Regional extinction(s) but continental persistence in European Acheulean culture

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Abstract

Traces of early hominin cultural dynamics are revealed through the spatial and temporal character of the archaeological record. In the European Lower Palaeolithic, biface occurrences provide insights into episodes of cultural loss, persistence and convergence during the Acheulean, the longest-known prehistoric cultural phenomenon. Here, the cohesiveness of Europe's Acheulean record is statistically assessed under multiple spatial scenarios. Repeated cycles of cultural loss are identified in northern Europe, while southern Europe is demonstrated to have a continuous record of Acheulean presence. These data support longstanding hypotheses concerning an absence of Acheulean populations in northern Europe during glacial periods; a result that should increasingly be applied with caution. In southern Europe, Iberia displays the loss of Acheulean cultural information between c. 850 to 500 thousand years ago, with the Italian peninsula potentially acting as a source population for its later reintroduction. When investigated at a continental-level there are no clear episodes of cultural loss. Current evidence therefore suggests that once Acheulean cultural information was introduced to Europe, it never wholly left.

Impact Statement

Present in Europe for more than 700,000 years, there has long been debate concerning the presence and loss of Acheulean Palaeolithic culture on the continent. Attention has often focused on the role of glaciation and demographic factors in northern and southern regions. Here, the temporal cohesion of the European Acheulean archaeological record is statistically assessed

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under multiple spatial scenarios. Few breaks in the archaeological record are identified, suggesting Acheulean cultural information to have only occasionally been regionally absent. Four absences appear linked to northern glacial cycles, while the fifth is observed in Iberia soon after the Acheulean's introduction to Europe c. 880,000 years ago. This study represents the first to assess an exhaustive database of reliably dated European Acheulean sites in the pursuit of identifying cultural and demographic patterns during this pivotal point in the early colonisation of Europe. At a continental level, the Acheulean appears to have constantly been present in Europe after its first introduction, demonstrating the importance of these technologies to hominin populations and its durability as a cultural phenomenon. These data have implications for understanding the persistence of Acheulean culture in Africa and elsewhere in Eurasia across its c. 1.5 million years.

1. Introduction

Understanding the spatial and temporal character of the archaeological record is a fundamental goal of archaeologists. Diverse processes determine when and where we observe past human material culture, but by gaining an accurate picture of the artefact record it becomes easier to identify these cultural evolutionary, demographic, ecological and geological influences, among others. In the case of prehistoric humans, archaeologists are faced with identifying these varied and dynamic processes using a sparse and highly fragmented archaeological record (Isaac, 1969; Binford, 1987; Lycett and Eren, 2013; Kuhn and Clark, 2015; French, 2016; Gallotti, 2016; Pope et al., 2016; Key et al., 2021; Kuhn, 2021).

Europe displays perhaps the richest record of dated prehistoric sites in the world. As such, it provides an opportunity to gain insight into large, continental-scale cultural processes at resolutions that may be unachievable elsewhere in the world. Nowhere is this more apparent than when considering the Lower Palaeolithic/Early Stone Age (ESA), given more than 160 years of research on the continent (Prestwich, 1860; Evans, 1872; White, 2022). The Acheulean represents the most heavily studied of European Lower Palaeolithic cultural phenomena and covers a majority of the period from c. 900 to 150 thousand years ago (ka) (Moncel et al., 2020a; Ashton and Davis, 2021; Key et al., 2021; Ollé et al., 2023). As such, it provides a relatively rich record of sites, many of which have been robustly dated using modern radiometric techniques (Ollé et al., 2016).

The Acheulean replaces the purely flake-and-core focused technologies observed in earlier, more sporadically evidenced European populations, likely representing a dispersal of new cultural information from western/central Eurasia and, potentially, Africa (Dennell and Roebrokes, 1996; Sharon, 2011; Mosquera et al., 2013; Gallotti, 2016; Sharon and Barsky, 2016; Arroyo et al., 2019; Méndez-Quintas et al., 2020; Moncel et al., 2020a, 2020b). The tradition persists until Neanderthals and later prepared core technologies appear from c. 400 to 300 ka (Arsuaga et al., 2014; Ollé et al., 2016; Moncel et al., 2020c; Key et al., 2021), with many of the youngest known Acheulean sites being observed in southern France and Iberia (Michel et al., 2009; Monteiro-Rodrigues and Cunha-Ribeiro, 2014; Méndez-Quintas et al., 2019) (Table 1; Figure 1).

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Morphological, technological, temporal and spatial evidence points to a single, but variable, cultural tradition being represented by the Acheulean phenomenon (Gowlett, 1979; Lycett and Gowlett, 2008; Shipton, 2020; Key, 2022), which itself is most often defined by the presence of bifacially flaked core technologies (Sharon, 2010; Kuhn, 2020; de la Torre and Mora, 2020). Within Europe, two forms of bifaces – handaxes and cleavers – are produced, although each varies within and between assemblages, and variants such as picks and ficrons have been defined (Santonja and Villa, 1990; Wymer, 1999; Vaughan, 2001; Lycett and Gowlett, 2008; Emery, 2010; Key, 2019; Méndez-Quintas et al., 2020; McNabb, 2022; García-Medrano et al., 2023).

Acheulean cultural information is not ubiquitous in Europe after c. 900 ka. Its absence from eastern and central Europe has long been known (Klein, 1966; Dennell and Roebrokes, 1996; Rocca et al., 2016; Sharon and Barsky, 2016), potentially due to the influence of climatic factors, including low temperatures and low precipitation, on ecology (Leonardi et al., in review). Climatically linked cycles of Acheulean presence and absence have also long been proposed in northern Europe (Roe, 1981; Wymer, 1999; White and Schreve, 2000). During warmer interglacial periods populations with Acheulean culture have been suggested to occupy northwestern Europe, only to be driven out during colder glacial periods (Ashton and Lewis, 2012; Moncel et al., 2015; Shipton and White, 2020; Ashton and Davis, 2021). As evidenced through the warm marine isotope stages (MIS) associated with nearly all biface sites in the region (Table 1; Supplementary Data 1) (although see: Moncel et al., 2022).

Other episodes of Acheulean cultural loss – or extirpation (localised, regional extinction) – have been proposed in southern Europe (MacDonald et al., 2012). The recent discovery of early, temporally outlying, biface sites in Iberia have created a substantial gap in the region's Acheulean record between c. 850 and 500 ka (Mosquera et al., 2013; Walker et al., 2020; Ollé et al., 2023). The Italian peninsula has evidence of sparsity in its Acheulean record too, with early sites such as Notarchirico (Moncel et al., 2019) and Valle Giumentina (Villa et al., 2024) evidencing an 80,000 year gap to later occurrences such as Fontana Ranuccio (Muttoni et al., 2009). Elsewhere in Europe, temporal breaks of thirty thousand years or more are evidenced in the Acheulean record (Table 1; Supplementary Tables 1 and 2). These breaks do not necessitate an absence of hominin populations – as in the case of the northern 'Clactonian' (Ashton and Davis, 2021) or the diverse Middle Pleistocene flake and core sites in southern Europe (Martínez and Garriga, 2016) – but instead a loss of populations retaining the cultural information required for the production of bifaces (Lycett and von Cramon Taubadel, 2008).

Our ability to understand *why* there may have been regional or continental-level breaks in the archaeological record is, however, dependent on gaining an accurate picture of *where* these gaps occur. We may infer an Acheulean absence based on a 50,000-year gap in the archaeological record, but search intensity biases, taphonomic processes, and past demographic variation, among other factors, could all have plausibly created the perception of a gap, when in reality the cultural information was present (Surovell et al., 2009; Pope et al., 2016; Ollé et al., 2016; Key

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and Ashton, 2023). Even when these processes were equal, archaeologists may infer a cultural absence simply because a temporal break is subjectively perceived to be large. In 2005, Solow and Smith (2005) introduced the 'surprise test' to Palaeolithic archaeology, a statistical method capable of assessing the temporal exceptionality of an outlying occurrence (dated site) relative to a sample or earlier or later occurrences. The technique assesses the scale of a break in the known archaeological record relative to the sites preceding or following it, and objectively records how likely it is to represent an absence of the cultural phenomenon under investigation.

Following Solow and Smith (2005) and Roberts et al. (2023), Key (2022) used the surprise test to demonstrate the early and late Acheulean records of Africa and Eurasia to be temporally cohesive. This included in Europe, where no significant breaks in the Acheulean record were identified between 300 to 160 ka (Key, 2022). In turn, it became possible to infer that during this time a continuous lineage of Acheulean cultural information was likely present on the continent. Here, the temporal cohesiveness of the entire European Acheulean archaeological record is statistically assessed for the first time. Using a comprehensive sample of reliably dated biface-retaining sites, gathered from an exhaustive review of published literature, the relative scale of regional and continental-level breaks in the continent's entire Acheulean record is examined. Significant breaks and long periods of continuity are observed, providing new insight into the loss (extirpation) and persistence of Acheulean cultural information in Europe.

2. Methods

Following Solow and Smith (2005), the 'surprise test' was used to identify whether temporal gaps in the European Acheulean archaeological record should be considered representative of cultural absence. The surprise test asks whether a new, potentially outlying record was generated by the same process that created previous or later consecutive records (Solow and Smith, 2005). In the present context, it asks whether a dated Acheulean occurrence (site) can be considered part of the same lineage of cultural information that preceded or followed it, or alternatively, whether it represents a culturally distinct, temporally 'surprising', occurrence (Roberts et al., 2023; Key, 2022). Rejection of the null hypothesis – cultural continuity between the proceeding or following occurrences and the occurrence of interest – indicates a relative temporal gap sufficient to infer cultural absence.

The surprise test uses range and spacing data across a series of k consecutive temporal occurrences – here, dated Acheulean sites. The record of interest could be an outlier site or a site at the start of a new series of consecutive occurrences, preceded by a temporal gap of any scale. The occurrences (sample) against which the record of interest is tested is assumed to represent the k largest or smallest records of a larger collection of records generated from a distribution from the Gumbel domain of attraction (Solow and Smith, 2005). The Gumbel distribution can be used to fit diverse scenarios, including those characterised by symmetrical, skewed, unimodal and bimodal data (Al-Aqtash et al., 2014).

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As a generalised extreme value distribution, the Gumbel distribution can be used to model the range limits of scaled linear data. In this case, years before present, represented by the age of dated Acheulean sites, with the youngest or oldest records in this sample feasibly representing the start or end of a lineage of cultural information. If the record of interest is identified as being statistically surprising relative to the larger sample, it can be considered part of a separate lineage of cultural information. Thus, the temporal gap evidencing this cultural distinction could represent Acheulean absence and subsequent re-emergence. As outlined by Key (2022), in Europe this would not necessarily represent an episode of cultural convergence, but most likely implies an extirpation event followed by the Acheulean's later reintroduction from elsewhere in Eurasia or Africa (Figure 3). If the record of interest is not statistically exceptional or surprising relative to the main site sample, then persistence of the Acheulean across the investigated temporal gap can be supported.

2.1 The Surprise Test

As described by Solow and Smith (2005), and more recently by Roberts et al. (2023), for tests in the forwards temporal direction,

Let $t_1 > t_2 > \ldots > t_k$ be the k most recent Acheulean records ordered from the most recent to the earliest. With the record of interest being dated at time y, the test assesses the exceptionality of this more recent occurrence. Following the null hypothesis that the later record of interest was generated by the same process as the earlier occurrences (i.e., the main sample), Solow and Smith (2005) demonstrated the quantity,

$$S_k = \frac{y-t_1}{(y-t_1)+\Sigma_{j=1}^{k-1}(j+1)(t_j-t_{j+1})},$$

to have a □ distribution with parameters 1 and k-1 so that the P-value corresponding to an observed value S_k is

$$P = (1-S_k)^{k-1}.$$

Solow and Smith (2005) demonstrate the power of the surprise test does not heavily depend on k, with k of 5 and 10 performing adequately; both are applied here. Due to the finite record of Acheulean occurrences, both forwards and reverse versions of the model are also used when possible (Table 2). Thus, both 'origination' and 'extinction' Gumbel distribution tails are modelled, dependent on whether the test is run in the reverse or forwards temporal direction (respectively). Alter the above instruction as appropriate in the case of tests in the reverse temporal direction (see: Supplementary Information 2). In all instances $\alpha = 0.05$.

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As all dated European Acheulean sites are represented by age ranges (Ollé et al., 2016), the resampling procedure applied by Roberts et al. (2023) was followed here to account for this uncertainty. Dates were drawn randomly from a normal distribution bounded by the defined age range for a given occurrence. The central age (see below) of each Acheulean occurrence was used as the mean value, while the standard deviation was half the difference between the central age and the relevant range boundary. These randomly generated datasets were investigated using the surprise test as outlined above, with the process being repeated 5,000 times. The mean across all iterations was used as the resampling result. The resampling procedure was used in addition to running the surprise test using each occurrence's central age value. R version 4.3.2 was used throughout (R Core Team, 2013). Associated code is available in Supplementary Information 2 and Roberts et al. (2023).

2.2 European Acheulean Site Sample and Data Scenarios

An exhaustive review of Acheulean sites in Europe was undertaken (Figure 1). European Acheulean sites were spatially defined as belonging to the European continent (or outlying islands) up to the western borders of modern Russia and Turkey. Technologically, sites were only included if they displayed the presence of bifacially flaked core-tools (handaxes or cleavers) and were associated with the Acheulean tradition by the individuals who excavated and/or dated the site (i.e., those who know the site best [Supplementary Information 1]). Sites or archaeological layers described as Acheulean but also displaying prepared core technologies were excluded due to the presence of Middle Palaeolithic-defining cultural information.

The surprise test procedure, as outlined above, required three pieces of temporal data for each occurrence; a central age, as well as upper and lower range boundaries. Sites without these data were excluded from the sample, as were all sites with unreliable age determinations. Individual sites could return multiple occurrences for inclusion, so long as no date-range overlap was observed between each Acheulean layer (e.g., la Noira, France [Moncel et al., 2013]).

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Table 1: All dated Acheulean sites in Europe ranked from the earliest to most recent. The full database of retrieved information for each site is available in Supplementary Information 1. This includes citations to the relevant articles from which data were retrieved. Dates are in years before present.

Age determination reliability was graded between three and zero for each site. Three represented a securely dated site, while zero represented a site with age associations that could potentially negatively impact model accuracy. Central age values often represented the author's 'preferred' site age (Supplementary Information 1); sometimes reported as a date range's mean value, or a centralised date determined based on sediment accumulation rates or other evidence. Date ranges were almost exclusively determined using radiometric methods. Occasionally, dating procedures resulted in marine isotope stage (MIS) age associations. In these instances, MIS boundaries were used for date ranges, following Lisiecki and Raymo (2005). Data reflect current understanding in September 2023, but it is important to recognise that some age determinations are subject to ongoing debate and/or research. Additional justification for the inclusion or exclusion of specific sites can be seen in Supplementary Information 1. The site review was intended to be exhaustive, but it is acknowledged a small number of sites could have been missed. Middle Pleistocene archaeological sites often display poor chronological resolution and unclear technological comparability between sites (MacDonald and Roebroeks, 2012), but the present investigation represents an analysis of the field's current understanding. As new data and refined understanding comes to light the analyses should be repeated.

Longitudinal and latitudinal data were recorded for each site to facilitate investigation of five spatially defined data scenarios. These scenarios reflect current understanding concerning the presence and absence of Acheulean culture in Europe.

Scenario 1 (S1): Europe S1. Every securely dated Acheulean site in Europe (n = 67). This represents all sites assigned a date reliability value of three. Sites with reliability values from two to zero were excluded. S1 examines whether the Acheulean was ever absent from Europe after its earliest known presence at Barranc de la Boella (Ollé et al., 2023).

Scenario 2 (S2): Europe S2. Every dated Acheulean site in Europe (n = 82; Table 1). This represents all sites assigned a date reliability value from three to one. Sites with reliability values of zero were excluded. S2 similarly examines whether the Acheulean was ever absent from Europe after its earliest known presence.

Scenario 3 (S3): Northern Europe. Defined as all sites above 49° latitude with a date reliability of three through to one (n = 36). This scenario investigates the widely held view that Acheulean hominins were repeatedly forced from northern latitudes during glacial periods due to inhospitable climatic conditions. The most southerly located site in this sample is St Pierre-les-Elbeuf (Cliquet et al., 2009).

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Scenario 4 (S4): Southern Europe. Defined as all sites below 45° latitude with a date reliability of three through to one (n = 38). In this scenario, Barbas 1 (Boëda et al., 1996) represents the most northerly site included in the sample. S4 examines Acheulean cultural continuity across southern Europe, on the basis that it is widely thought of as habitable by hominins across glacial and interglacial periods.

Scenario 5 (S5): Iberia. Defined as all sites south and west of La Cansaladeta (Ollé et al., 2016) and Atapuerca (García-Medrano et al., 2014) on the Iberian Peninsula with a date reliability of three through to one (n = 21). This scenario investigated Acheulean cultural continuity at a localised, regional level due to the peninsula's geographic isolation and its potential role as a refugium for Acheulean populations.

In each spatial scenario, the model tests the null hypothesis that temporal gaps in the archaeological record are not the result of the loss of Acheulean cultural information, be it at a localised (S3, S4, S5) or continental (S1, S2) level. While these regional categorisations are artificial and come with inherent inferential limitations (Ollé et al., 2016), they reflect a latitudinal and geographic reality that would have impacted demographic processes, and aid current understanding given the field often focuses on northern, southern and Iberian spatial scenarios.

Results

Table 2 displays all significant results across all spatial scenarios and versions of the model. From a total of 239 investigated temporal gaps (S1, S2, S3, S4 and S5 had 66, 81, 35, 37 and 20 gaps, respectively), 18 potential instances of Acheulean cultural absence were identified (Supplementary Tables 3 to 7). Some, such as the gap between Abbeville (France) and Old Park (UK), were significant in all relevant spatial scenarios (Supplementary Tables 3 to 5). Others, such as the temporal gap succeeding the site of Cueva Negra (Spain), were only significant in one scenario; in this case the Iberian Peninsula scenario (Supplementary Table 7). The European Acheulean archaeological record is, therefore, relatively cohesive with few periods when Acheulean cultural information may be lacking at a regional level.

Of the 18 significant results, only five can be considered reliable indicators of cultural absence (Table 2). This is due to the dating approaches used in northern Europe, where ESR, OSL, IRFR, and other radiometric techniques are used to determine sediment/site ages, and often these are subsequently used to associate artefacts with an interglacial MIS stage (e.g., Bridgeland, 1994; Antoine et al., 2015; Davis et al., 2021). This occasionally results in several sites with radiometrically determined, but identical, MIS stage age ranges and central age estimates clustering together. When three or more of these sites cluster, a significant result can be returned even when the investigated temporal gap is relatively small. A phenomenon more likely to occur when $k = 5$. By combining the results in Table 2 with the dating techniques and age associations in Supplementary Information 1, these instances can be identified. When this is considered, 13 significant temporal gaps are revealed to be the product of this phenomenon, meaning only five

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can be considered a reliable (clear) indicator of Acheulean absence (Table 2). A ‘clear’ inference of Acheulean absence is based on 1) a significant result and 2) a majority of the relevant main sample sites not displaying identical (or near-identical) ages assigned through MIS-stage associations. Only one clear instance of cultural absence included a significant resampling result, emphasising how our understanding of the phenomenon’s temporal character is limited by the date ranges associated with many sites.

Of these five instances, the 423,000-year gap between Cueva Negra and Sima de los Huesos on the Iberian Peninsula (S5) is the largest and clearest period of Acheulean absence. All four model versions were significant (Table 2), strongly supporting the inference that, based on current evidence, Acheulean culture was not present in Iberia during this time. The northern European scenario (S3) returned the four other significant and seemingly reliable periods of Acheulean absence. The earliest, between Moulin Quignon (660 ka) and Rampart Field (592 ka), broadly aligns with the cold glacial MIS 16. This is followed by the period between Maidscross Hill (580 ka) and Abbeville (525 ka), which aligns with the cold MIS 14. High Lodge (492 ka) and Beeches Pit (414 ka) bound the next significant period of Acheulean absence in northern Europe, which can be associated with MIS 12. Finally, a period of biface absence is inferred between St Pierre-les-Elbeuf (385 ka) and Stoke Newington (318 ka), another glacial stage; in this case MIS 10. The current middle Pleistocene archaeological record of northern Europe therefore supports repeated cycles of Acheulean presence and absence in-line with interglacial and glacial marine isotope stages.

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Table 2: All significant results returned across all spatial scenarios and model versions. See supplementary tables 3 - 7 for the results pertaining to each investigated temporal gap. A clear inference of Acheulean absence (i.e., 'yes') is based on a significant result being returned and a majority of the sites in the main sample not displaying identical (or near-identical) ages assigned principally through MIS-stage associations only. When the latter criteria cannot be met, absence of cultural information is determined to be 'unclear'. Note that only the Iberia scenario returned a significant result via. the resampling procedure.

Discussion

The European Acheulean was overwhelmingly a story of cultural persistence. Only five regionally-defined breaks in the European archaeological record are great enough, on a relative basis, to reliably infer a period of Acheulean cultural absence. The majority of these appear to have been driven by glacial cycles in northern Europe, where current site-dating suggests the region became too cold for populations with Acheulean culture to survive during MIS 16, 14, 12, and 10 (although see counter argument below). A substantial break in the Acheulean record is evidenced in Iberia between c. 850 ka and 500 ka. At a continental level, neither investigated scenario (S1, S2) returned a reliable significant result, suggesting Acheulean cultural information to have been permanently present on the continent after its first introduction. The Acheulean cultural phenomenon appears to have only ended at a continental-level once Middle Palaeolithic (e.g., Levallois) technologies start to emerge in Europe (Moncel et al., 2020b; Key et al., 2021), potentially due to functional and economic (raw material) advantages (Brantingham and Kuhn, 2001; Lycett and Eren, 2022).

Discussion of trends in the European Lower Palaeolithic must acknowledge the diverse natural (e.g., geological, taphonomic) and human-led (e.g., search intensity biases, variation in funding) factors impacting where and when we see evidence of hominin populations (Surovell et al., 2009; MacDonald and Roebroeks, 2012; Pope et al., 2016; Key and Ashton, 2023). Undoubtedly, present trends will vary in some ways relative to those realised in the Middle Pleistocene. Nonetheless, more than 160 years of archaeological discovery has informed these analyses and many trends will be correct, particularly for the denser portions of the Acheulean record, and as with the present study, archaeologists have a wealth of statistical means at their disposal to help navigate such challenges (e.g., Surovell et al., 2009; Faith et al., 2021; Key et al., 2021; Vidal-Cordasco et al., 2022). New archaeological sites, new dating methods and revised dating efforts are also constantly updating Acheulean temporal records. Future reanalysis is therefore encouraged, and while results may vary to the present data these differences should be slight (assuming all test assumptions are met equally).

Regional Acheulean Extinction(s)

Iberia

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The present data provide empirical support for long-standing inferences concerning the loss of Acheulean cultural information in Iberia and northern Europe. In the former, a notable break in the Acheulean record has been evident since the discovery of Barranc de la Boella and Cueva Negra, two temporally outlying Acheulean sites in Spain (Walker et al., 2020; Ollé et al., 2023). Indeed, a c. 423,000-year break in the archaeological record is substantial; greater even than the remainder of the Iberian Acheulean after its reappearance at Sima de los Huesos (Ollé et al., 2016). Potential explanation for this absence includes an early but short-lived Acheulean dispersal event from North Africa (Ollé et al., 2023), the extinction of *H. antecessor* and any associated cultural information c. 800 ka (Mosquera et al., 2013), and geological and/or research biases impacting the known archaeological record (Vallverdú et al., 2014). A lack of ecological (utilitarian) selective pressures could feasibly have restricted the production of bifaces (Gowlett, 2011; Key and Lycett, 2017), but habitats suitable for Acheulean-retaining populations were present in Iberia during this period (Leonardi et al., in review) and hominin presence is evidenced through flake-and-core technologies and palaeoclimatic data (Martínez and Garriga, 2016; Rodríguez et al., 2022). Diverse other demographic and climatic factors could also have played a role, with Acheulean cultural information either going regionally extinct or populations dispersing elsewhere (Lycett and von Cramon-Taubadel, 2008; MacDonald et al., 2012; Mosquera et al., 2013; French, 2021; Ollé et al., 2023).

Of course, substantial date ranges are attached to the sites that bound this early Iberian temporal gap, but these reinforce the inference of Acheulean absence; there is no overlap in their ranges and the resampling technique identified a significant break. An inference of Acheulean absence therefore appears robust given the known archaeological record. It is however unclear what portions of the Iberian Acheulean record remain unknown (Vallverdú et al., 2014; Ollé et al., 2023), with happenstance and/or sites excluded from the present analyses potentially playing a role. It is feasible that a site bridging the Cueva Negra to Sima de los Huesos temporal gap may be discovered in the future, even if the high density of Iberian sites currently known at c. 400 ka suggests this to be unlikely (following an assumption of even likelihood of discovery through time).

Northern Europe

Northern Europe is widely thought to have become uninhabitable for hominin populations during the MIS 16, 14, 12 and 10 glacial periods (White and Schreve, 2000; Ashton and Lewis, 2012; Moncel et al., 2015; Ashton and Davis, 2021). Such has been the strength of narrative concerning an absence of hominins during glacial periods, radiometric and terrace-stratigraphy based dating of artefacts are often applied in combination with, or superseded by, interglacial MIS stage associations (e.g., Bridgeland, 1994; Keen et al., 2006; Parfitt et al., 2010; Antoine et al., 2015; Davis et al., 2021; Key et al., 2022). Paleoclimatic data supports a contraction of the northern range for Acheulean populations in glacial periods (Leonardi et al., in review), but a notable north-western persistence was present with areas as far north as southern Britain (~52° latitude) appearing habitable (Rodríguez et al., 2022; Leonardi et al., in review). The site of Moulin Quignon in northern France further supports an Acheulean presence above 49° latitude during the MIS 16 glacial period (Antoine et al., 2019).

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There is, therefore, discrepancy between the present results, which suggest Acheulean absence in northern Europe during MIS 14, 12 and 10, along with most of MIS 16 (Table 2), and the aforementioned palaeoclimatic modelling (Rodríguez et al., 2022; Leonardi et al., in review). Given the present episodes of cultural absence have been identified using sites where some ages were determined via interglacial MIS-stage associations (Supplementary Information 1), it is not surprising that significant gaps in the archaeological record were identified during glacial periods. The present northern European results can therefore be interpreted in two ways. If the inference of Acheulean absence in northern Europe during glacial stages is upheld, then the present results provide theoretically grounded empirical support in favour of these absences.

Alternatively, palaeoclimatic data and Moulin-Quignon provide evidence of a need to revise our understanding of Acheulean presence in northern Europe during glacial periods. In short, hominins could have been present in northern Europe during glacial periods – potentially with reduced population levels or as part of seasonal migratory patterns (Figure 3B) (Hosfield, 2016; Rodríguez et al., 2022; Moncel et al., 2022; Leonardi et al., in review) – and Acheulean sites dated using interglacial associations may not necessarily be reliable. In this scenario, the surprise test would only return accurate northern European results after the age of many sites has been re-evaluated. Caution is therefore essential when interpreting the present northern European data. They accurately represent current understanding concerning the presence and absence of Acheulean cultural information in the region, but there is a growing need to reassess the theoretical foundation on which this understanding is based.

Regional Acheulean Continuity

Southern Europe, Iberia and northern Europe all identified long periods of temporal cohesion, and therefore Acheulean presence, in the Middle-to-Late Pleistocene. Subsequent to the Acheulean's emergence in Europe prior to 885 ka (Ollé et al., 2023) it appears to be continually present in southern Europe until soon after the 160.5 ka dated occurrence of Arbo (Spain) (Méndez-Quintas et al., 2019; Key et al., 2021). The Italian peninsula may have facilitated this continuity by acting as source population for Acheulean information during Iberia's early period of absence, as evidenced by the sites of Notarchirico and Loreto (Lefèvre et al., 2010; Moncel et al., 2019) (Figure 3). Potentially hinting at a barrier to the flow of Acheulean cultural information to southwest Europe between c. 800 and 500 ka. The re-emergence of bifaces in Iberia after a >400,000-year break could represent an episode of cultural convergence as opposed to a dispersal from elsewhere in southern Europe, but it is potentially more likely that Acheulean populations dispersed from the Italian peninsula given the close proximity (Lycett and von Cramon-Taubadel, 2008; Shipton, 2020; Key, 2022). North Africa could have also contributed additional cultural information at this point too (Sharon, 2011; Mosquera et al., 2013; Méndez-Quintas et al., 2020), leading to an Iberian Acheulean 'melting pot'. Alternatively, the Acheulean may have been present in Iberia during this c. 300,000-year period, but site discovery rates in Iberia and the Italian Peninsula may vary. Acheulean cultural persistence in southern Europe during MIS 16, 14, 12 and 10 would have

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allowed the region to act as a source population for northern dispersals (Ollé et al., 2016; Figure 3).

In Iberia, Acheulean bifaces are constantly present after the tradition's re-emergence c. 427ka, while in northern Europe the tradition is present after MIS 10 (c. 337ka [Lisiecki and Raymo, 2005]). Suggesting Acheulean hominins to have occupied Iberia through the MIS 10 and 8 glacial periods, and northern Europe through MIS 8. During this period there are notable biological and technological changes in populations, with an early Neanderthal phenotype and the earliest Levallois tools appearing (Arsuaga et al., 2014; Moncel et al., 2020c). Potentially these cultural and biological changes helped populations maintain durable (larger, more genetically diverse) and permanent populations through glacial periods. The precise nature of how, when, where and why the Acheulean in Europe ceased to be a distinct cultural entity free from prepared core technologies remains debated (Moncel et al., 2012; Lycett et al., 2016; Malinsky-Buller, 2016; de Lombera-Hermida et al., 2020; Moncel et al., 2020c; Kuhn et al., 2021), but based on current site definitions considerable overlap is present in Europe between these technologically distinct phenomena (Key et al., 2021).

Acheulean Persistence in Europe

Both continental-scale scenarios (Europe S1, Europe S2) identified the European Acheulean archaeological record to be temporally cohesive. Once Acheulean cultural information was introduced to the continent, it appears to have never left. This reading of the European record differs from some previous studies, where Acheulean reintroduction events have been proposed from c. 700 - 500 ka (MacDonald et al., 2012; Mosquera et al., 2013; Vallverdú et al., 2014; Moncel et al., 2020; French, 2021). Relevant population levels and hominin spatial presence would have varied through this c. 720,000-year period, and potentially we see demographic signals through reduced discovery rates in the archaeological record; for example, between 700 and 800 ka (Figure 3B). Indeed, the temporal gap between Cueva Negra and la Noira returned lower *p* values compared to most (~0.200 [Supplementary Tables 3 and 4]). The regional-scale losses identified above provide additional evidence of demographic fluctuation within the continent. Diverse factors, including climatic and ecological change, pressures from non-Acheulean hominin populations, and disease, could have created pressures leading to lower presence at times (Bar-Yosef and Belfer-Cohen, 2001; Lycett and Norton, 2010; French, 2016). Fundamentally, however, temporal evidence suggests that after c. 885 ka, Acheulean populations were continuously present in Europe and the relevant cultural information was remarkably durable.

Cultural evolutionary mechanisms, including the introduction of new Acheulean information from central Eurasia, and potentially Africa, would have impacted the way the phenomenon was expressed in Europe between 885 - 160 ka (Lycett et al., 2016; Kuhn, 2021). This was likely to have been in regionally dependent ways (Sharon and Barsky, 2016; Key, 2019; Shipton and White, 2020; García-Medrano et al., 2023). The fundamental *bauplan* that allows bifaces at both Barranc de la Boella and Arbo to be defined as part of the same cultural tradition, did not, however, change (Lycett and Gowlett, 2008). The present results therefore support the presence of a single,

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but variable, Acheulean tradition in Europe by supporting the presence of a single branching lineage of Acheulean cultural information (Isaac, 1977; Crompton and Gowlett, 1993; Lycett and Gowlett, 2008; Shipton, 2020; Key, 2022). At times it may have been regionally absent, but any later reintroduction would have been from another channel in the larger ‘braided stream’ of European Acheulean cultural information (Figure 3).

It is important to re-emphasise that any change to the age of European Acheulean sites, particularly in the north (see above), or the discovery of new sites, could adjust some of the results reported here. Use of the surprise test is also dependent on the assumption that all sites in the main sample represent a continuous lineage of cultural information (i.e., they themselves do not contain an episode of cultural absence). Finally, it is again worth restressing that any Lower Palaeolithic temporal analyses are inevitably limited by the large date ranges associated with most sites (Pope et al., 2016; Ollé et al., 2016). Our understanding of prehistoric material culture is, however, bounded by the sum of all information currently known, and as it stands, the most accurate interpretation for European Acheulean continuity is one of cultural persistence that is only rarely punctuated.

Conclusion

Demographic trends in Lower Palaeolithic Europe have recently been argued to represent “*discontinuous, fragmented European populations who, like those of the Early Pleistocene, visited rather than occupied the continent*” (French, 2021: 128). Other studies have returned similar conclusions for the European Middle Pleistocene based on the fragmented evidence we currently possess (e.g., MacDonald et al., 2012; Mosquera et al., 2013; Moncel et al., 2020a; Ashton and Davis, 2021; Margari et al., 2023). A sparse archaeological record is not, however, tantamount to an absence of hominin populations. What appears to be a substantial temporal gap may in fact represent cultural continuity when contextualised against the rest of the archaeological record.

Here, the temporal cohesion of the European Acheulean archaeological record has been statistically assessed. Five regionally-defined breaks in the Acheulean record were identified; between c. 800 and 500 ka in Iberia, and during MIS 16, 14, 12, and 10 in northern Europe. For each, hominins retaining Acheulean cultural information are inferred to have been absent; be it due to cultural extirpation or populations dispersing to alternative regions. The northern results should, however, be used with caution given increasing evidence that hominins may have been present in northern latitudes during glacial periods. At a continental level, the Acheulean was identified as being continuously present. No breaks were substantial enough, on a relative basis, to infer an absence of hominin populations retaining Acheulean cultural information. The European Acheulean is therefore overwhelmingly characterised as a period of cultural persistence; it was likely a single, braided lineage of cultural information that appears to have always been present in Europe after its first introduction. Regional extinctions occurred and variable technological and morphological trajectories developed, but cultural information would have flowed between populations and dispersal events would have reintroduced the overarching ‘tradition’ (Lycett and Gowlett, 2008) back into unoccupied regions.

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AK undertook all aspects of the work.

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All data and code are included in the supplementary information.

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Figure Captions

Figure 1: The location of each dated Acheulean site in Europe (white circles [reliability graded three to one]), alongside a series of undated or poorly evidenced biface occurrences which are sometimes suggested to be Acheulean occurrences (red triangles). The latter are noted here due to being widely known, spatially remarkable (e.g., Piekary IV) or being of importance to the discipline in another way.

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Figure 2: Temporal placement of archaeological sites in the European Acheulean record. The ‘peak of the European Acheulean’ is defined by the 25 and 75 percent quartiles across all site central dates.

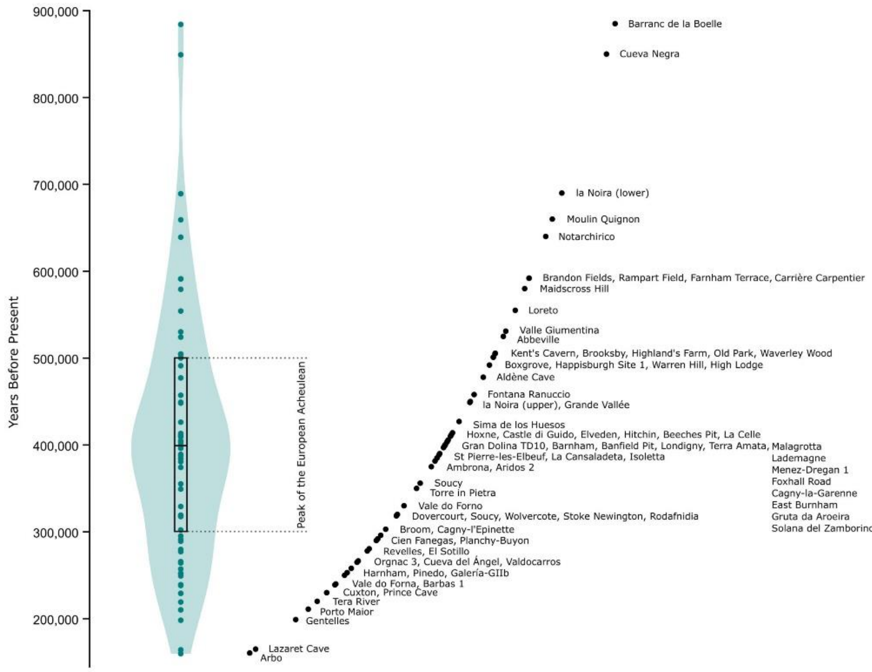

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Figure 3: Two ‘braided stream’ interpretations of Acheulean presence in Europe based on the present results. Figure 3A illustrates the current state-of-the-art interpretation, where glacial stages led to an absence of Acheulean populations in northern Europe. Figure 3B portrays a revised interpretation where the dates of some northern European Acheulean sites are hypothetically revised to more strongly reflect their radiometric ages, and not MIS stage associations. This results in a continuous sequence of Acheulean presence in northern Europe after its first introduction; albeit with demographic dips during glacial stages. Note the role of Eurasia, and potentially Africa, in providing sources for the flow of new Acheulean cultural information.

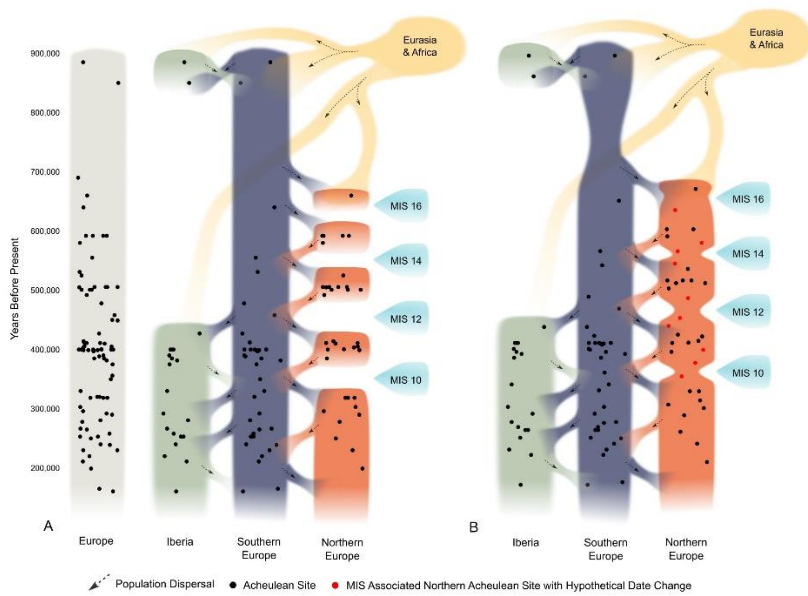

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Table 1: All dated Acheulean sites in Europe ranked from the earliest to most recent.The full database of retrieved information for each site is available in Supplementary Information 1. This includes citations to the relevant articles from which data were retrieved. Dates are in years before present.

Rank	European Acheulean Site	Central Date	Rank	European Acheulean Site	Central Date	Rank	European Acheulean Site	Central Date
1	Barranc de la Boella (Spain)	885000	**28**	Beeches Pit (UK)	414000	**55**	Torre in Pietra (Italy)	350000
2	Cueva Negra (Spain)	850000	**29**	Castle di Guido (Italy)	412000	**56**	Vale do Forno (Portugal)	330000
3	la Noira (France)	690000	**30**	Elveden (UK)	411000	**57**	Soucy (France)	320000
4	Moulin Quignon (France)	660000	**31**	Hitchin (UK)	411000	**58**	Rodafnidia (Greece)	320000
5	Notarchirico (Italy)	640000	**32**	Hoxne (UK)	410000	**59**	Stoke Newington (UK)	318500
6	Rampart Field (UK)	592000	**33**	La Celle (France)	405500	**60**	Wolvercote (UK)	318500
7	Farnham Terrace A (UK)	592000	**34**	East Burnham (UK)	405000	**61**	Dovercourt (UK)	318500
8	Brandon Fields (UK)	592000	**35**	Barnfield Pit (UK)	403500	**62**	Broom (UK)	303000
9	Carrière Carpentier (France)	592000	**36**	Barnham (UK)	400500	**63**	Cagny-l'Epinette (France)	296000
10	Maidscross Hill (UK)	580000	**37**	Menez-Dregan 1 (France)	400000	**64**	Cien Fanegas (Spain)	292000
11	Loreto (Italy)	555000	**38**	Cagny-la-Garenne (France)	400000	**65**	Plachy-Buyon (France)	290000
12	Valle Giumentina (Italy)	531000	**39**	Londigny (France)	400000	**66**	El Sotillo (Spain)	280500
13	Abbeville (France)	525000	**40**	Caune de l'Arago (France)	400000	**67**	Revelles (France)	278000
14	Old Park (UK)	505500	**41**	Atapuerca Galería-GIIa (Spain)	400000	**68**	Cueva del Ángel (Spain)	266500
15	Highland's Farm (UK)	505500	**42**	Atapuerca Gran Dolina (Spain)	400000	**69**	Orgnac 3 (France)	265000
16	Brooksby (UK)	505500	**43**	Gruta da Aroeira (Portugal)	400000	**70**	Valdocarros (Spain)	258000
17	Kent's Cavern (UK)	505500	**44**	Foxhall Road (UK)	399000	**71**	Atapuerca Galería-GIIb (Spain)	253000
18	Waverley Wood (UK)	505000	**45**	Terra Amata (France)	399000	**72**	Pinedo (Spain)	253000
19	Warren Hill (UK)	501000	**46**	Malagrotta (Italy)	399000	**73**	Harnham (UK)	250000
20	Boxgrove (UK)	501000	**47**	Lademagne (Italy)	397000	**74**	Vale do Forno (Portugal)	240000
21	Happisburgh Site 1 (UK)	501000	**48**	Solana del Zamborino (Spain)	390000	**75**	Barbas 1 (France)	239000
22	High Lodge (UK)	492000	**49**	Isoletta (Italy)	388500	**76**	Cuxton (UK)	230000
23	Aldène Cave (France)	478000	**50**	St Pierre-les-Elbeuf (France)	385000	**77**	Prince Cave (Italy)	230000
24	Fontana Ranuccio (Italy)	458000	**51**	La Cansaladeta (Spain)	385000	**78**	Tera River (Spain)	220000
25	Grande Vallée (France)	450000	**52**	Aridos 2 (Spain)	381500	**79**	Porto Maior (Spain)	211000
26	la Noira (France)	449000	**53**	Ambrona (Spain)	375000	**80**	Gentelles (France)	199000
27	Atapuerca Sima de los Huesos (Spain)	427000	**54**	Soucy (France)	356000	**81**	Lazaret Cave (France)	165000
						82	Arbo (Spain)	160500

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Table 2: All significant results returned across all spatial scenarios and model versions. See supplementary tables 3 - 7 for the results pertaining to each investigated temporal gap. A clear inference of Acheulean absence (i.e., 'yes') is based on a significant result being returned and a majority of the sites in the main sample not displaying identical (or near-identical) ages assigned principally through MIS-stage associations only. When the latter criteria cannot be met, absence of cultural information is determined to be 'unclear'.

Spatial Scenario	**Exceptional Temporal Gap Identified** (Acheulean Absence Inferred)		***p***	**Model Temporal Direction**	***k***	**Model Version**	**Acheulean Absence Inferred?**
	Sites	Central Dates					
Europe S1	Abbeville ↔ Old Park	525000 ↔ 505500	0.050	Reverse	5	Central	Unclear
	Barnfield Pit ↔ Barnham	403500 ↔ 400500	0.004	Reverse	5	Central	Unclear
	Lademagne ↔ Solana del Zamborino	397000 ↔ 390000	0.016	Forwards	10	Central	Unclear
Europe S2	Abbeville ↔ Old Park	525000 ↔ 505500	<0.0001	Reverse	5	Central	Unclear
	Waverley Wood ↔ Warren Hill	505000 ↔ 501000	0.002	Forwards	5	Central	Unclear
	Barnfield Pit ↔ Barnham	403500 ↔ 400500	0.004	Reverse	5	Central	Unclear
	Malagrotta ↔ Lademagne	399000 ↔ 397000	0.026	Forwards	10	Central	Unclear
	Lademagne ↔ Solana del Zamborino	397000 ↔ 390000	0.006	Forwards	10	Central	Unclear
	Vale do Forno ↔ Soucy	330000 ↔ 320000	0.009	Reverse	5	Central	Unclear
	Dovercourt ↔ Broom	318500 ↔ 303000	0.006	Forwards	5	Central	Unclear
Northern Europe	Moulin Quignon ↔ Rampart Field	660000 ↔ 592000	0.048	Reverse	5	Central	Yes
	Maidscross Hill ↔ Abbeville	580000 ↔ 525000	0.009	Forwards	5	Central	Yes
			0.030	Reverse	5	Central	
	Abbeville ↔ Old Park	525000 ↔ 505500	<0.001	Reverse	5	Central	Unclear
	Waverley Wood ↔ Warren Hill	505000 ↔ 501000	0.002	Forwards	5	Central	Unclear
	High Lodge ↔ Beeches Pit	492000 ↔ 414000	0.012	Forwards	5	Central	Yes
			0.009	Reverse	5	Central	
	St Pierre-les-Elbeuf ↔ Stoke Newington	385000 ↔ 318500	0.031	Forwards	5	Central	Yes
			0.024	Forwards	10	Central	
Southern Europe	Castle di Guido ↔ Caune de l'Arago	412000 ↔ 400000	0.007	Reverse	5	Central	Unclear
Iberia	Cueva Negra ↔ Sima de los Huesos	850000 ↔ 427000	0.002	Reverse	5	Central	Yes
			0.041	Reverse	10	Central	
			0.026	Reverse	5	Resamp.	
			0.047	Reverse	10	Resamp.	

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