

# The Beaker Phenomenon and the Genomic Transformation of Northwest Europe

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99 **Bell Beaker pottery spread across western and central Europe beginning around 2750**  
100 **BCE before disappearing between 2200–1800 BCE. The mechanism of its expansion is a**  
101 **topic of long-standing debate, with support for both cultural diffusion and human**  
102 **migration. We present new genome-wide ancient DNA data from 170 Neolithic, Copper**  
103 **Age and Bronze Age Europeans, including 100 Beaker-associated individuals. In contrast**  
104 **to the Corded Ware Complex, which has previously been identified as arriving in central**  
105 **Europe following migration from the east, we observe limited genetic affinity between**  
106 **Iberian and central European Beaker Complex-associated individuals, and thus exclude**  
107 **migration as a significant mechanism of spread between these two regions. However,**  
108 **human migration did have an important role in the further dissemination of the Beaker**  
109 **Complex, which we document most clearly in Britain using data from 80 newly reported**  
110 **individuals dating to 3900–1200 BCE. British Neolithic farmers were genetically similar to**  
111 **contemporary populations in continental Europe and in particular to Neolithic Iberians,**  
112 **suggesting that a portion of the farmer ancestry in Britain came from the Mediterranean**  
113 **rather than the Danubian route of farming expansion. Beginning with the Beaker period,**  
114 **and continuing through the Bronze Age, all British individuals harboured high**  
115 **proportions of Steppe ancestry and were genetically closely related to Beaker-associated**  
116 **individuals from the Lower Rhine area. We use these observations to show that the spread**  
117 **of the Beaker Complex to Britain was mediated by migration from the continent that**  
118 **replaced >90% of Britain’s Neolithic gene pool within a few hundred years, continuing the**  
119 **process that brought Steppe ancestry into central and northern Europe 400 years earlier.**

120 During the third millennium Before the Common Era (BCE), two new archaeological pottery  
121 styles expanded across Europe, replacing many of the more localized styles that preceded them<sup>1</sup>.  
122 The “Corded Ware Complex” in central, northern and eastern Europe was associated with  
123 people who derived most of their ancestry from eastern European Yamnaya steppe pastoralists<sup>2–</sup>  
124 <sup>4</sup>. Bell Beaker pottery is known from around 2750 cal BCE<sup>5,6</sup> in Atlantic Iberia, although its  
125 exact origin is still a matter of debate<sup>7,8</sup>. By 2500 BCE, it is possible to distinguish in many  
126 regions the “Beaker Complex”, defined by assemblages of grave goods including stylised bell-  
127 shaped pots, distinctive copper daggers, arrowheads, stone wristguards and V-perforated  
128 buttons<sup>9</sup>. Regardless of the geographic region where it originated (if it did have a single origin),  
129 elements of the Beaker Complex rapidly spread throughout western Europe (and northern  
130 Africa), reaching southern and Atlantic France, Italy and central Europe<sup>10–12</sup> where they  
131 overlapped geographically with the Corded Ware Complex, and from there expanding to Britain  
132 and Ireland<sup>13,14</sup>. A major debate has centred on whether the spread of the Beaker Complex was  
133 mediated by the movement of people, culture, or a combination of these<sup>15–18</sup>. Genome-wide data  
134 have revealed high proportions of Steppe ancestry in Beaker Complex-associated individuals

135 from Germany and the Czech Republic<sup>2-4</sup>, consistent with their being a mixture of populations  
136 from the Steppe and the preceding farmers of Europe. However, a deeper understanding of the  
137 ancestry of people associated with the Beaker Complex requires genomic characterization of  
138 individuals across the geographic range and temporal duration of this archaeological  
139 phenomenon.

#### 140 **Ancient DNA data and authenticity**

141 To understand the genetic structure of ancient people associated with the Beaker Complex and  
142 their relationship to preceding, subsequent and contemporary peoples, we enriched ancient  
143 DNA libraries for sequences overlapping 1,233,013 single nucleotide polymorphisms (SNPs) by  
144 hybridization DNA capture<sup>4,19</sup>, and generated new sequence data from 170 ancient Europeans  
145 dating to ~4700–1200 BCE (Supplementary Table 1; Supplementary Information, section 1).  
146 We also generated 62 new direct radiocarbon dates (Extended Data Table 1). We filtered out  
147 libraries with low coverage (<10,000 SNPs) or evidence of contamination (Methods) to obtain a  
148 final set of 166 individuals: 97 Beaker-associated individuals and 69 from other ancient  
149 populations (Fig. 1b; Extended Data Table 2), including 61 individuals from Neolithic and  
150 Bronze Age Britain. We combined our data with previously published ancient DNA data<sup>2-4,20-37</sup>  
151 to form a genome-wide dataset of 476 ancient individuals (Supplementary Table 1). The  
152 combined dataset included Beaker-associated individuals from Iberia (n=20), southern France  
153 (n=4), northern Italy (n=1), central Europe (n=56), The Netherlands (n=9) and Britain (n=19).  
154 We further merged these data with 2,572 present-day individuals genotyped on the Affymetrix  
155 Human Origins array<sup>22,31</sup> and 300 high coverage genomes sequenced as part of the Simons  
156 Genome Diversity Project<sup>38</sup>.

#### 157 **Y-chromosome analysis**

158 We determined Y-chromosome haplogroups for the 54 male Beaker-associated individuals  
159 (Supplementary Table 3). Individuals from the Iberian Peninsula carried Y haplogroups known  
160 to be common across Europe during the earlier Neolithic period<sup>2,4,20,26,32,39</sup>, such as I2a (n=3) and  
161 G2 (n=1) (Supplementary Table 3). In contrast, Beaker-associated individuals outside Iberia  
162 (n=44) largely carried R1b lineages (84%), associated with the arrival of Steppe migrants in  
163 central Europe during the Late Neolithic/Early Bronze Age<sup>2,3</sup>. For individuals in whom we  
164 could determine the R1b subtype (n=22), we found that all but one had the derived allele for the  
165 R1b-S116/P312 polymorphism, which defines the dominant subtype in western Europe today<sup>40</sup>.  
166 Finding this early predominance of the R1b-S116/P312 polymorphism in ancient individuals  
167 from central and northwestern Europe suggests that people associated with the Beaker Complex  
168 may have had an important role in the dissemination of this lineage throughout most of its  
169 present-day distribution.

## 170 **Genomic insights into the spread of the Beaker Complex**

171 Principal component analysis (PCA) revealed striking heterogeneity among individuals assigned  
172 to the Beaker Complex (Fig. 1c, Extended Data Fig. 1a). Genetic differentiation in our dataset  
173 was mainly driven by variable amounts of Steppe-related ancestry, with Beaker Complex  
174 individuals falling along the axis of variation defined by Yamnaya steppe pastoralists and  
175 Middle Neolithic/Copper Age European populations. We obtained qualitatively consistent  
176 inferences using ADMIXTURE model-based clustering<sup>41</sup> (Extended Data Fig. 1b).

177 We grouped Beaker Complex individuals based on geographic proximity and genetic similarity  
178 (Supplementary Information, section 4), and used *qpAdm*<sup>2</sup> to model their ancestry as a mixture  
179 of western European hunter-gatherers (WHG), northwestern Anatolian farmers, and Yamnaya  
180 steppe pastoralists (the first two of which contributed to earlier European farmers;  
181 Supplementary Information, section 6). We find that the great majority of Beaker Complex  
182 individuals outside of Iberia derive a large portion of their ancestry from Steppe populations  
183 (Fig. 2a), whereas in Iberia, such ancestry is absent in all sampled individuals, with the  
184 exception of two (I0461 and I0462) from the Arroyal I site in northern Spain. We detect striking  
185 differences in ancestry not only at a pan-European scale, but also within regions and even  
186 within sites. Unlike other individuals from the Upper Alsace region of France (n=2), an  
187 individual from Hégenheim resembles previous Neolithic populations and can be modelled as a  
188 mixture of Anatolian Neolithic and western hunter-gatherers without any Steppe-related  
189 ancestry. Given that the radiocarbon date of the Hégenheim individual is older (2832–2476 cal  
190 BCE (quoting 95.4% confidence intervals for this and other dates) (Supplementary Information,  
191 section 1) than other samples from the same region (2566–2133 cal BCE), the pattern could  
192 reflect temporal differentiation. At Szigetszentmiklós in Hungary, we find Beaker Complex-  
193 associated individuals with very different proportions (from 0% to 74%) of Steppe ancestry but  
194 overlapping dates. This genetic heterogeneity is consistent with early stages of mixture between  
195 previously established European farmers and migrants with Steppe ancestry. An implication is  
196 that, even at a local scale, the Beaker Complex was associated with people of diverse ancestries.

197 While the Yamnaya-related ancestry in Beaker Complex associated individuals had an origin in  
198 the Steppe<sup>2,3</sup>, the other ancestry component (from European Neolithic farmers) could potentially  
199 be derived from several parts of Europe, as genetically closely related populations were widely  
200 distributed across the continent during the Neolithic and Copper Age periods<sup>2,4,22,25,26,28,32</sup>. To  
201 obtain insight into the origin of the Neolithic-related ancestry in Beaker Complex-associated  
202 individuals, we began by looking for regional patterns of genetic differentiation within Europe  
203 during the Neolithic and Copper Age periods. To study genetic affinity to different Early  
204 Neolithic (EN) populations, we computed  $f_4$ -statistics of the form  $f_4(\text{Outgroup}, \text{Test}; \text{Iberia\_EN},$



205 *LBK\_EN*) for Neolithic and Copper Age test populations predating the emergence of the Beaker  
206 Complex. As previously described<sup>2</sup>, there is genetic affinity to Iberian Early Neolithic farmers  
207 in Iberian Middle Neolithic/Copper Age populations, but not in central and northern European  
208 Neolithic populations (Fig. 2b), which could be explained by differential affinities to hunter-  
209 gatherer individuals from different regions<sup>42</sup> (Extended Data Fig. 2). A new finding that  
210 emerges from our analysis is that Neolithic individuals from southern France and Britain also  
211 show a greater affinity to Iberian Early Neolithic farmers than to central European Early  
212 Neolithic farmers (Fig. 2b), similar to previous results obtained in a Neolithic farmer genome  
213 from Ireland<sup>28</sup>. By modelling Neolithic populations and WHG in an admixture graph  
214 framework, we replicate these results and further show that they are not driven by different  
215 proportions of hunter-gatherer admixture (Extended Data Fig. 3; Supplementary Information,  
216 section 5). Our results suggest that a portion of the ancestry of the Neolithic farmers of Britain  
217 was derived from migrants who spread along the Atlantic coast. Megalithic tombs document  
218 substantial interaction along the Atlantic façade of Europe, and our results are consistent with  
219 such interactions reflecting movements of people. More data from southern Britain (where our  
220 sampling is sparse) and nearby regions in continental Europe will be needed to fully understand  
221 the complex interactions between Britain and the continent in the Neolithic<sup>43</sup>.

222 The distinctive genetic signatures of pre-Beaker Complex populations in Iberia compared to  
223 central Europe allow us to test formally for the origin of the Neolithic farmer-related ancestry in  
224 Beaker Complex individuals in our dataset (Supplementary Information, section 6). We grouped  
225 individuals from Iberia (n=19) and from outside Iberia (n=84) to increase power, and evaluated  
226 the fit of different Neolithic/Copper Age groups with *qpAdm* under the model: Yamnaya +  
227 Neolithic/Copper Age. For Beaker Complex individuals from Iberia, the best fit was obtained  
228 when Middle Neolithic and Copper Age populations from the same region were used as a  
229 source for their Neolithic farmer-related ancestry, and we could exclude central and northern  
230 European populations ( $P < 4.69E-03$ ) (Fig. 2c). Conversely, the Neolithic farmer-related  
231 ancestry in Beaker Complex individuals outside Iberia was most closely related to central and  
232 northern European Neolithic populations with relatively high hunter-gatherer admixture (e.g.  
233 *Globular\_Amphora\_LN*,  $P = 0.14$ ; *TRB\_Sweden\_MN*,  $P = 0.29$ ), and we could significantly  
234 exclude Iberian sources ( $P < 3.18E-08$ ) (Fig. 2c). These results support largely different origins  
235 for Beaker Complex individuals, with no discernible Iberia-related ancestry outside Iberia.

### 236 **Nearly complete turnover of ancestry in Britain**

237 British Beaker Complex individuals (n=19) show strong similarities to the central European  
238 Beaker Complex both in genetic profile (Extended Data Fig. 1) and in material culture: the great  
239 majority of individuals from both regions are associated with “All Over Corded” Beaker

240 pottery. The presence of large amounts of Steppe-related ancestry in the British Beaker  
241 Complex (Fig. 2a) contrasts sharply with Neolithic individuals from Britain (n=35), who have  
242 no evidence of Steppe genetic affinities and cluster instead with Middle Neolithic and Copper-  
243 Age populations from mainland Europe (Extended Data Fig. 1). Thus, the arrival of Steppe  
244 ancestry in Britain was mediated by a migration that began with the Beaker Complex. A  
245 previous study showed that Steppe ancestry arrived in Ireland by the Bronze Age<sup>28</sup>, and here we  
246 show that – at least in Britain – it arrived by the Copper Age / Beaker period.

247 Among the different continental Beaker Complex groups analysed in our dataset, individuals  
248 from Oostwoud (Province of Noord-Holland, The Netherlands) are the most closely related to  
249 the great majority of the Beaker Complex individuals from southern Britain (n=14). They had  
250 almost identical Steppe ancestry proportions (Fig. 2a), the highest shared genetic drift  
251 (Extended Data Fig. 4b) and were symmetrically related to other ancient populations using  $f_4$ -  
252 statistics (Extended Data Fig. 4a), showing that they are consistent with being derived from the  
253 same ancestral population without additional mixture into either group. We next investigated the  
254 magnitude of population replacement in Britain with  $qpAdm^2$  by modelling Beaker Complex  
255 and Bronze Age individuals as a mixture of continental Beaker Complex (using the Oostwoud  
256 individuals as a surrogate) and the British Neolithic population (Supplementary Information,  
257 section 6). Fig. 3a shows the results of this analysis, ordering individuals by date and showing  
258 excess Neolithic ancestry compared to continental Beaker Complex as a baseline. For the  
259 earliest individuals (between ~2400–2000 BCE), the Neolithic ancestry excess is highly  
260 variable, consistent with migrant communities who were just beginning to mix with the  
261 previously established Neolithic population of Britain. During the subsequent Bronze Age we  
262 observe less variation among individuals and a modest increase in Neolithic-related ancestry  
263 (Fig. 3a), which could represent admixture with persisting populations with high levels of  
264 Neolithic-related ancestry (or alternatively incoming continental populations with higher  
265 proportions of Neolithic-related ancestry). In either case, our results imply a minimum of  
266  $93\pm 2\%$  local population turnover by the Middle Bronze Age (Supplementary Information,  
267 section 6). Specifically, for individuals from Britain around 2000 BCE, at least this fraction of  
268 their DNA derives from ancestors who at 2500 BCE lived in continental Europe. An  
269 independent line of evidence for population turnover comes from Y-chromosome haplogroup  
270 composition: while R1b haplogroups were completely absent in the Neolithic samples (n=25),  
271 they represent 95% and 75% of the Y-chromosomes in Beaker Complex-Early Bronze Age and  
272 Middle Bronze Age males in Britain, respectively (Fig. 3b; Supplementary Table 3).

273 Our genetic time transect in Britain also allowed us to track the frequencies of alleles with  
274 known phenotypic effects. Derived alleles at rs12913832 (SLC45A2) and rs16891982  
275 (HERC2/OCA2), which contribute to reduced skin and eye pigmentation in Europeans,

276 dramatically increased in frequency during the Beaker and Bronze Age periods (Extended Data  
277 Fig. 5). Thus, the arrival of migrants associated with the Beaker Complex significantly altered  
278 the pigmentation phenotypes of British populations. However, the lactase persistence allele at  
279 SNP rs4988235 remained at very low frequencies in our dataset both in Britain and continental  
280 Europe, showing that the major increase in its frequency in Britain, as in mainland Europe,  
281 occurred in the last 3,500 years<sup>3,4,39,44</sup>.

## 282 **Discussion**

283 The term “Bell Beaker” was introduced by late 19<sup>th</sup>-century and early 20<sup>th</sup>-century  
284 archaeologists to refer to the distinctive pottery style found across western and central Europe at  
285 the end of the Neolithic, initially hypothesized to have been spread by a genetically  
286 homogeneous group of people. This idea of a “Beaker Folk” became unpopular after the 1960s  
287 as scepticism about the role of migration in mediating change in archaeological cultures grew<sup>45</sup>,  
288 although J.G.D. Clark speculated that the Beaker Complex expansion into Britain was an  
289 exception<sup>46</sup>, a prediction that has now been borne out by ancient genomic data.

290 Our results clearly prove that the expansion of the Beaker Complex cannot be described by a  
291 simple one-to-one mapping of an archaeologically defined material culture to a genetically  
292 homogeneous population. This stands in contrast to other archaeological complexes analysed to  
293 date, notably the *Linearbandkeramik* first farmers of central Europe<sup>2</sup>, the Yamnaya of the  
294 Pontic-Caspian Steppe<sup>2,3</sup>, and to some extent the Corded Ware Complex of central and eastern  
295 Europe<sup>2,3</sup>. Instead, our results support a model in which both cultural transmission and human  
296 migration played important roles, with the relative balance of these two processes depending on  
297 the region. In Iberia, the majority of Beaker Complex-associated individuals lacked Steppe  
298 affinities and were genetically most similar to preceding Iberian populations. In central Europe,  
299 Steppe ancestry was widespread and we can exclude a substantial contribution from Iberian  
300 Beaker Complex-associated individuals, contradicting initial suggestions of gene flow between  
301 these groups based on analysis of mtDNA<sup>47</sup> and dental morphology<sup>48</sup>. Small-scale contacts  
302 remain plausible, however, as we observe small proportions of Steppe ancestry in two  
303 individuals from northern Spain.

304 Although cultural transmission seems to have been the main mechanism for the diffusion of the  
305 Beaker Complex between Iberia and central Europe, other parts of the Beaker Complex  
306 expansion were driven to a substantial extent by migration, with Beaker-associated burials in  
307 southern France, northern Italy, and Britain, representing the earliest occurrence of Steppe-  
308 related ancestry so far known in all three regions. This genomic transformation is clearest in  
309 Britain due to our dense genetic time transect. The earliest Beaker pots found in Britain show  
310 influences from both the lower Rhine region and the Atlantic façade of western Europe<sup>49</sup>.



311 However, such dual influence is not mirrored in the genetic data, as the British Beaker Complex  
312 individuals were genetically most similar to lower Rhine individuals from the Netherlands. The  
313 arrival of the Beaker Complex precipitated a profound demographic transformation in Britain,  
314 exemplified by the absence of individuals in our dataset without large amounts of Steppe-related  
315 ancestry after 2400 BCE. It is possible that the uneven geographic distribution of our samples,  
316 coupled with different burial practises between local and incoming populations (cremation  
317 versus burial) during the early stages of interaction could result in a sampling bias against local  
318 individuals. However, the signal observed during the Beaker period persisted through the later  
319 Bronze Age, without any evidence of genetically Neolithic-like individuals among the 27  
320 Bronze Age individuals we newly report, who traced more than 90% of their ancestry to  
321 individuals of the central European Beaker Complex. Thus, the genetic evidence points to a  
322 substantial amount of migration into Britain from the European mainland beginning around  
323 2400 BCE. These results are notable in light of strontium and oxygen isotope analyses of British  
324 skeletons from the Beaker and Bronze Age periods<sup>50</sup>, which have provided no evidence of  
325 substantial mobility over individuals' lifetimes from locations with cooler climates or from  
326 places with geologies atypical of Britain. However, the isotope data are only sensitive to first-  
327 generation migrants, and do not rule out movements from regions such as the lower Rhine,  
328 which is consistent with the genetic data, or from other geologically similar regions for which  
329 DNA sampling is still sparse. Further sampling of regions on the European continent may reveal  
330 additional candidate sources.

331 By analysing DNA data from ancient individuals we have been able to provide important  
332 constraints on the processes underlying cultural and social changes in Europe during the third  
333 millennium BCE. Our results raise new questions and motivate further archaeological research  
334 to identify the changes in social organization, technology, subsistence, climate, population  
335 sizes<sup>51</sup> or pathogen exposure<sup>52,53</sup> that could have precipitated the demographic changes  
336 uncovered in this study.

## 337 **Methods**

### 338 **Ancient DNA analysis**

339 We screened skeletal samples for DNA preservation in dedicated clean rooms. We extracted  
340 DNA<sup>54–56</sup> and prepared barcoded next generation sequencing libraries, the majority of which  
341 were treated with uracil-DNA glycosylase to greatly reduce the damage (except at the terminal  
342 nucleotide) that is characteristic of ancient DNA<sup>57,58</sup> (Supplementary Information, section 2).  
343 We initially enriched libraries for sequences overlapping the mitochondrial genome<sup>59</sup> and ~3000  
344 nuclear SNPs using synthesized baits (CustomArray Inc.) that we PCR amplified. We  
345 sequenced the enriched material on an Illumina NextSeq instrument with 2x76 cycles, and 2x7  
346 cycles to read out the two indices<sup>60</sup>. We merged read pairs with the expected barcodes that  
347 overlapped by at least 15 base pairs, mapped the merged sequences to hg19 and to the  
348 reconstructed mitochondrial DNA consensus sequence<sup>61</sup> using the *samse* command in bwa  
349 (v0.6.1)<sup>62</sup>, and removed duplicated sequences. We evaluated DNA authenticity by estimating  
350 the rate of mismatching to the consensus mitochondrial sequence<sup>63</sup>, and also requiring that the  
351 rate of damage at the terminal nucleotide was at least 3% for UDG-treated libraries<sup>63</sup> and 10%  
352 for non-UDG-treated libraries<sup>64</sup>.

353 For libraries that were promising after screening, we enriched in two consecutive rounds for  
354 sequences overlapping 1,233,013 SNPs ('1240k SNP capture')<sup>2,19</sup> and sequenced 2x76 cycles  
355 and 2x7cycles on an Illumina NextSeq500 instrument. We processed the data bioinformatically  
356 as for the mitochondrial capture data, this time mapping only to the human reference genome  
357 *hg19* and merging the data from different libraries of the same individual. We further evaluated  
358 authenticity by studying the ratio of X-to-Y chromosome reads and estimating X-chromosome  
359 contamination in males based on the rate of heterozygosity<sup>65</sup>. Samples with evidence of  
360 contamination were either filtered out or restricted to sequences with terminal cytosine  
361 deamination to remove sequences that could have derived from modern contaminants. Finally,  
362 we filtered out from our analysis dataset samples with fewer than 10,000 targeted SNPs covered  
363 at least once and samples that were first-degree relatives of others in the dataset (keeping the  
364 sample with the larger number of covered SNPs) (Supplementary Table 1).

### 365 **Mitochondrial haplogroup determination**

366 We used the mitochondrial capture bam files to determine the mitochondrial haplogroup of each  
367 sample with new data, restricting to reads with MAPQ $\geq$ 30 and base quality  $\geq$ 30. First, we  
368 constructed a consensus sequence with samtools and bcftools<sup>66</sup>, using a majority rule and  
369 requiring a minimum coverage of 2. We called haplogroups with HaploGrep2<sup>67</sup> based on

370 phylotree<sup>68</sup> (mtDNA tree Build 17 (18 Feb 2016)). Mutational differences compared to the  
371 rCRS and corresponding haplogroups can be viewed in Supplementary Table 2.

372

### 373 **Y-chromosome analysis**

374 We determined Y-chromosome haplogroups for both new and published samples  
375 (Supplementary Information, section 3). We made use of the sequences mapping to 1240k Y-  
376 chromosome targets, restricting to sequences with mapping quality  $\geq 30$  and bases with quality  
377  $\geq 30$ . We called haplogroups by determining the most derived mutation for each sample, using  
378 the nomenclature of the International Society of Genetic Genealogy (<http://www.isogg.org>)  
379 version 11.110 (21 April 2016). Haplogroups and their supporting derived mutations can be  
380 viewed in Supplementary Table 3.

381

### 382 **Merging newly generated data with published data**

383 We assembled two datasets for population genetics analyses:

384

385 - *HO* includes 2,572 present-day individuals from worldwide populations genotyped on the  
386 Human Origins Array<sup>22,31,69</sup> and 470 ancient individuals. The ancient set includes 103 Beaker  
387 Complex individuals (87 newly reported, 5 with shotgun data<sup>3</sup> for which we generated 1240k  
388 capture data and 11 previously published<sup>3,4</sup>), 68 newly reported individuals from relevant  
389 ancient populations and 298 previously published<sup>2-4,20-37</sup> individuals (Supplementary Table 1).  
390 We kept 591,642 autosomal SNPs after intersecting autosomal SNPs in the 1240k capture with  
391 the analysis set of 594,924 SNPs from Lazaridis et al.<sup>22</sup>.

392

393 -*HOIII* includes the same set of ancient samples and 300 present-day individuals from 142  
394 populations sequenced to high coverage as part of the Simons Genome Diversity Project<sup>38</sup>. For  
395 this dataset, 1,054,671 autosomal SNPs were used, excluding SNPs of the 1240k array located  
396 on sex chromosomes or with known functional effects.

397

398 For both datasets, ancient individuals were merged by randomly sampling one read at each SNP  
399 position, discarding the first and the last two nucleotides of each read.

### 400 **Principal component analysis**

401 We carried out principal component analysis (PCA) on the *HO* dataset using the *smartpca*  
402 program in EIGENSOFT<sup>70</sup>. We computed principal components on 990 present-day West  
403 Eurasians and projected ancient individuals using lsqproject: YES and shrinkmode: YES.

#### 404 **ADMIXTURE analysis**

405 We performed model-based clustering analysis using ADMIXTURE<sup>41</sup> on the *HO* reference  
406 dataset, including 2,572 present-day individuals from worldwide populations and the ancient  
407 individuals. First, we carried out LD-pruning on the dataset using PLINK<sup>71</sup> with the flag --  
408 indep-pairwise 200 25 0.4, keeping 306,393 SNPs. We ran ADMIXTURE with the cross  
409 validation (--cv) flag specifying from K=2 to K=20 clusters, with 20 replicates for each value of  
410 K and keeping for each value of K the replicate with highest log likelihood. In Extended Data  
411 Fig. 1b we show the cluster assignments at K=8 of newly reported individuals and other  
412 relevant ancient samples for comparison. This value of K was the lowest for which components  
413 of Caucasus hunter-gatherers (CHG) and European hunter-gatherers were maximized.

#### 414 ***f*-statistics**

415 We computed *f*-statistics on the *HOIII* dataset using ADMIXTOOLS<sup>69</sup> with default parameters  
416 (Supplementary Information, section 4). We used *qpDstat* with f4mode:Yes for *f*<sub>4</sub>-statistics and  
417 *qp3Pop* for outgroup *f*<sub>3</sub>-statistics. We computed standard errors using a weighted block  
418 jackknife<sup>72</sup> over 5 Mb blocks.

#### 419 **Inference of mixture proportions**

420 We estimated ancestry proportions on the *HOIII* dataset using *qpAdm*<sup>2</sup> and a basic set of 9  
421 *Outgroups*: Mota, Ust\_Ishim, MA1, Villabruna, Mbuti, Papuan, Onge, Han, Karitiana. For  
422 some analyses (Supplementary Information, section 6) we added additional outgroups to this  
423 basic set.

#### 424 **Allele frequency estimation from read counts**

425 We used allele counts at each SNP to perform maximum likelihood estimation of allele  
426 frequencies in ancient populations as in ref.<sup>4</sup>. In Extended Data Fig. 5, we show derived allele  
427 frequency estimates at three SNPs of functional importance for different ancient populations.

428 **Data availability**

429 All 1240k and mitochondrial capture sequencing data is available from the European Nucleotide  
430 Archive, accession number XXXXXXXXX [to be made available on publication].

431 Pseudo haploid genotype data is available from the Reich Lab website at [to be made available  
432 on publication].

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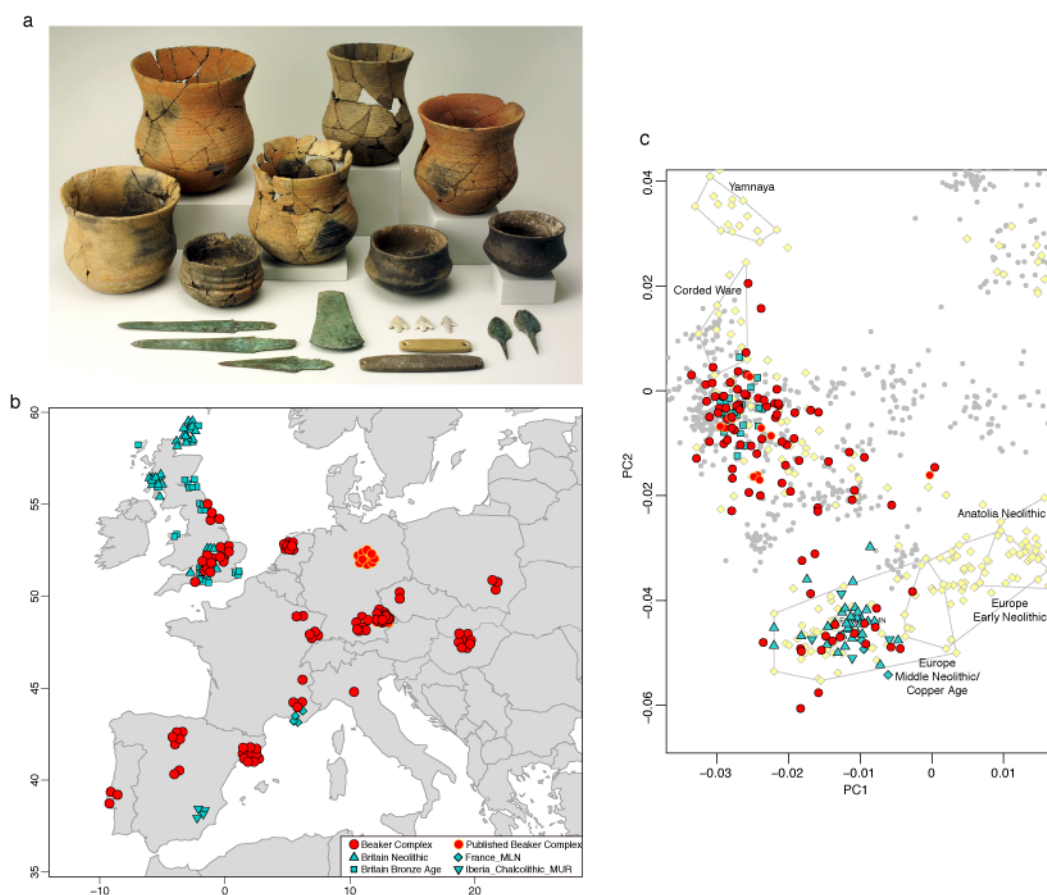
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457 **Author Contributions**

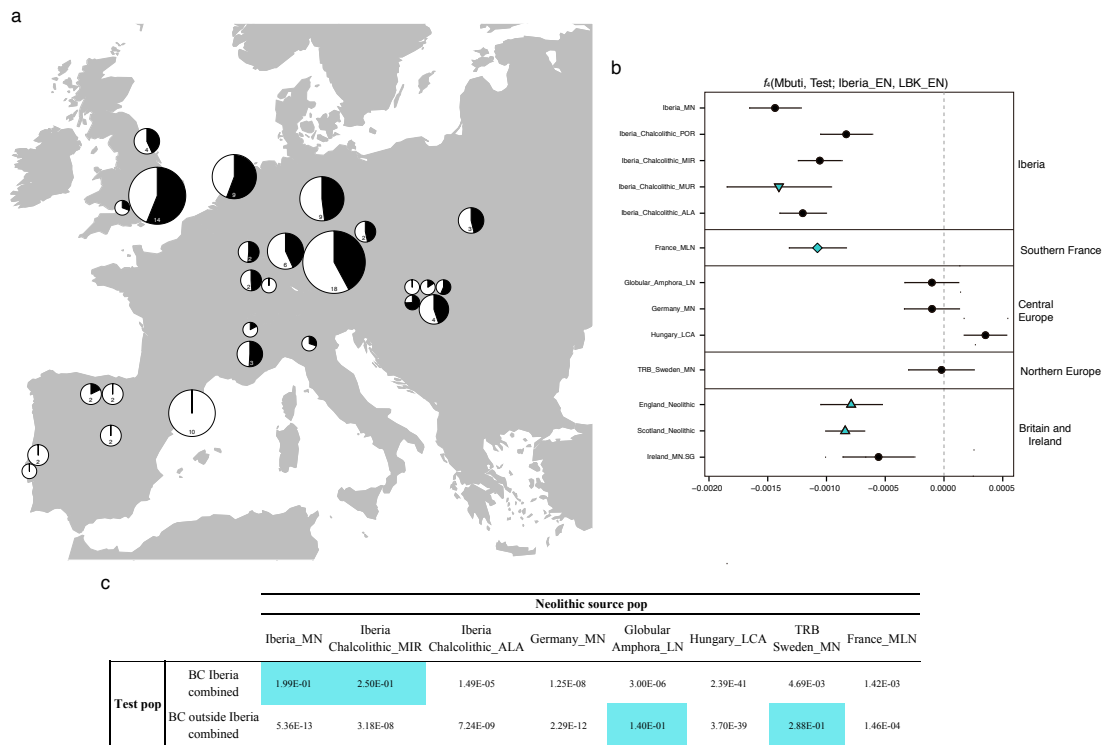
458 S.B., M.E.A, N.R., A.S.-N., A.M., N.B., M.F., E.H., M.M., J.O., K.S., R.P., J.K., W.H., I.B. and  
459 D.R. performed or supervised wet laboratory work. G.T.C. undertook the radiocarbon dating of  
460 a large fraction of the British samples. I.A., K.K., A.B., K.W.A., A.A.F., E.B., M.B.-B., D.B.,  
461 C.B., C.Bo., L.B., T.A., L.Bü., S.C., L.C.N., O.E.C., G.C., B.C., A.D., K.E.D., N.D., M.E.,



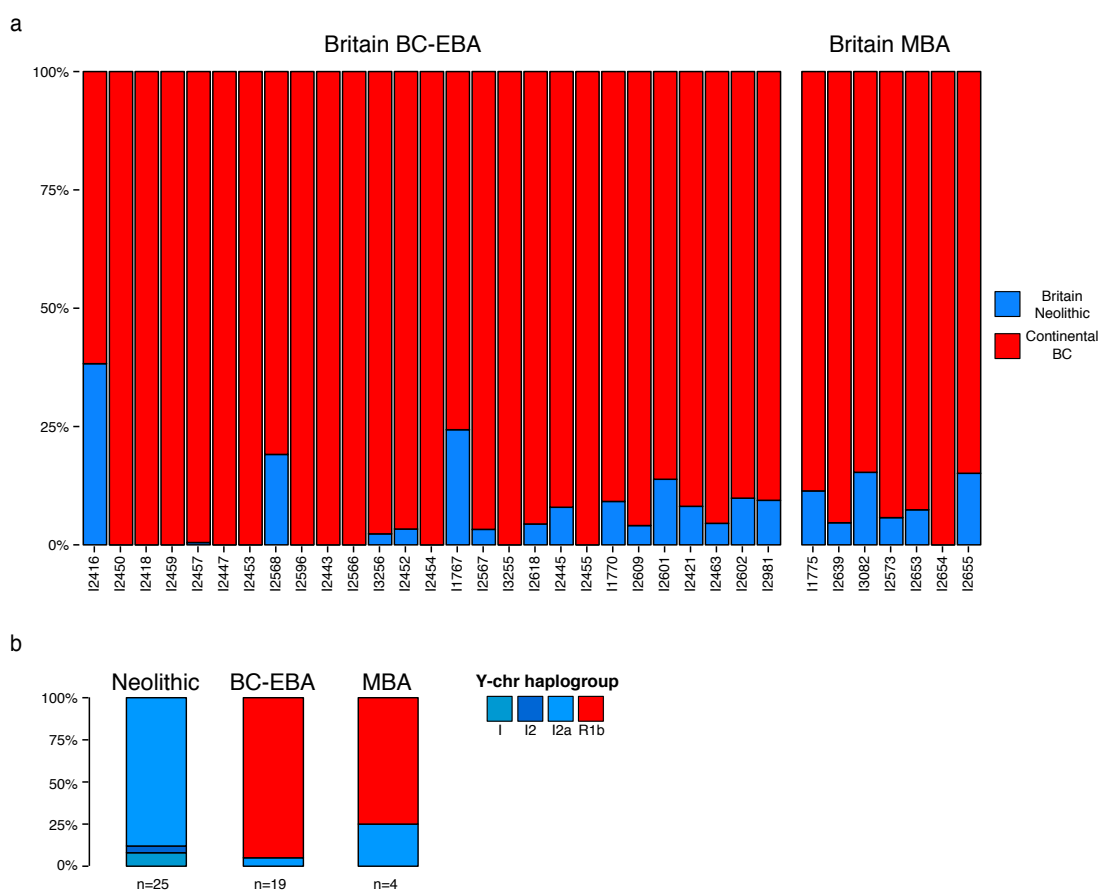
462 C.E., M.K., J.F.F., H.F., C.F., M.G., R.G.P., M.H.-U., E.Had., G.H., N.J., T.K., K.M., S.P.,  
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466 F. and D.R. assembled archaeological material. I.O., S.M., T.B., A.M., E.A., M.L., I.L., N.P.,  
467 Y.D., Z.F., D.F., P.d.K., M.G.T. and D.R. analysed or supervised analysis of data. I.O., C.L.-F.  
468 and D. R. wrote the manuscript with input from all co-authors.



**Figure 1. Genetic structure of individuals included in this study.** **a**, Beaker Complex grave goods from La Sima III barrow<sup>73</sup>. Photo: Alejandro Plaza, Museo Numantino. **b**, Geographic distribution of samples with new genome-wide data, with random jitter added for clarity. **c**, Principal component analysis of 990 present-day West Eurasian individuals (grey dots), with previously published (pale yellow) and new ancient samples projected onto the first two principal components. This figure is a zoom of Extended Data Fig 1a.



**Figure 2. Investigating the genetic makeup of Beaker Complex individuals.** **a**, Proportion of Steppe-related ancestry (shown in black) in Beaker Complex groups, computed with *qpAdm* under the model Yamnaya\_Samara + Anatolia\_Neolithic + WHG. The area of the pie is proportional to the number of individuals (shown inside the pie if more than one). See Supplementary Information, section 6 for mixture proportions and standard errors. **b**,  $f_4$ -statistics of the form  $f_4(\text{Mbuti}, \text{Test}; \text{Iberia\_EN}, \text{LBK\_EN})$  computed for European populations before the emergence of the Beaker Complex. Error bars represent  $\pm 1$  standard errors. **c**, Testing different populations as a source for the Neolithic farmer ancestry component in Beaker Complex individuals. The table shows the P-values (highlighted if  $> 0.05$ ) for the model: Yamnaya\_Samara + Neolithic farmer population. BC, Beaker complex.



**Figure 3. Population transformation in Britain associated with the arrival of the Beaker Complex.** **a**, Modelling Beaker Complex and Bronze Age individuals from Britain as a mixture of continental Beaker Complex (red, represented by Beaker Complex samples from Oostwoud) and Britain\_Neolithic (blue). Individuals are ordered chronologically (oldest on the left) and included in the plot if represented by more than 100,000 SNPs. See Supplementary Information, section 6 for mixture proportions and standard errors. **b**, Y-chromosome haplogroup distribution in males from Britain. EBA, Early Bronze Age; MBA, Middle Bronze Age. BC, Beaker complex.

## Supplementary Tables

**Supplementary Table 1.** Ancient individuals included in this study.

**Supplementary Table 2.** Mitochondrial haplogroup calls for individuals with newly reported data.

**Supplementary Table 3.** Y-chromosome calls for males with newly reported data .

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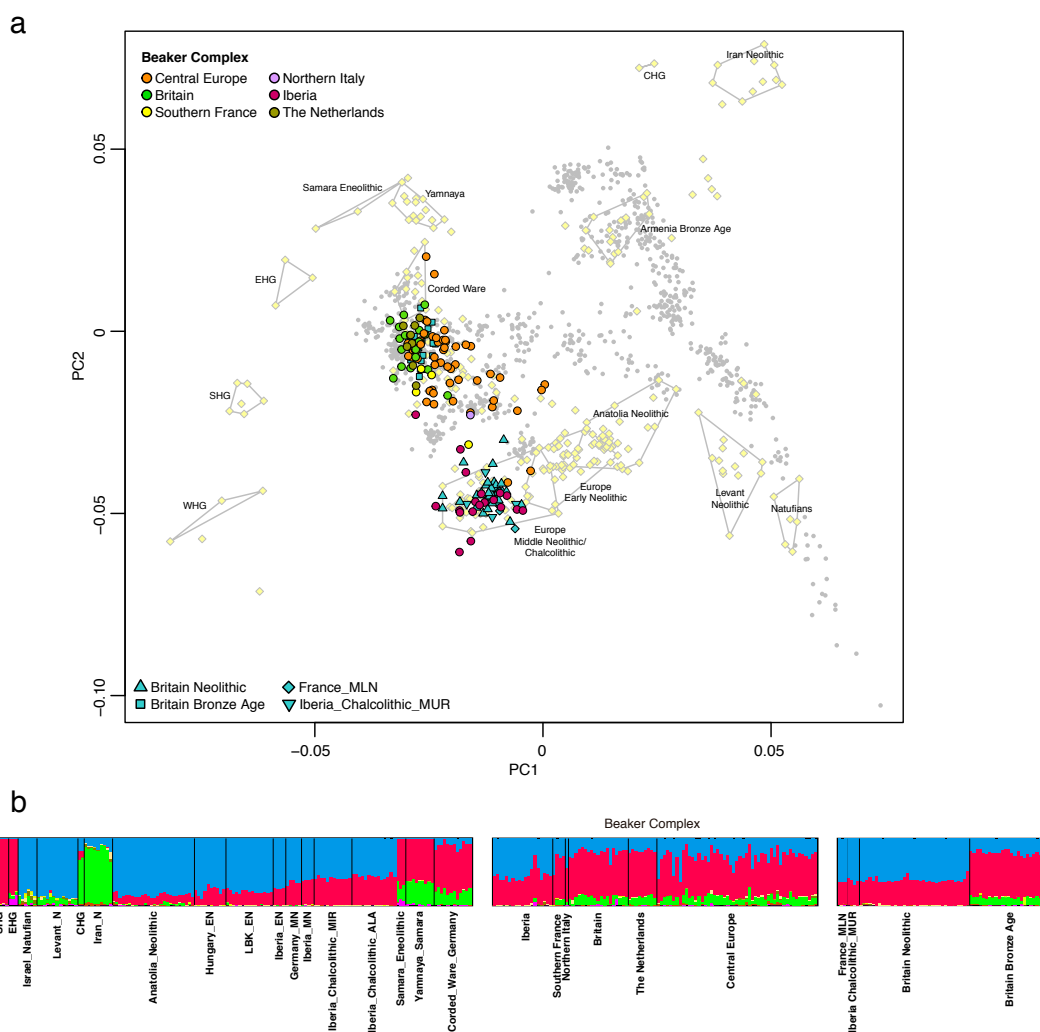
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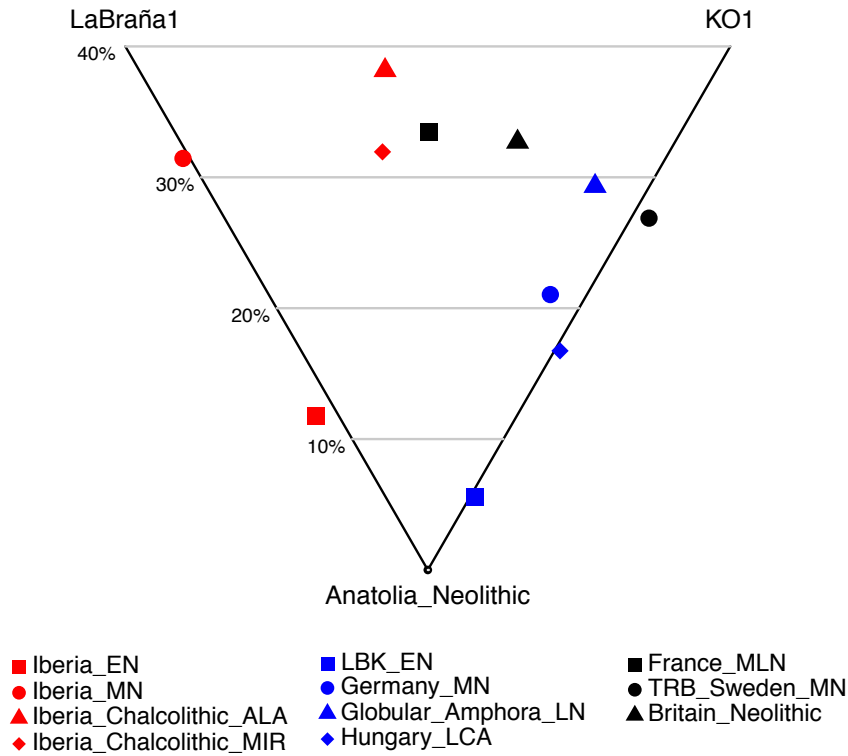
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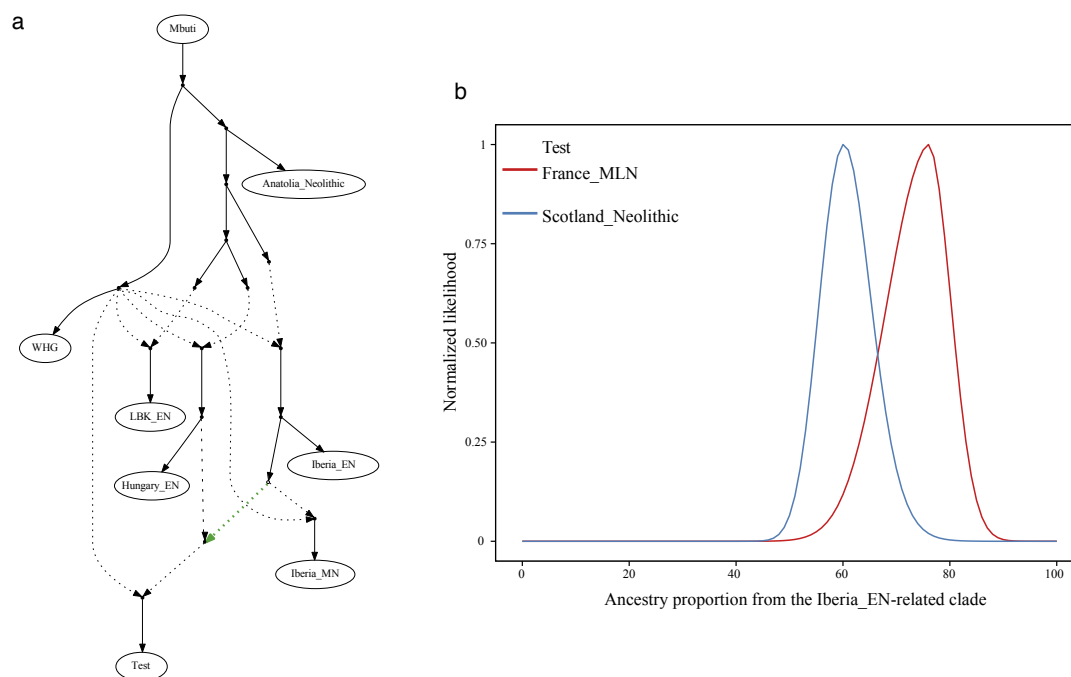
**Extended Data Figure 1. Population structure.** **a**, Principal component analysis of 990 present-day West Eurasian individuals (grey dots), with previously published (pale yellow) and new ancient samples projected onto the first two principal components. **b**, ADMIXTURE clustering analysis with  $k=8$  showing ancient individuals. E/M/MLN, Early/Middle/Middle Late Neolithic; W/E/S/CHG, Western/Eastern/Scandinavian/Caucasus hunter-gatherers.



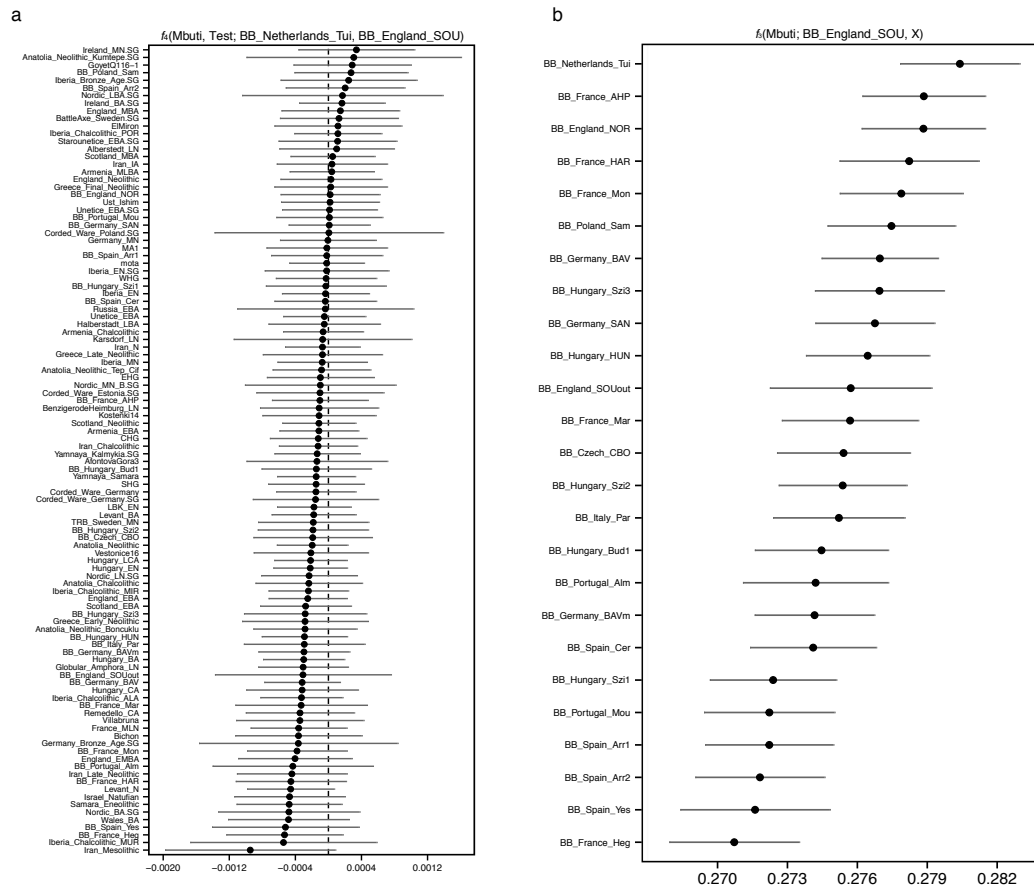
**Extended Data Figure 2. Hunter-gatherer affinities in Neolithic/Copper Age Europe.**

Differential affinity to hunter-gatherer individuals (LaBraña1<sup>36</sup> from Spain and KO1<sup>39</sup> from Hungary) in European populations before the emergence of the Beaker Complex. See Supplementary Information, section 6 for mixture proportions and standard errors computed with *qpAdm*.

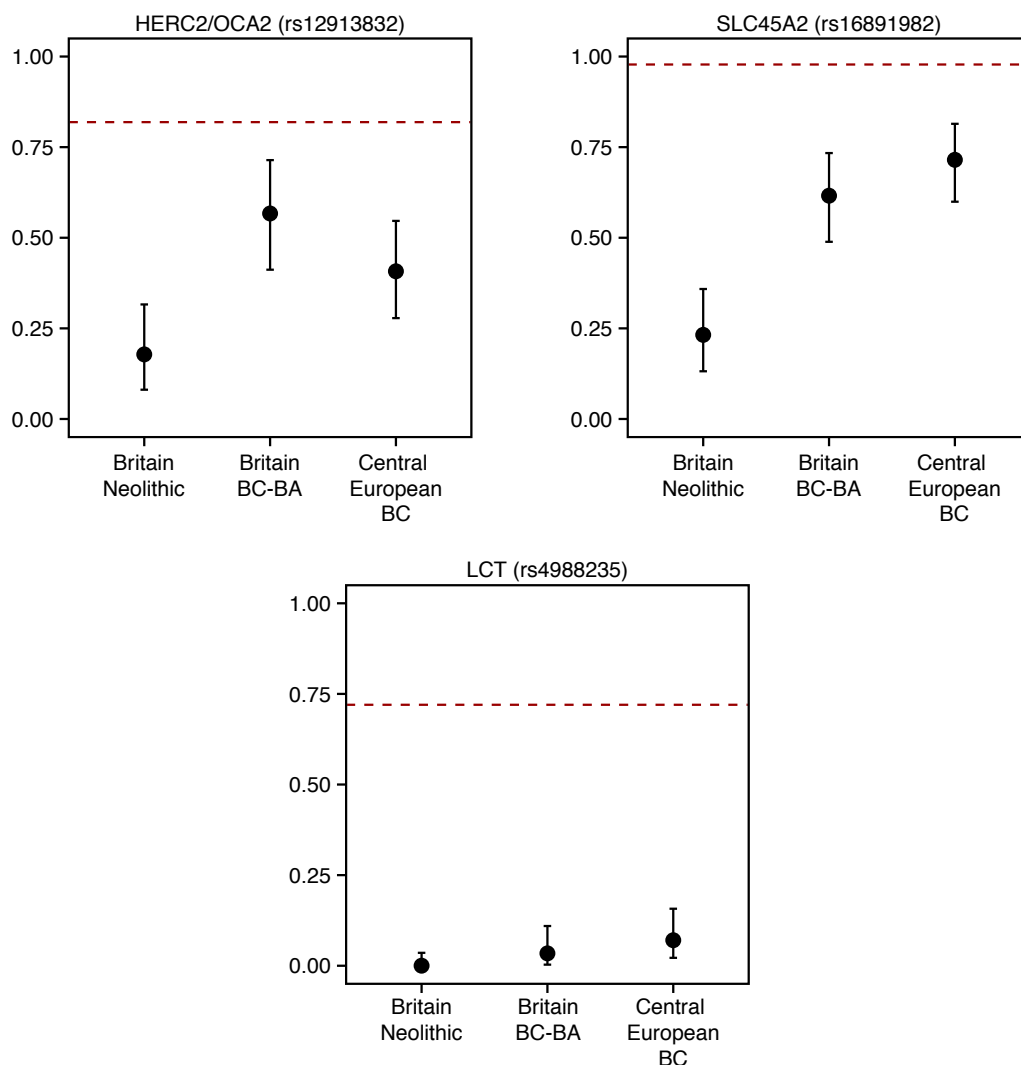




**Extended Data Figure 3. Modelling the relationships between Neolithic populations. a,** Admixture graph fitting a *Test* population as a mixture of sources related to both Iberia\_EN and Hungary\_EN. **b,** Likelihood distribution for models with different proportions of the source related to Iberia\_EN (green admixture edge in (a)) when *Test* is Great Britain\_Neolithic or France\_MLN.



**Extended Data Figure 4. Genetic affinity between Beaker complex individuals from southern Great Britain and the Netherlands. a**,  $f_4$ -statistics of the form  $f_4(\text{Mbuti, Test; BB\_Netherlands\_Tui, BB\_Great Britain\_SOU})$ . Negative values indicate that Test is closer to BB\\_Netherlands\\_Tui than to BB\\_Great Britain\\_SOU, and the opposite for positive values. Error bars represent  $\pm 3$  standard errors. **b**, Outgroup- $f_3$  statistics of the form  $f_3(\text{Mbuti; BB\_Great Britain\_SOU, X})$  measuring shared genetic drift between BB\\_Great Britain\\_SOU and other Beaker Complex groups. Error bars represent  $\pm 1$  standard errors.



**Extended Data Figure 5. Derived allele frequencies at three SNPs of functional importance.** Error bars represent 1.9-log-likelihood support interval. The red dashed lines show allele frequencies in the 1000 Genomes GBR population (present-day people from Great Britain). BC, Beaker Complex; BA, Bronze Age.

**Extended Data Table 1. 62 Newly reported radiocarbon dates**

| Sample   | Date                                       | Location                                      | Country        |
|----------|--|---|----------------|
| I4145    | 2279–2033 calBCE (3740±35 BP, Poz-84460)   | Kněževes                                      | Czech Republic |
| I1392    | 2832–2476 calBCE (4047±29 BP, MAMS-25935)  | Hégenheim Necropole, Haut-Rhin                | France         |
| I4144    | 2572–2512 calBCE (3955±35 BP, Poz-84553)   | Osterhofen-Altenmarkt                         | Germany        |
| E09537_d | 2471–2300 calBCE (3909±29 BP, MAMS 29074)  | Unterer Talweg 58-62, Augsburg, Bavaria       | Germany        |
| I4249    | 2336–2141 calBCE (3802±26 BP, BRAMS1217)   | Irlbach LKR                                   | Germany        |
| E09538   | 2464–2212 calBCE (3870±30 BP, MAMS 29075)  | Unterer Talweg 58-62, Augsburg, Bavaria       | Germany        |
| I3592    | 2458–2204 calBCE (3844±33 BP, BRAMS-1218)  | Alburg-Lerchenhaid, Spedition Häring, Bavaria | Germany        |
| I4250    | 2434–2150 calBCE (3825±26 BP, BRAMS1219)   | Irlbach LKR                                   | Germany        |
| I3593    | 2398–2146 calBCE (3817±26 BP, BRAMS-1215)  | Alburg-Lerchenhaid, Spedition Häring, Bavaria | Germany        |
| I3590    | 2339–2143 calBCE (3802±26 BP, BRAMS-1217)  | Alburg-Lerchenhaid, Spedition Häring, Bavaria | Germany        |
| I2657    | 3952–3781 calBCE (5052±30 BP, SUERC-68701) | Macarthur Cave                                | Great Britain  |
| I2633    | 3766–3642 calBCE (4911±32 BP, SUERC-68634) | Tulloch of Assery B                           | Great Britain  |
| I2659    | 3762–3644 calBCE (4914±27 BP, SUERC-68702) | Distillery Cave                               | Great Britain  |
| I2691    | 3701–3640 calBCE (4881±25 BP, SUERC-68704) | Distillery Cave                               | Great Britain  |
| I2796    | 3706–3536 calBCE (4856±33 BP, SUERC-69074) | Point of Cott, Orkney                         | Great Britain  |
| I2634    | 3704–3535 calBCE (4851±34 BP, SUERC-68638) | Tulach an t'Sionnach                          | Great Britain  |
| I2635    | 3653–3390 calBCE (4796±37 BP, SUERC-68639) | Tulloch of Assery A                           | Great Britain  |
| I2636    | 3520–3362 calBCE (4651±33 BP, SUERC-68640) | Holm of Papa Westray North                    | Great Britain  |
| I2988    | 3517–3362 calBCE (4645±29 BP, SUERC-68711) | Clachaig                                      | Great Britain  |
| I2660    | 3514–3353 calBCE (4631±29 BP, SUERC-68703) | Distillery Cave                               | Great Britain  |
| I2650    | 3500–3360 calBCE (4754±36 BP, SUERC-68642) | Holm of Papa Westray North                    | Great Britain  |
| I2637    | 3510–3340 calBCE (4697±33 BP, SUERC-68641) | Holm of Papa Westray North                    | Great Britain  |
| I2605    | 3632–3373 calBCE (4710±35 BP, Poz-83483)   | Eton Rowing Course                            | Great Britain  |
| I2980    | 3361–3102 calBCE (4530±33 BP, SUERC-69073) | Point of Cott, Orkney                         | Great Britain  |
| I2651    | 3330–3090 calBCE (4525±36 BP, SUERC-68643) | Holm of Papa Westray North                    | Great Britain  |
| I3085    | 3339–3027 calBCE (4471±29 BP, SUERC-68724) | Isbister, Orkney                              | Great Britain  |
| I2978    | 3336–3024 calBCE (4464±29 BP, SUERC-68725) | Isbister, Orkney                              | Great Britain  |
| I2934    | 3327–3036 calBCE (4466±33 BP, SUERC-69071) | Isbister, Orkney                              | Great Britain  |
| I2935    | 3336–3012 calBCE (4451±29 BP, SUERC-68723) | Isbister, Orkney                              | Great Britain  |
| I2979    | 3334–2942 calBCE (4447±29 BP, SUERC-68726) | Isbister, Orkney                              | Great Britain  |
| I2631    | 3098–2907 calBCE (4384±36 BP, SUERC-68633) | Quoyness                                      | Great Britain  |
| I2933    | 3011–2886 calBCE (4309±29 BP, SUERC-68722) | Isbister, Orkney                              | Great Britain  |
| I2977    | 3009–2764 calBCE (4275±33 BP, SUERC-69072) | Isbister, Orkney                              | Great Britain  |
| I2630    | 2581–2464 calBCE (3999±32 BP, SUERC-68632) | Isbister, Orkney                              | Great Britain  |
| I2932    | 2571–2348 calBCE (3962±29 BP, SUERC-68721) | Isbister, Orkney                              | Great Britain  |
| I2612    | 2465–2209 calBCE (3865±35 BP, Poz-83492)   | Hasting Hill, Sunderland, Tyne and Wear       | Great Britain  |
| I2416    | 2470–2285 calBC (3830±30 BP, Beta-432804)  | Amesbury Down, Wiltshire                      | Great Britain  |
| I2418    | 2440–2200 calBCE (3835±25 BP, NZA-32788)   | Amesbury Down, Wiltshire                      | Great Britain  |
| I2565    | 2470–2140 calBCE (3829±38 BP, OxA-13562)   | Amesbury Down, Wiltshire                      | Great Britain  |
| I2459    | 2460–2140 calBCE (3829±30 BP, SUERC-54823) | Amesbury Down, Wiltshire                      | Great Britain  |
| I2457    | 2480–2280 calBCE (3890±30 BP, SUERC-36210) | Amesbury Down, Wiltshire                      | Great Britain  |
| I2457    | 2200–2031 calBCE (3717±28 BP, SUERC-69975) | Amesbury Down, Wiltshire                      | Great Britain  |
| I2453    | 2289–2041 calBCE (3760±35 BP, Poz-83404)   | West Deeping                                  | Great Britain  |
| I2445    | 2137–1930 calBCE (3650±35 BP, Poz-83407)   | Yarnton                                       | Great Britain  |
| I2596    | 2280–2030 calBCE (3739±30 BP, NZA-32484)   | Amesbury Down, Wiltshire                      | Great Britain  |
| I2566    | 2210–2030 calBCE (3734±25 BP, NZA-32490)   | Amesbury Down, Wiltshire                      | Great Britain  |
| I2452    | 2195–1920 calBCE (3700±30 BP, Beta-444979) | Dairy Farm, Willington                        | Great Britain  |
| I2452    | 2277–2030 calBCE (3735±35 BP, Poz-83405)   | Dairy Farm, Willington                        | Great Britain  |
| I2598    | 2140–1940 calBCE (3664±30 BP, NZA-32494)   | Amesbury Down, Wiltshire                      | Great Britain  |
| I2460    | 2030–1820 calBCE (3575±27 BP, SUERC-53041) | Amesbury Down, Wiltshire                      | Great Britain  |
| I2609    | 2023–1772 calBCE (3560±40 BP, Poz-83423)   | Hexham Golf Course, Northumberland            | Great Britain  |
| I2610    | 1936–1746 calBCE (3515±35 BP, Poz-83498)   | Summerhill, Blyadon, Tyne and Wear            | Great Britain  |
| I1775    | 1693–1600 calBCE (3344±27 BP, OxA-14308)   | Great Orme Mines, Llandudno, North Wales      | Great Britain  |
| I2574    | 1415–1228 calBCE (3065±36 BP, SUERC-62072) | North Face Cave, Llandudno, North Wales       | Great Britain  |
| I2786    | 2459–2206 calBCE (3850±35 BP, Poz-83639)   | Szigetszentmiklós, Felső Úrge-hegyi dűlő      | Hungary        |
| I2787    | 2458–2202 calBCE (3840±35 BP, Poz-83640)   | Szigetszentmiklós, Felső Úrge-hegyi dűlő      | Hungary        |
| I2741    | 2458–2154 calBCE (3835±35 BP, Poz-83641)   | Szigetszentmiklós, Felső Úrge-hegyi dűlő      | Hungary        |
| I4229    | 2289–2135 calBCE (3775±25 BP, PSU-1750)    | Cova da Moura                                 | Portugal       |
| I0826    | 2833–2480 calBCE (4051±28 BP, MAMS-25940)  | Paris Street, Cerdanyola, Barcelona           | Spain          |
| I0257    | 2571–2350 calBCE (3965±29 BP, MAMS-25937)  | Paris Street, Cerdanyola, Barcelona           | Spain          |
| I0462    | 2566–2346 calBCE (3950±26 BP, MAMS-25936)  | Arroyal I, Burgos                             | Spain          |
| I0825    | 2474–2300 calBCE (3915±29 BP, MAMS-25939)  | Paris Street, Cerdanyola, Barcelona           | Spain          |

**Extended Data Table 2. Sites with new genome-wide data reported in this study.**

| Site  | N  | Approx. date range (BCE) | Country         |
|---|----|--------------------------|-----------------|
| Eton Rowing Course                                | 1  | 3700–3300                | Great Britain   |
| Banbury Lane                                      | 3  | 3360–3100                | Great Britain   |
| Totty Pot, Cheddar, Somerset                      | 1  | 2900–2400                | Great Britain   |
| Abingdon Spring Road cemetery, Oxfordshire        | 1  | 2500–2200                | Great Britain   |
| Hasting Hill, Sunderland, Tyne and Wear           | 2  | 2500–1700                | Great Britain   |
| Amesbury Down, Wiltshire                          | 10 | 2500–1400                | Great Britain   |
| Windmill Fields, Ingleby Barwick, County Durham   | 2  | 2400–1900                | Great Britain   |
| Yarnton   | 4  | 2400–1900                | Great Britain   |
| Staxton Beacon, Staxton, North Yorkshire          | 1  | 2400–1600                | Great Britain   |
| West Deeping                                      | 1  | 2300–2000                | Great Britain   |
| Dairy Farm, Willington, Bedfordshire              | 1  | 2300–1900                | Great Britain   |
| Over Narrows, Needingworth Quarry, Cambridgeshire | 2  | 2300–1900                | Great Britain   |
| Porton Down, Wiltshire                            | 1  | 2200–1900                | Great Britain   |
| Reaverhill, Barrasford, Northumberland            | 1  | 2200–1900                | Great Britain   |
| Trumpington Meadows                               | 2  | 2200–1900                | Great Britain   |
| Hexham Golf Course, Northumberland                | 1  | 2100–1700                | Great Britain   |
| Summerhill, Blaydon, Tyne and Wear                | 1  | 2000–1700                | Great Britain   |
| Thanet, Kent                                      | 3  | 2000–1600                | Great Britain   |
| Boscombe Airfield, Wiltshire                      | 1  | 1800–1600                | Great Britain   |
| Canada Farm, Sixpenny Handley, Dorset             | 1  | 1500–1300                | Great Britain   |
| Macarthur Cave                                    | 1  | 4000–3700                | Great Britain   |
| Distillery Cave                                   | 3  | 3800–3300                | Great Britain   |
| Raschoille Cave, Oban, Argyll and Bute            | 6  | 3800–3200                | Great Britain   |
| Tulach an t'Sionnach                              | 1  | 3700–3500                | Great Britain   |
| Tulloch of Assery A                               | 1  | 3700–3300                | Great Britain   |
| Point of Cott, Orkney                             | 2  | 3700–3100                | Great Britain   |
| Clachaig  | 1  | 3600–3300                | Great Britain   |
| Holm of Papa Westray North                        | 4  | 3600–3000                | Great Britain   |
| Isbister, Orkney                                  | 10 | 3400–2300                | Great Britain   |
| Quoyness  | 1  | 3100–2900                | Great Britain   |
| Dryburn Bridge                                    | 2  | 2300–1800                | Great Britain   |
| Eweford Cottages                                  | 1  | 2200–1900                | Great Britain   |
| Stenchme, Lop Ness, Orkney                        | 1  | 2000–1400                | Great Britain   |
| Longniddry, Evergreen                             | 3  | 1500–1300                | Great Britain   |
| Pabbay Mor  | 1  | 1500–1200                | Great Britain   |
| Great Orme Mines, Llandudno                       | 1  | 1700–1600                | Great Britain   |
| North Face Cave, Llandudno                        | 1  | 1500–1200                | Great Britain   |
| Kněževes  | 2  | 2500–1900                | Czech Republic  |
| Augsburg, Bavaria                                 | 2  | 2800–1800                | Germany         |
| Osterhofen-Altenmarkt, Bavaria                    | 1  | 2600–2000                | Germany         |
| Unterer Talweg 58-62, Augsburg, Bavaria           | 2  | 2500–2200                | Germany         |
| Manching-Oberstimm, Bavaria                       | 1  | 2500–2000                | Germany         |
| Irlbach, County of Straubing-Bogen, Bavaria       | 2  | 2500–2000                | Germany         |
| Bruck, City of Künzing, Bavaria                   | 2  | 2500–2000                | Germany         |
| Hugo-Eckener-Straße, Augsburg                     | 3  | 2500–2000                | Germany         |
| Unterer Talweg 85, Augsburg, Bavaria              | 1  | 2400–2100                | Germany         |
| Alburg, Lerchenhaid-Spedition Häring, Bavaria     | 11 | 2300–2150                | Germany         |
| Budakalász, Csajerszke (M0 Site 12)               | 2  | 2500–2200                | Hungary         |
| Szigetszentmiklós, Felső Űrge-hegyi dűlő          | 4  | 2500–2100                | Hungary         |
| Budapest-Békásmegyér                              | 2  | 2500–2000                | Hungary         |
| Samborzec   | 3  | 2600–2100                | Poland          |
| De Tuithoorn, Oostwoud, Noord-Holland             | 9  | 2300–1600                | The Netherlands |
| Via Guidorossi, Parma                             | 1  | 2200–1900                | Italy           |
| Clos de Roque, Saint Maximin-la-Sainte-Baume      | 3  | 4700–4400                | France          |
| Collet Redon, La Couronne-Martigues               | 1  | 3500–3100                | France          |
| Hégenheim Necropole, Haut-Rhin                    | 1  | 2900–2400                | France          |
| Dolmen of Villard, Lauzet-Ubaye                   | 2  | 2459–2242                | France          |
| Sierentz, Les Villas d'Aurele, Haut-Rhin          | 2  | 2600–2200                | France          |
| La Fare, Forcalquier                              | 1  | 2500–2200                | France          |
| Marlens, Sur les Barmes, Haute-Savoie             | 1  | 2500–2100                | France          |
| Mondelange, PAC de la Sente, Moselle              | 2  | 2500–1900                | France          |
| Rouffach, Haut-Rhin                               | 1  | 2400–2100                | France          |
| Galeria da Cisterna, Almonda                      | 2  | 2500–2200                | Portugal        |
| Cova da Moura                                     | 1  | 2300–2100                | Portugal        |
| Paris Street, Cerdanyola, Barcelona               | 10 | 2900–2200                | Spain           |
| Camino del Molino, Caravaca, Murcia               | 4  | 2900–2100                | Spain           |
| Camino de las Yeseras, San Fernando de Henares    | 2  | 2280–1790                | Spain           |
| Arroyal I, Burgos                                 | 5  | 2600–2200                | Spain           |