a great impact on the age calculation. Note also that the ages of shallow marine sediments at Valdoe seem to be systematically under-estimated. With the exception of the aforementioned samples, the ESR results obtained for pre- and post-MIS 12 sites agree with other age estimates (Table 1) 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 preexisting 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.*, 2013). 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 (Ashton *et al.*, 1998; Schreve *et al.*, 2002; Bridgland *et al.*, 2013). 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 analyses generate age estimates that are consistent, within uncertainties, with an MIS 11 age (Beeches Pit 397 ± 45 ka, Barnham 393 ± 83 and 448 ± 55 ka). The age estimates for Purfleet are far more variable. While the dating of the teeth from Purfleet has yielded an age that is consistent with MIS 9 (319 ± 26 ka), the sediment ESR analyses yield dates that indicate either an MIS 9 age, but with very large associated uncertainties (392 ± 211 ka), or unrealistically old ages (699 ± 73 ka) when the biostratigraphy of the site and fluvial history of the Thames are 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

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 and water attenuation values from Grün (1994). Dose rates were determined taking into account alpha and beta attenuations estimated for the selected grain sizes from the tables of Brennan (Brennan *et al.*, 1991; Brennan, 2003); dose rate conversion factors from Adamiec and Aitken (1998); *k*-value of 0.15 (Yokoyama *et al.*, 1985); the internal dose rate was considered as negligible due to the low content of radionuclides from the quartz grains (Murray and Roberts, 1997; Vandenberghe *et al.*, 2008); we removed the external part of the grain (around 20 μm) by HF etching; cosmic dose rate calculated from the equations of Prescott and Hutton (1994) corrected according to altitude and latitude. The bleaching rate δbl (%) is determined by comparison of the ESR intensities of the natural and bleached aliquotes (δbl = ((Inat–Ibl)/Inat) × 100).

Sector	Site	Sample and unit	D_a (μGy a^{-1})	δ_{Bl} (%)	D_e (Gy)	Age (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
		Q1 – Sheet VI – Fluvial sands	1114 ± 25	52	638 ± 159	573 ± 143
	Amiens Rue du Manège	Q3 – Sheet VI – Fluvial sands	915 ± 22	46	522 ± 81	570 ± 89
		Q4 – Sheet VI – Fluvial sands	1327 ± 61	47	704 ± 77	531 ± 61
Seine Valley	Saint. Pierre-les-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 – niv VI	2529 ± 92	48	1132 ± 115	448 ± 46

from older sites. Furthermore, as the MIS 9 and 11 sites described above contain some of the youngest Acheulian artefacts in Britain, the results presented here are consistent with the youngest Acheulian 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.*, 2013). 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 Acheulian 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 (Ashton and Lewis, 2005). Archaeological finds associated with Bytham river deposits are therefore automatically of pre-MIS 12 age (Ashton *et al.*, 2008). The deposits at Valdoe, the Slindon Sands, are beyond the Anglian ice limits and therefore cannot 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

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 (p.p.m.)	D_e (Gy)	Uptake parameter p (US) or n (*AU*)	D_a (μGy a^{-1})	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	Rootledbed	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	Saint Pierre les Elbeuf	Whitesands	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*		

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

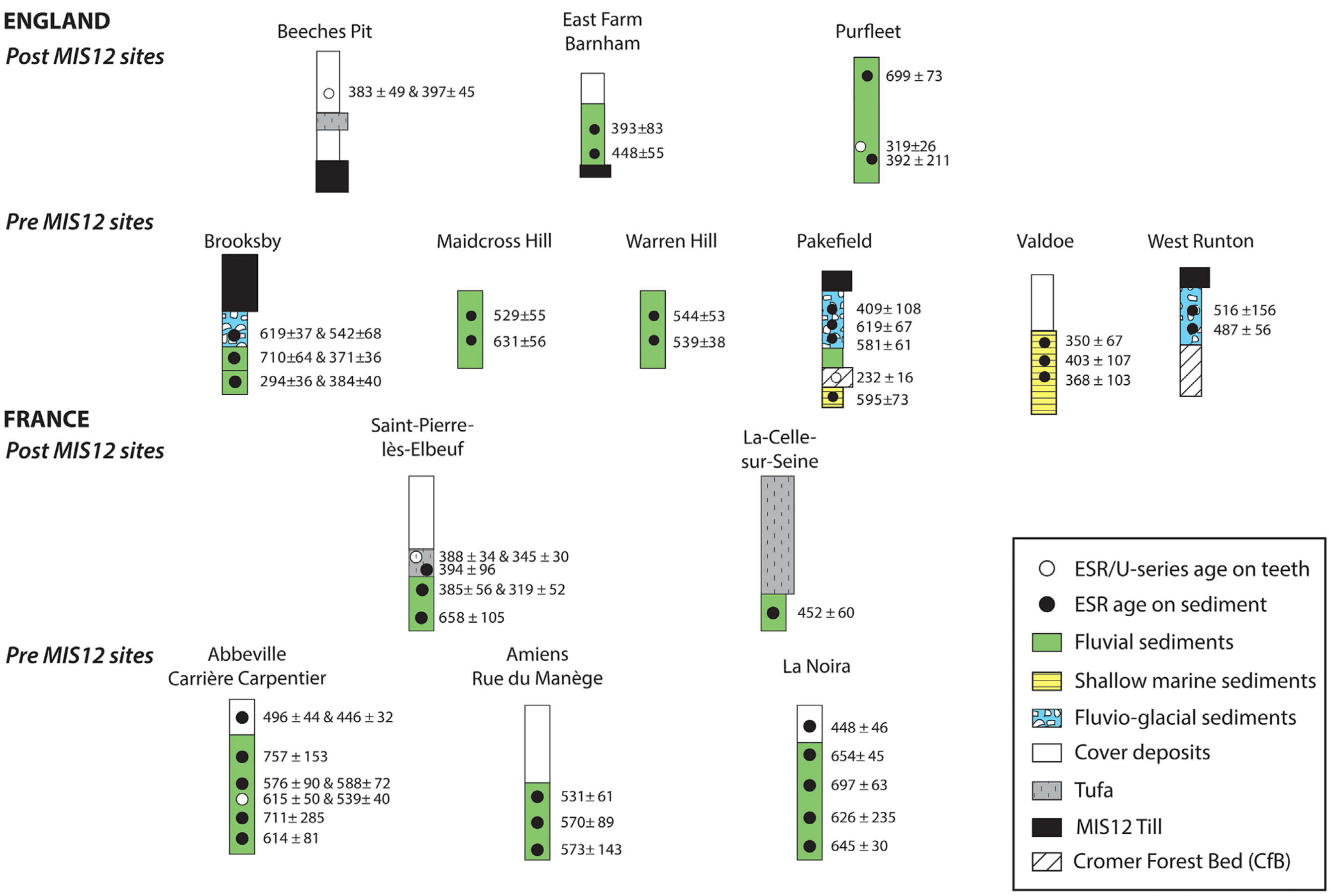

Figure 2. ESR and ESR/U-series ages obtained for the studied sites of England and northern France.

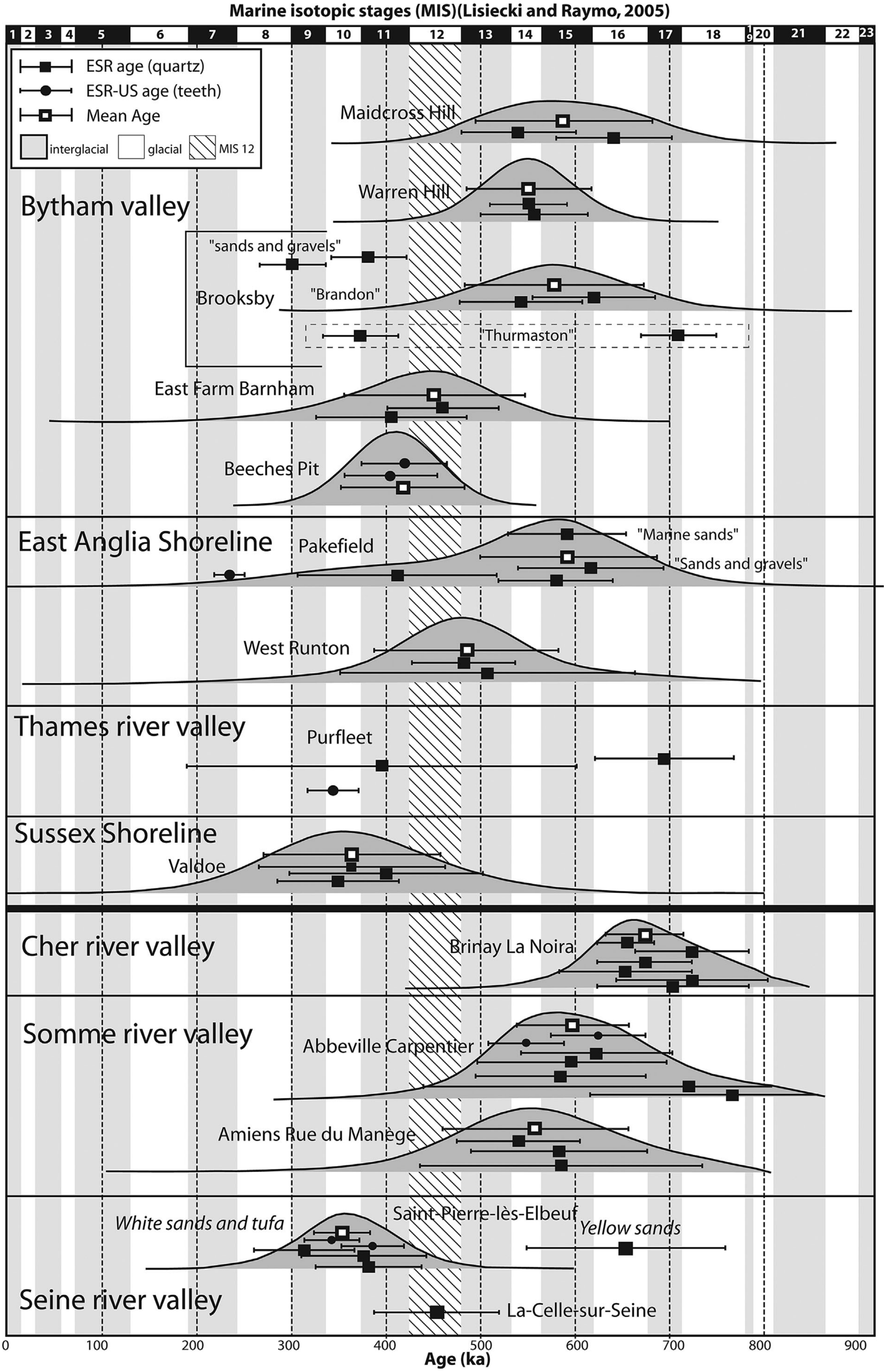

Figure 3. Age density plots obtained from ESR and ESR/U-series results for the studied sites of England and northern France. The mean ages and density plots were obtained using Isoplot software (Ludwig, 2008).

(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 MIS 13/12 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 CFbF deposits at Pakefield and West Runton represent the oldest sediments analysed 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.*, 2013). At both sites it is likely that MIS 15 is a minimum age for the CFbF deposits, while 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 CFbF 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 ± 53 and 539 ± 38 ka) and Maidcross Hill (529 ± 55 and 631 ± 56 ka) are consistent with the sediments being deposited during the late 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 estimated average of all three dates implies deposition during MIS 11/10. The uncertainties associated with these dates are, however, large and, for one 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 CFbF at both sites. At West Runton, tidal sands were sampled that directly overlie the CFbF deposits; these yielded MIS 13 aged (487 ± 56 and 516 ± 156 ka), implying that the CFbF at this site must be older than MIS 13. This is consistent with current suggestions that the CFbF at West Runton is MIS 15 or older (Preece and Parfitt, 2012; Penkman *et al.*, 2013), although it does imply that there is a significant hiatus between the CFbF and the overlying tidal sediments. At Pakefield, the three ESR quartz ages that are taken from sediments units that directly frame the CFbF have yielded estimates of MIS 15 (581 ± 61, 595 ± 73 and 619 ± 67 ka). This would again imply that the CFbF 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 ± 108 ka), perhaps in relation to water circulation associated with the till installation rather than with the sediment deposition. These large uncertainties mainly relate to the determination of the total dose. The dispersion of points allowing the construction of the ESR signal growth curve implies a significant error to the total dose (Fig. S1). Note that the ESR/U-series age from tooth enamel recovered from the CFbF at Pakefield is unrealistically young, yielding an age of 232 ± 16 ka. 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 ± 64 ka) and 8 (294 ± 36 ka). Currently it is unclear why this scatter in derived ages exists. The sand and gravel ages (Q1 and Q2) are under-estimated due to the (as yet) unexplained small D_e. For the Thurmaston Formation (Q3 and Q4), reproducibility is very poor and further sampling is advisable to understand the dataset. For Q5 and Q6, the ages are more consistent with the early Middle Pleistocene age inferred from the lithostratigraphy, but with respect to the entire Brooksby dataset, these ages should be treated with caution pending future work. Despite thestratigraphic 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 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 (among 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 MIS 16/15 and MIS 14/13, respectively. The age estimate for Abbeville Carpentier is consistent with the biostratigraphical record, which includes several early Middle Pleistocene species, such as *M. savini* and the mollusc *Tanousia* (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 urbanization.

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-Pierre-lès-Elbeuf and La-Celle-sur-Seine are both localities that contain the well-defined MIS 11 *Lyrodiscus* assemblage (Limondin-Lozouet and Antoine, 2006). This is also observed at Saint-Acheul (Formation IV of the Somme system, Antoine *et al.*, 2007) and in England at Beeches Pit and Hitchin (Limondin-Lozouet *et al.*, 2015\). The ESR/U-series and ESR dates obtained on teeth and sediments from the White Sands at Saint-Pierre-lès-Elbeuf agree with the MIS 11 attribution of this malacological assemblage, whereas ESR dates on the underlying Yellow Sands seem over-estimated in comparison with the stratigraphical estimates, which place its deposition during MIS 14 (Lautridou *et al.*, 1999; Antoine *et al.*, 2007). Work done recently on a nearby site (Fiefs Mancels) in the same alluvial terrace confirm this assignment (Tissoux in Jamet, 2014).

At La-Celle-sur-Seine, the ESR age (452 ± 60 ka) obtained on the fluvial sands underlying the thick tufa formation places its deposition during MIS 12. This result is in good agreement with the other available geochronological data of 424 ± 38 ka and around 390 ka based on ESR/U-series and U-series dating, respectively (Bahain *et al.*, 2010), as well as the malacological record derived from the overlying tufa (Limondin-Lozouet *et al.*, 2010, 2015).

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, have 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.*, 2013). The new ages obtained at la Noira agree 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 Acheulian in NW Europe

The new age estimates support existing chronological frameworks of early hominin occupation and archaeology in NW Europe.

With respect to British sites, the following conclusions can be drawn. First, 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 Acheulian sites are found in late Middle Pleistocene deposits and are dated to MIS 11 and 9. Secondly, sites containing core and flake industries technologically related to either Mode 1 or Mode 2 (except the Clactonian) are dated to MIS 15 or older (see *Candy et al.*, 2016, 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 Acheulian 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. Note that this chronological model is consistent with the biostratigraphical model proposed by Preece and Parfitt (2012); i.e. that Acheulian bifacial 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 as 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 MIS 16 (Pereira *et al.*, 2015). This does not discount the possibility that, locally, *A. t. cantiana* may appear before this age but supports the general suggestion that any deposits that contain this biostratigraphically significant indicator species must be, in NW Europe, of MIS 15 age or younger (Candy *et al.*, 2016).

With respect to French sites, for NW 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 Acheulian 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 ofthe 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 NW Europe (Limondin-Lozouet *et al.*, 2010, 2015). Finally the new dates obtained at Saint-Pierre-lès-Elbeuf, Seine Valley, are consistent with the infrared stimulated luminescence 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 palaeosol Elbeuf IV, yielding *in situ* Acheulian artefacts and faunal remains.

Conclusions

The ESR and U–Th series dating techniques applied in this study to sedimentary quartz and fossil teeth provide a chronological framework within which the Acheulian sites of northern France and Britain may be placed. While 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 geochronological data. These dates suggest that core-and-flake industries (series without bifaces related to Mode I or Mode 2 without bifaces) in Britain are >MIS 15 in age, while the oldest assemblages with bifacial technology (Acheulian, Mode 2) date to late MIS 15/MIS 13. The youngest Lower Palaeolithic Acheulian assemblages are dated to MIS 11/9. Undoubtedly the oldest ESR ages for an Acheulian site come from la Noira (most probably MIS 17 in age), making this the earliest handaxe locality in NW Europe. In Britain, no Acheulean site has yielded ages older than MIS 15/13. With the exception of La Noira, most Acheulian sites in both Britain and northern France therefore date to the interval MIS 15–9. There is therefore some regional consistency in the time interval over which Acheulian industries occur in both Britain and France. This study therefore provides the first radiometric dating evidence that supports the arrival of Acheulean technology in northern Europe before 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 (at least 100 ka) 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.

The relative paucity of archaeological evidence of bifaces during the period 700–400 ka, in combination with the new dates presented here, confirms our hypothesis of short-lived dispersal events, first from the south with a source–sink dynamic, and subsequently moving northward, onto a local substratum occupied by populations using core-and-flake industries. These core-and-flake industries pre-date all series with bifaces but persist later under other forms (e.g. Mode 2 groups without bifaces such as the Clactonian). In both France and Britain, the bifacial series do not indicate any sign of a local origin. This accordingly implies fluctuating colonization attempts (both successful and unsuccessful). This may possibly also explain the diversity of strategies and assemblage composition seen in each Acheulian site, as each one is an individual case. After MIS 12, sites are more numerous and populations better established, before the development of the earliest evidence for Middle Palaeolithic-type strategies.

Supporting Information

Fig. S1. Examples of the ESR versus gamma dose signal growth curve.

Table S1. Radionuclide contents, obtained with high-resolution gamma spectrometry, and associated dose rates for analysed sediments of Acheulian sites of England and NW France.

Table S2. U-series and ESR preparation data for analysed teeth of Acheulian sites of England and NW France.

Table S3. Radionuclide contents, obtained with high resolution gamma spectrometry, of sediments associated with analysed teeth from Acheulian sites of England and NW France.

Acknowledgments. This study is part of an ANR (Agence Nationale pour la Recherche no. 2010-BLANC-2006-01 coordinated by M. H. Moncel and D. Schreve) project; fieldwork, sampling and dating at several sites in the north-west of France and England will provide new data on occupation along the Palaeo-Thames, Bytham, Somme and Loire Rivers. We also thank the Région centre and the French Ministry of Culture for the financial support of PCR 'Les peuplements du Paléolithique inférieur dans les formations fluviatiles de la région Centre ' (coordinated by J. Despriée) and the French Ministry of Culture for the financial support of PCR 'les premiers hommes en Normandie' (coordinated by D. Cliquet). This work has also benefited from the help of the French government's National Research Agency, LabEx ANR-10-LABX-0003-BCDiv, within the project 'Investissements d'avenir' no. ANR-11-IDEX-0004-02.

Abbreviations. AAR, amino acid racemization; CFbF, Cromer Forest-bed Formation; ESR, electron spin resonance; MIS, Marine Oxygen Isotope Stage; OSL, optically stimulated luminescence; TL, thermoluminescence.

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