Report

Current Biology

The Demographic Development of the First Farmers in Anatolia

Highlights

- Pre-pottery farmers had low genetic diversity, akin to Mesolithic hunter-gatherers
- Genetic diversity levels are higher in the subsequent Pottery Neolithic
- Central Anatolian farmers belonged to the same gene pool as early European farmers
- Copper Age genetic affinities suggest a second wave of Anatolian gene flow

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In Brief

Kılınç et al. study ancient genomes from the earliest farmers of central Anatolia, one of the first areas where farming appears outside the Fertile Crescent. Genetic diversity increases as the Neolithic develops, indicating rising mobility. Similarities between Anatolian and European farmers suggest two gene flow events from Anatolia into Europe.

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Current Biology
Report

The Demographic Development of the First Farmers in Anatolia

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SUMMARY

The archaeological documentation of the development of sedentary farming societies in Anatolia is not yet mirrored by a genetic understanding of the human populations involved, in contrast to the spread of farming in Europe [1–3]. Sedentary farming communities emerged in parts of the Fertile Crescent during the tenth millennium and early ninth millennium calibrated (cal) BC and had appeared in central Anatolia by 8300 cal BC [4]. Farming spread into west Anatolia by the early seventh millennium cal BC and quasi-synchronously into Europe, although the timing and process of this movement remain unclear. Using genome sequence data that we generated from nine central Anatolian Neolithic individuals, we studied the transition period from early Aceramic (Pre-Pottery) to the later Pottery Neolithic, when farming expanded west of the Fertile Crescent. We find that genetic diversity in the earliest farmers was conspicuously low, on a par with European foraging groups. With the advent of the Pottery Neolithic, genetic variation within societies reached levels later found in early European farmers. Our results confirm that the earliest Neolithic central Anatolians belonged to the same gene pool as the first Neolithic migrants spreading into Europe. Further, genetic affinities between later Anatolian farmers and fourth to third millennium BC Chalcolithic south Europeans suggest an additional wave of Anatolian migrants, after the initial Neolithic spread but before the Yamnaya-related migrations. We propose that the earliest farming societies demographically resembled foragers and that only after regional gene flow and rising heterogeneity did the farming population expansions into Europe occur.

RESULTS AND DISCUSSION

The causes, effects, and mechanisms of the transition from foraging to farming in western Eurasia are key issues in understanding the development of our species, especially in understanding the development of larger, more dense, and more socially complex populations. Over the past decade, archaeogenetic studies have largely focused on processes that drove the spread of farming practices, particularly the introduction of farming and sedentism into Europe [2, 3, 5–9]. However, the demographic aspects of the transformation of forager communities in Southwest Asia into communities practicing substantial-scale mixed farming and the full extent of the role of Anatolian populations in the spread of farming into Europe have remained unclear. Here, we investigate human remains excavated from two different Neolithic settlements in central Anatolia, Boncuklu and Tepecik-Çiftlik, between circa (ca.) 8300 and 5800 calibrated (cal) BC to explore the demographic processes during the earliest (Aceramic) phase of the Neolithic transition, as well as the later Pottery Neolithic period in Anatolia.

Archaeological records show that the Neolithic era in Anatolia spanned more than 3,000 years—from around 9500 cal BC to around 6000 cal BC [4]. Farming practices were first established in the Fertile Crescent in the tenth and early ninth millennium cal BC [10] and in central Anatolia by 8300 cal BC [11, 12], or possibly earlier [12]. Between ca. 8000 cal BC and 6600 cal BC, farming spread west of central Anatolia, reaching the Aegean coast before 6600 cal BC and northwest Anatolia by 6600 at the latest [13, 14]. Debate exists as to whether this

Table 1. Summary Statistics of the Sequencing Data for Nine Ancient Individuals

Sample	Genome Coverage	mtDNA Coverage	Read Length (Mean)	mtDNA Haplogroup	Genetic Sex
Bon001	0.166	654.604	63.208	U3	XY
Bon002	6.688	2,379.090	69.841	K1a	XX
Bon004	0.243	351.234	70.703	N1a1a1	XY
Bon005	0.039	68.615	71.021	N1a1a1	XX
Tep001	0.023	66.812	80.863	K1a	XY
Tep002	0.721	730.833	60.814	K1a12a	XX
Tep003	0.694	281.963	60.849	N1b1a	XY
Tep004	0.473	391.608	61.473	N1a1a1	XX
Tep006	0.267	259.879	83.585	N1a1a1	XY

See Data S2 for summary statistics for each library and for SNPs used for haplogroup classification.

may have been a slow, steady process over those 1,400 years or relatively rapid between ca. 7000 and 6600 cal BC. Boncuklu, the earliest Anatolian site in our sample, and with evidence of very early crop cultivation in central Anatolia, is a small settlement mound dating between ca. 8300 and 7500 cal BC in the Aceramic Neolithic [11]. The excavators suggest that the Boncuklu community consisted of indigenous foragers who adopted small-scale cultivation and possibly experimented with animal herding alongside substantial traditional foraging practices [4, 11]. Tepecik-Çiftlik is a village with mixed and complex plant and animal exploitation practices, including notable elements of farming, located in the volcanic Cappadocian region of central Anatolia, dating between ca. 7500 and 5800 cal BC, from the latter Pre-Pottery Neolithic into the Pottery Neolithic [15, 16]. The evidence from Tepecik-Çiftlik indicates more substantial scale mixed farming relative to Boncuklu, although both hunting and gathering played a part in plant and animal exploitation. Both Boncuklu and Tepecik-Çiftlik show evidence of significant scale regional and inter-regional interactions, in the Tepecik-Çiftlik case especially with communities in the Fertile Crescent possibly related to the widespread distribution of obsidian [11, 15, 16]. The differences in subsistence patterns between these two settlements reflect a larger regional pattern seen in several other Aceramic and Pottery Neolithic sites in Anatolia [4, 13].

We investigated a total of nine ancient individuals excavated from Boncuklu (n = 4) and Tepecik-Çiftlik (n = 5) (Data S1). We generated genome sequence data from these individuals with a mean coverage between 0.03-fold and 6-fold per individual, using a combination of whole-genome capture and direct shotgun sequencing strategies (Supplemental Experimental Procedures; Table 1; Data S2; Figures S1A and S1B). We authenticated the sequence data using multiple well-established approaches (Supplemental Experimental Procedures; Data S1; Figure S1C). Mitochondrial genome coverages were between 66- and 2,379-fold (Table 1), and all five Tepecik-Çiftlik and three Boncuklu individuals carried the haplogroups previously found in Neolithic farmers in Europe (haplogroups K and N) (Table 1; Data S2; Figure S1D) [17]. One of the Boncuklu individuals carried the haplogroup U3, which has also been observed in a later northwest Anatolian (Pottery) Neolithic site, Barcın (Figure 1), and in early Neolithic European farmers [8, 17, 18], but not among Eurasian hunter-gatherers [19]. We identified four individuals as females and the other five as males (Table 1; Data S1).

We analyzed the new sequence data in the context of published ancient genetic variation (Figure 1). To discover the genetic affinities among ancient and modern-day individuals, we carried out principal component analysis (PCA). We calculated the principal components from 55 modern-day west Eurasian populations and projected the Boncuklu and Tepecik-Çiftlik individuals, as well as 85 published ancient individuals (Supplemental Experimental Procedures; Table S1), onto the first two principal components (Figure 2A). All individuals from the central Anatolian Neolithic, both the Aceramic Boncuklu group and the Pottery Neolithic Tepecik-Çiftlik group, were positioned within the genetic variation of present day southern European populations, consistent with outgroup f_3 statistics (Figure S2; Data S3). Our central Anatolian Neolithic individuals (Boncuklu and Tepecik-Çiftlik), together with later (Pottery) Neolithic and Chalcolithic (Copper Age) individuals from northwest Anatolia (Barcın, Menteşe, and Kumtepe) and with early and middle Neolithic individuals from Europe, formed a distinct cluster to the exclusion of hunter-gatherers from western and eastern Europe (WHG and EHG, respectively), Sweden (SHG), and the Caucasus (CHG) (Figure 2A). Consistent with the PCA, D tests confirmed a clustering of Neolithic and Chalcolithic Anatolians to the exclusion of hunter-gatherers from Europe and the Caucasus. Hunter-gatherers from Europe and the Caucasus also share more alleles with their own groups than with Neolithic Anatolians (Figure S3A; Data S3). Interestingly, although geographically close, the Anatolian Neolithic populations from different time phases each formed discrete but proximate clusters in the PCA. Boncuklu individuals, representing the earliest phase of the Neolithic transition on the central Anatolian plateau, clustered tightly together, implying low genetic diversity within the population. In contrast, Tepecik-Çiftlik individuals, representing the later phase of the Neolithic in central Anatolia, were positioned at a peripheral position within the whole cluster and displayed high within-group diversity (Figure 2A). Pairwise f_3 statistics between populations also showed significant differentiation between Boncuklu and Tepecik-Çiftlik populations (permutation test $p < 0.05$) (Data S3).

To directly gauge levels of genetic diversity in Anatolian Neolithic populations, we calculated conditional nucleotide diversity in Boncuklu, Tepecik-Çiftlik, and Barcın, as well as in European Neolithic and hunter-gatherer populations (Data S3). Herein, we restricted the analysis to transversions identified in Yoruba as in [5] to avoid ascertainment bias, sequencing errors, and post-mortem degradation effects (Supplemental Experimental Procedures; Table S1). The Boncuklu population had remarkably low diversity relative to later ancient Anatolian populations, Tepecik-Çiftlik and Barcın, and European early Neolithic individuals from Hungary (Figure 2B). Comparison of the mean pairwise f_3 statistics within populations also supported this result, with conspicuously higher genetic similarity within the Boncuklu group compared to Barcın and Tepecik-Çiftlik (Figure S3B; Data S3; 100% jackknife support). We further investigated short and intermediate runs of homozygosity (0.5–1.6 Mb); this is an indicator of historical effective population size and is expected to be influenced by geographic isolation and bottlenecks, but not recent inbreeding [20]. Our highest

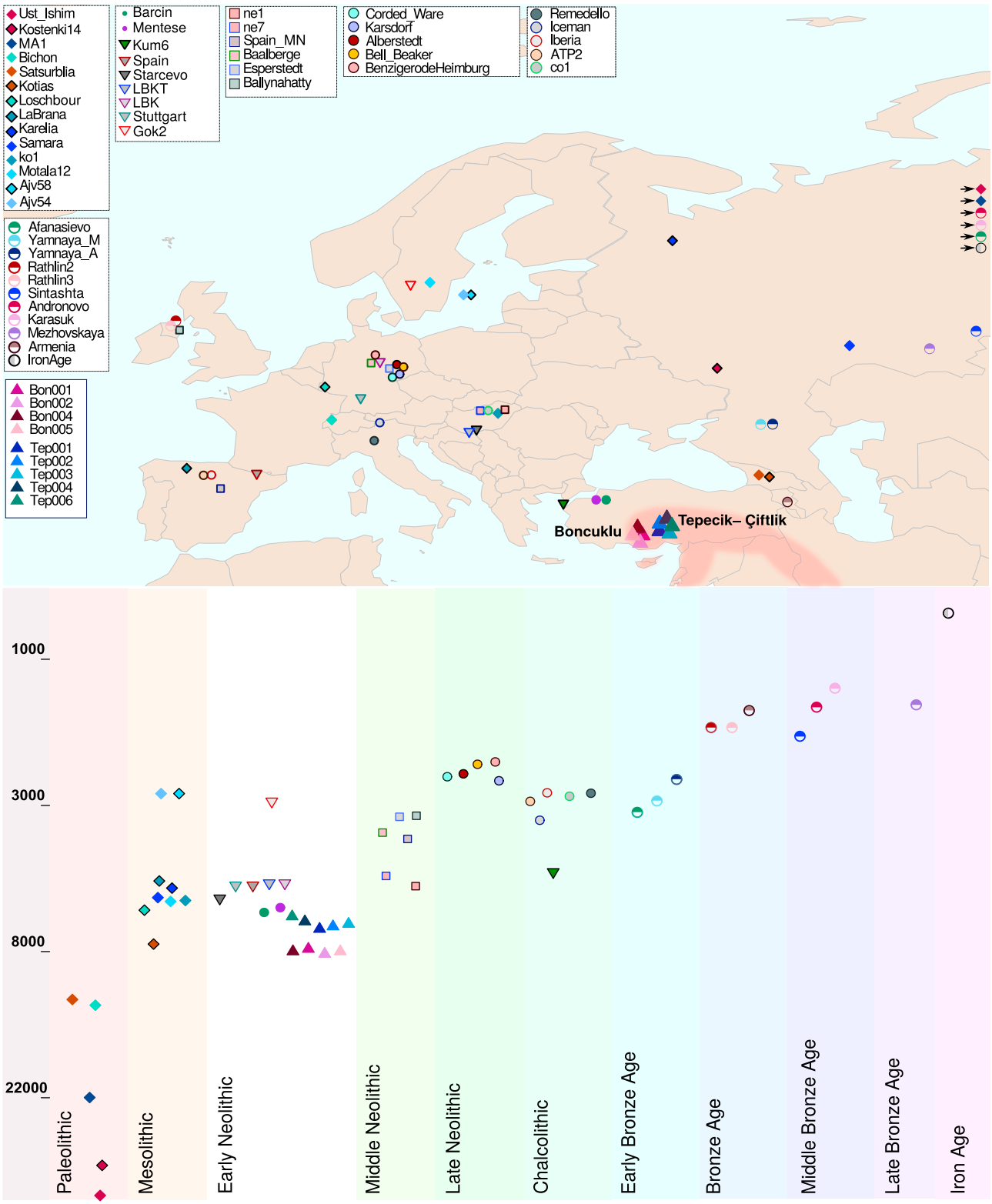

Figure 1. Geographical Location and Timeline of Ancient Individuals Included in This Study

Map showing the geographical distribution and timeline showing the approximate log-scaled time period (BC) of the ancient individuals used in this study. The colors and symbols for each individual are same with the principal component analysis (PCA). The regions where the Neolithic first emerged and was established are shaded. See Figure S1 for deamination patterns, sequencing efficiency using different methods for the individuals sequenced in this study, and an mtDNA haplogroup network. See also Data S1.

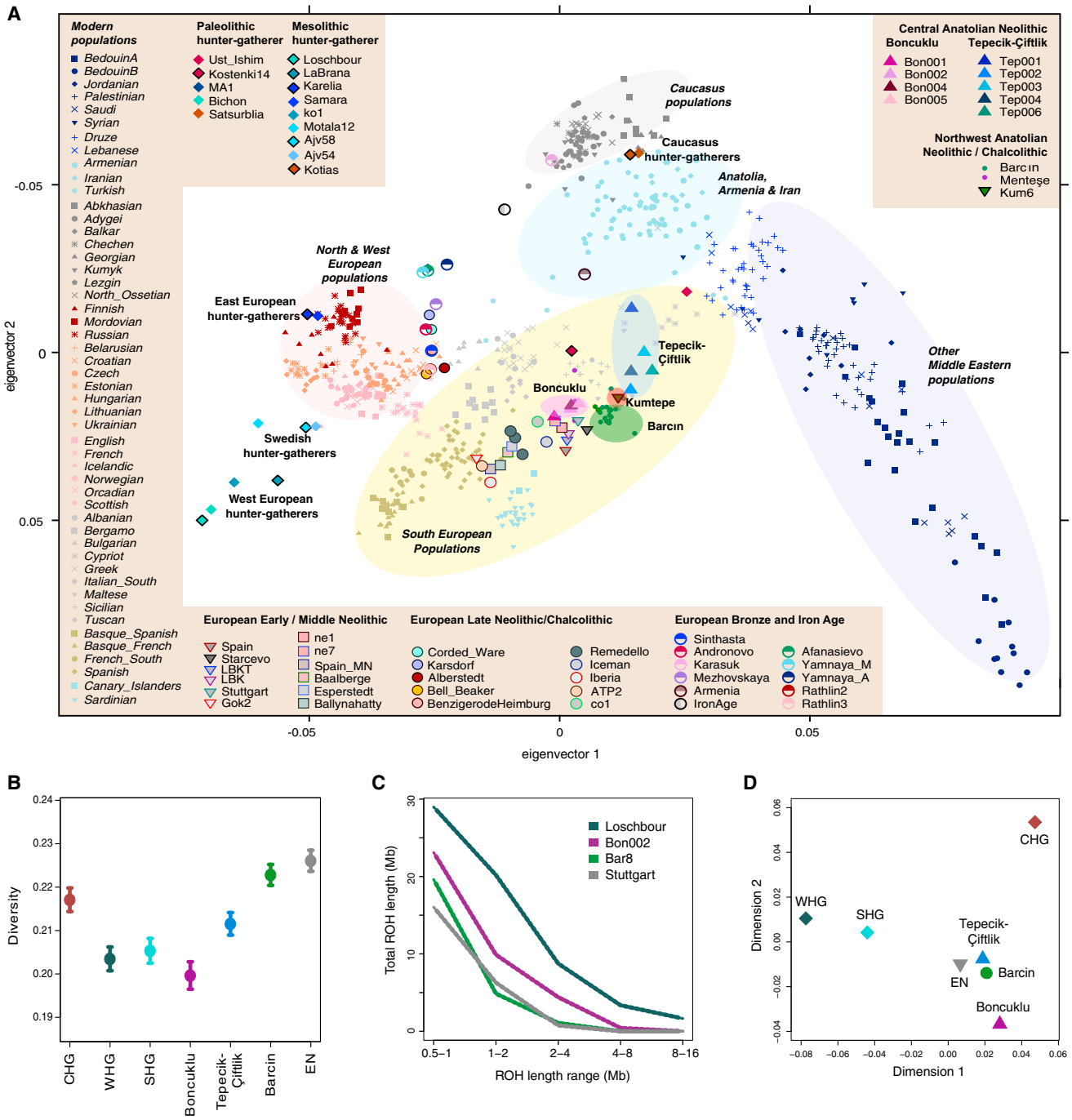

Figure 2. Genetic Structure and Diversity of Central Anatolian Neolithic Populations

(A) PCA on contemporary west Eurasian populations onto which a total of 85 ancient individuals are projected from this study and previous studies. See Table S1 for number of SNPs per individual. Neighboring modern populations and ancient Anatolian populations are shown encircled. Modern population names are in italics.

(B) Conditional nucleotide diversity calculated as the average pairwise mismatches between individuals. Diversities for each group were calculated using the SNPs identified in Yoruba individuals. We used two individuals per group, which yields the highest number of SNPs. Western European, eastern European, Swedish, and Caucasus hunter-gatherers are represented as WHG, EHG, SHG, and CHG, respectively. The European early Neolithic population is denoted with EN. Note that the diversities calculated for CHG and WHG are overestimates, as the individuals representing CHG are separated by three millennia and those representing WHG are separated by >1,000 km (Supplemental Experimental Procedures; Table S1). The error bars represent ±2 SEMs.

(C) Distribution of runs of homozygosity (ROH) for Loschbour (European Mesolithic), Bon002 (Anatolian Aceramic), Bar8 (Anatolian Pottery Neolithic), and Stuttgart (early European Neolithic).

(D) Multidimensional scaling analysis based on the Weir and Cockerham's F_{st} calculated between populations using transversions overlapping with African Yoruba individuals. See Data S3 for f_3 statistics, D statistics, pairwise mismatch estimates, and F_{st} estimates; Figure S2 for outgroup f_3 statistics with present-day populations; and Figure S3 for D statistics, mean pairwise f_3 statistics, and MDS analysis based on pairwise f_3 statistics.

quality genome, Bon002 of Boncuklu, had 30% fewer such runs than the central European forager Loschbour, but 25%–40% more such runs relative to high-quality genomes from the Pottery Neolithic, Bar8 of Barcın and Stuttgart of Germany (Supplemental Experimental Procedures; Figure 2C). This supports the notion of a small ancestral population size in the Boncuklu population.

We further evaluated genetic differentiation among Boncuklu, Tepecik-Çiftlik, Barcın, European Mesolithic, and Neolithic populations by calculating F_{st} (Supplemental Experimental Procedures; Data S3). The results were consistent with the pattern of differentiation in the PCA; particularly, Boncuklu appeared to be distinct from both Tepecik-Çiftlik and Barcın (F_{st} = 0.020 and 0.030, respectively; $Z > 4$). A multidimensional scaling (MDS) plot summarizing pairwise F_{st} values revealed clustering of Tepecik-Çiftlik and Barcın with European Neolithic populations, whereas Boncuklu attained a peripheral location (Figure 2C). This peripheral location is most likely due to high genetic homogeneity and drift in Boncuklu, as such a pattern was not observed in an MDS analysis of mean f_3 statistics (Figure S3C).

We next conducted ADMIXTURE analysis [21], inferring ancestral clusters from modern-day worldwide populations and estimating the ancestry proportions of each ancient individual based on the inferred ancestral cluster allele frequencies (Figures 3A and S4). With ten clusters (K = 10), ancestry proportions of all Anatolian (Boncuklu, Tepecik-Çiftlik, Barcın, Menteşe, and Kumtepe) and European Neolithic individuals consisted of two components, a ''northern component'' associated with European hunter-gatherers (WHG, SHG, and EHG) and found in modern-day northern Europe at highest frequency (orange), and a ''southern component'' found in the modern-day Middle East and North Africa (gray). Notably, Boncuklu displayed lower amounts of this ''southern component'' compared to individuals from Tepecik-Çiftlik and Barcın (Mann-Whitney U test, $p < 0.001$; Data S3), implying an influx of ''southern component'' alleles into late Aceramic and/or Pottery Neolithic settlements in Anatolia. This finding was also in line with higher genetic diversity in the later Neolithic Anatolian populations compared to Boncuklu (Figures 2B and 2C). D statistics results revealed genetic affinity between Caucasus hunter-gatherers (CHGs) and one of the individuals from Tepecik-Çiftlik, Tep003, which was greater than the rest of the individuals from Tepecik-Çiftlik and other Neolithic individuals from central Anatolia, northwest Anatolia, and Europe (Data S3). An admixture graph fitted by modeling gene flow from CHG to Tep003 using TreeMix [22] further confirmed the genetic relationship between Tep003 and CHG individuals (admixture proportion = 0.012, p = 0.002) (Figure S3D). These results show the buildup of genetic diversity during the development of the Neolithic in Anatolia.

We next used our data to investigate a more recent case of possible regional migration. Previous work [6] had noted genetic affinity between Kumtepe from northwest Anatolia and the Tyrolean Iceman [23] from northern Italy. We found that the three Remedello individuals from Chalcolithic northern Italy [24], largely contemporary and possibly genetically and culturally affiliated with the Iceman, also had high affinity to Kumtepe in D statistics (Figure 3B; Data S3). A similar tendency for Kumtepe allele sharing was seen for a Chalcolithic individual from Hungary, CO1 [7], but was non-significant (Figure S3E; Data S3). Intriguingly, the Iceman/Remedello group was more similar to Kumtepe than to Boncuklu, Barcın, Tepecik-Çiftlik, or European Neolithic individuals. We further found that both Kumtepe and the Iceman/Remedello group carried more CHG alleles than other Neolithic populations (Figure 3C). This pattern of additional CHG allele sharing simultaneously observed in Iceman/Remedello and in Kumtepe is not mirrored in convergent allele sharing with other European hunter-gatherers (Figures S3F and S3G). We also found that Tepecik-Çiftlik individuals were consistently closer to Iceman/Remedello and to Kumtepe than to any other Anatolian or European early Neolithic population, including their contemporary Barcın and the neighboring Boncuklu (Figure 3D). These results point to gene flow from an eastern source into Chalcolithic Kumtepe and later into Europe, which could have crossed central Anatolia already before the Chalcolithic.

Archaeogenetic studies have shown the existence of two distinct Mesolithic hunter-gatherer gene pools in west Eurasia: hunter-gatherers from Europe, ranging from Iberia to Scandinavia and to the Urals, and hunter-gatherers from the Caucasus [3, 5, 25]. The whereabouts of the so-called ''early/first European farmer'' gene pool [3], however, had remained unclear. Here we show that the genomes of Aceramic and Pottery Neolithic populations in central Anatolia belonged to the same group as northwestern Neolithic Anatolians and the first European farmers but were distinct from European and Caucasus foragers. The adoption of farming in central Anatolia by indigenous foragers, as suggested for Boncuklu [4, 11], would safely link the ''early/first European farmer'' gene pool to Anatolian foragers. However, the full geographic range of this forager population still remains to be described.

The low genetic diversity of the Boncuklu population, resembling the low diversity in European hunter-gatherers [5, 25] is interesting (Figures 2B and 2C). It suggests that the population sizes at the very early stages of the Neolithic were not different from those of hunter-gatherers. This accords well with the view of indigenous forager adoption of cultivation and possible local initiation of herding in central Anatolia [4, 11]. Nearly 1,500 years later, Tepecik-Çiftlik and Barcın, fully established Neolithic populations practicing mixed farming (and within 200 km east and 400 km northwest of Boncuklu, respectively), were significantly more diverse (Figure 2B). Part of this increased genetic diversity could be linked to (1) putative southern gene flow (Figure 3A) that could be related to the Aceramic Neolithic to Pottery Neolithic transition in the Neolithic Levant or could be related to widespread interactions in the late Aceramic Neolithic between central Anatolia and the Fertile Crescent in the late Pre-Pottery Neolithic B [26]; (2) migration from the east related to similar factors of inter-regional exchanges (Figure S3D); and (3) admixture among local populations. Southern and eastern gene flow into Tepecik-Çiftlik is consistent with the site's presumed role as an obsidian hub and its cultural links with the Levant and might have started already before the Pottery Neolithic [15, 16]. For Barcın, these results are also in line with archaeological evidence indicating cultural influx from central Anatolia [27]. This diverse Neolithic population most likely served as one of the sources for the well-documented wave of Neolithic migration to Europe [8, 9].

Post-Neolithic contacts between parts of Anatolia and central Europe are a matter of discussion. Genetic affinity between a

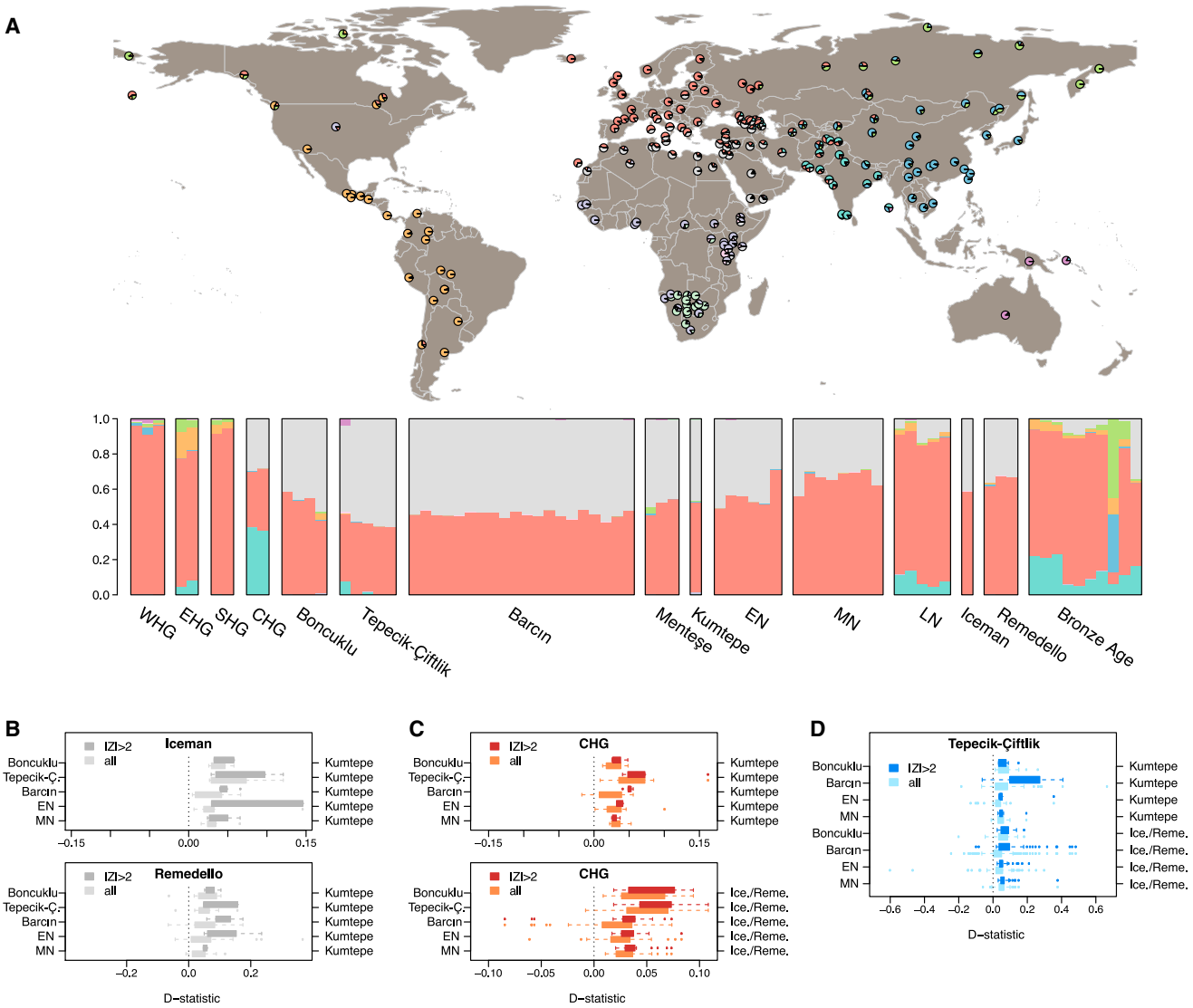

Figure 3. Admixture Analysis and Genetic Affinities among Neolithic/Chalcolithic Populations

(A) ADMIXTURE ancestry components (K = 10) for present-day world populations and for ancient individuals. Admixture fractions are shown on map for modern-day individuals and as bar charts for ancient individuals. See Figure S4 for K = 2 to K = 20 plots with all individuals. Western European, eastern European, Swedish, and Caucasus hunter-gatherers are represented as WHG, EHG, SHG, and CHG, respectively. European early, middle, and late Neolithic populations are denoted with EN, MN, and LN, respectively.

(B–D) Distributions of D statistics calculated as (B) *D(Denisova,Iceman;X,Kumtepe)* and *D(Denisova,Remedello;X,Kumtepe)*, (C) *D(Denisova,CHG;X,Kumtepe)* and *D(Denisova,CHG;X,Iceman/Remedello)*, and (D) *D(Denisova,Tepecik;X,Kumtepe)* and *D(Denisova,Tepecik;X,Iceman/Remedello)*, where *X* stands for an ancient Anatolian or European early Neolithic (EN) or middle Neolithic (MN) individual, indicated on the left-hand y axis. (See Figure S3 for a plot of D statistics of comparisons of CO1, EHG, and WHG.) In brief, $D < 0$ indicates higher genetic affinity between the test population (name indicated on the top) and *X*, and $D > 0$ indicates higher genetic affinity between the test population and the second population (name indicated on the right-hand y axis). In each comparison, lighter-color boxplots show all D statistics calculated using all available individuals in the populations compared, and darker-color boxplots show only nominally significant D statistics with $|Z| \geq 2$. The numbers in the middle indicate the percentage of comparisons where the test population resembles the population indicated on the right-hand y axis (i.e., $D > 0$). See Data S3 for D statistics.

Chalcolithic group in northwest Anatolia represented by Kum6 of Kumtepe and by a group represented by the Tyrolean Iceman was earlier explained by gene flow post-dating the earlier stages of the Neolithic in Europe [6]. But it has alternatively been interpreted as the Iceman representing a relic of the first migratory event from Anatolia [9]. As we have shown in this paper, individuals of the Chalcolithic Remedello group [24] from northern Italy also share strong affinity with Kumtepe. This pattern may be explained with one out of four scenarios: (1) Iceman/Remedello representing a relict population stemming from an early farmer migratory event, (2) late-Neolithic/Chalcolithic back-migration from central Europe into Anatolia, (3) a third source-population admixing with both the population represented by Iceman/Remedello and the population represented by Kumtepe, and (4)

secondary late-Neolithic/Chalcolithic migration from Anatolia. Because the Iceman/Remedello group is genetically closer to Chalcolithic Kumtepe than to earlier Anatolian Neolithic populations, including Boncuklu and Barcın, the first scenario seems unlikely. The fact that both Iceman/Remedello and Kumtepe display shared drift with Caucasus hunter-gatherers, independent of the Bronze Age Yamnaya expansions [24, 28], also argues against Iceman/Remedello being a relict population. Second, as Kumtepe predates the Iceman/Remedello group by some 1,300 years, back migration is an unlikely explanation. Finally, the Tepecik-Çiftlik population shows significant affinity to the Iceman/Remedello group and Kumtepe relative to other Anatolian and European Neolithic populations (Figure 3D); but Tepecik-Çiftlik also predates Iceman/Remedello by approximately 3,000 years. This implies gene flow events from Tepecik-Çiftlik-related populations into the Kumtepe-related west Anatolian populations, as predicted by archaeological evidence [29], and further gene flow that reached northern Italy by the fourth millennium BC. We propose an additional, yet undescribed, gene flow process from Anatolia into Europe as a better explanation than a contribution from a hypothetical third source into Neolithic central Anatolia, Chalcolithic northwest Anatolia, and Chalcolithic central Europe. Thus, Neolithic population dynamics that initiated in the Anatolian region resulted in multiple waves of expansion and admixture in west Eurasia.

EXPERIMENTAL PROCEDURES

DNA was isolated from petrous bone and teeth samples of nine ancient individuals. Double-stranded libraries were prepared and sequenced on Illumina HiSeq2500 and X platforms. Paired-end reads were merged, and adapters were removed. Reads were mapped to the human reference genome version hg18 and hs37d5 using BWA 0.7.12 [30]. Published ancient genomes were also mapped with the same parameters. Data was authenticated using four different methods [31–34]. Mitochondrial haplogroups were discovered using PhyloTree and Haplofind [35, 36]. Biological sex was determined using the R_y method [2, 37]. Principal component analysis was conducted using Eigensoft [38], and model-based clustering was performed using ADMIXTURE [21]. For ADMIXTURE analysis, ancestral components were determined using modern populations, and cluster memberships of each ancient individual were then inferred on the basis of these ancestral allele frequencies as in [39]. Outgroup f_3 statistics were computed using popstats.py (https://github.com/pontussk/popstats). D statistics were calculated using qpDstat program of ADMIXTOOLS [40]. For computation of conditional nucleotide diversity, two approximately contemporaneous individuals with the highest quality genomes were selected to represent each group, and the average number of mismatches per each site overlapping with African Yoruba population between two individuals was calculated as in [41]. Weir and Cockerham's F_{st} was calculated using popstats.py (https://github.com/pontussk/popstats). Runs of homozygosity for four high-quality genomes were calculated using PLINK [42]. See the Supplemental Experimental Procedures for details.

ACCESSION NUMBERS

The accession number for the genome data produced in this study is European Nucleotide Archive: PRJEB14675.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures, four figures, one table, and three data sets and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2016.07.057.

AUTHOR CONTRIBUTIONS

A. Götherström, M.J., J.S., İ.T., and M.S. designed and supervised the study; A.O., F. Ö., R.Y., M.K., E.D., E.Y., and N.D.D. performed the experiments; G.M.K. analyzed population-genetic data with contributions from M.S., A.O., T.G., H.M.D., A. Ghalichi, D.K., S.C.A., P.P., R.Y., E.Y., and N.D.D.; D.B., A.M.B., A.F., J.P., G.M., Y.S.E., Y.G.Ç., and E.B. excavated the samples, performed osteological assessments, and provided archaeological interpretations; and G.M.K., A.O., F.Ö., T.G., D.B., A.M.B., R.Y., A. Ghalichi, E.B., A. Götherström, M.J., J.S., İ.T., and M.S. wrote the manuscript with input from all authors.

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Supplemental Information

The Demographic Development of the First Farmers in Anatolia

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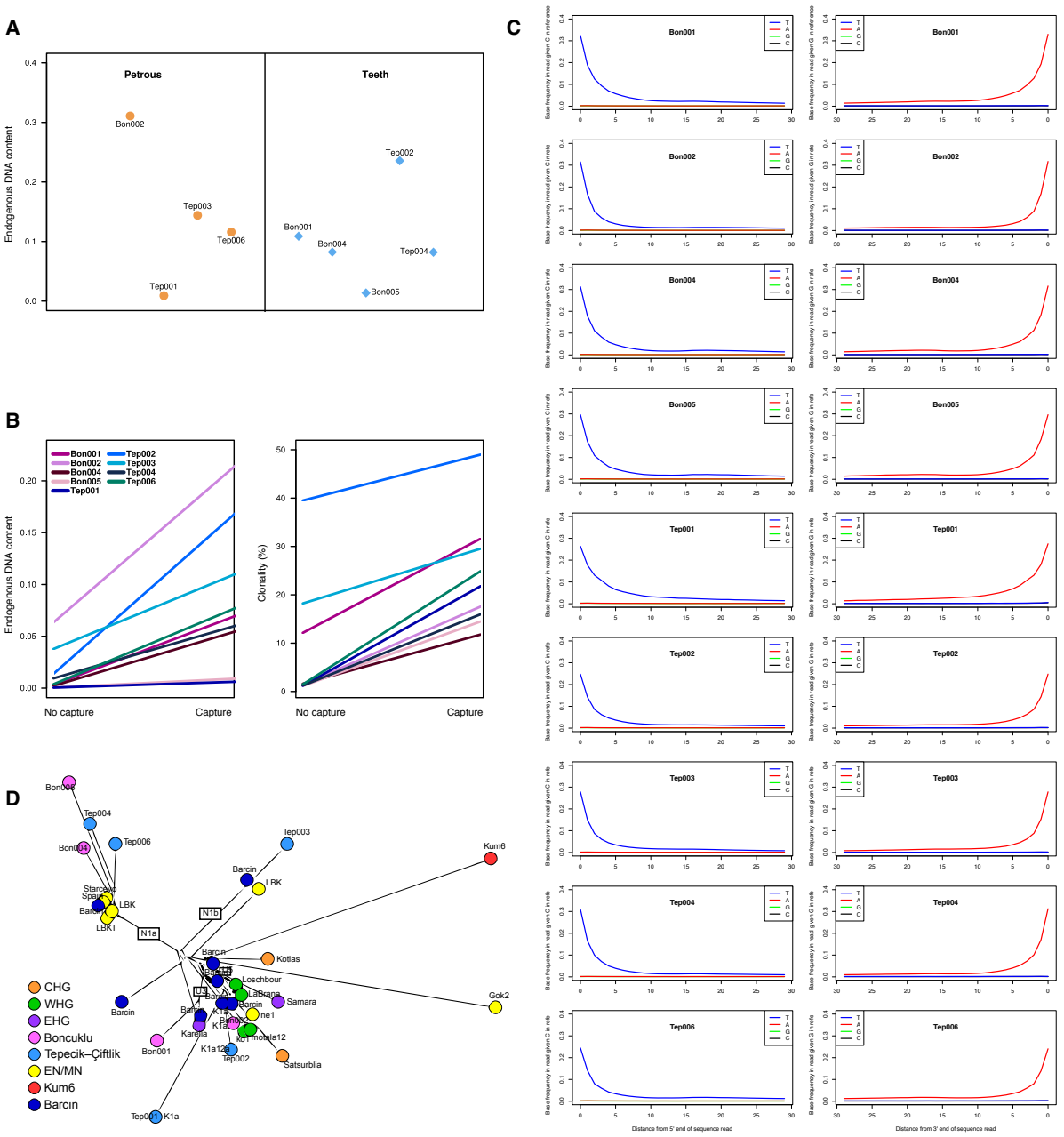

Figure S1. A) Mean endogenous aDNA content in individuals obtained from teeth and petrous bone. B) Mean endogenous aDNA content and clonality of the whole genome capture vs non-capture libraries. C) Nucleotide misincorporation patterns in Boncuklu and Tepecik-Çiftlik individuals. D) Mitochondrial DNA haplogroup network. CHG: Caucasus hunter-gatherer, WHG: West European hunter-gatherer, EHG: East European hunter-gatherer, EN: Early European Neolithic, MN: Middle European Neolithic (Related to Figure 1)

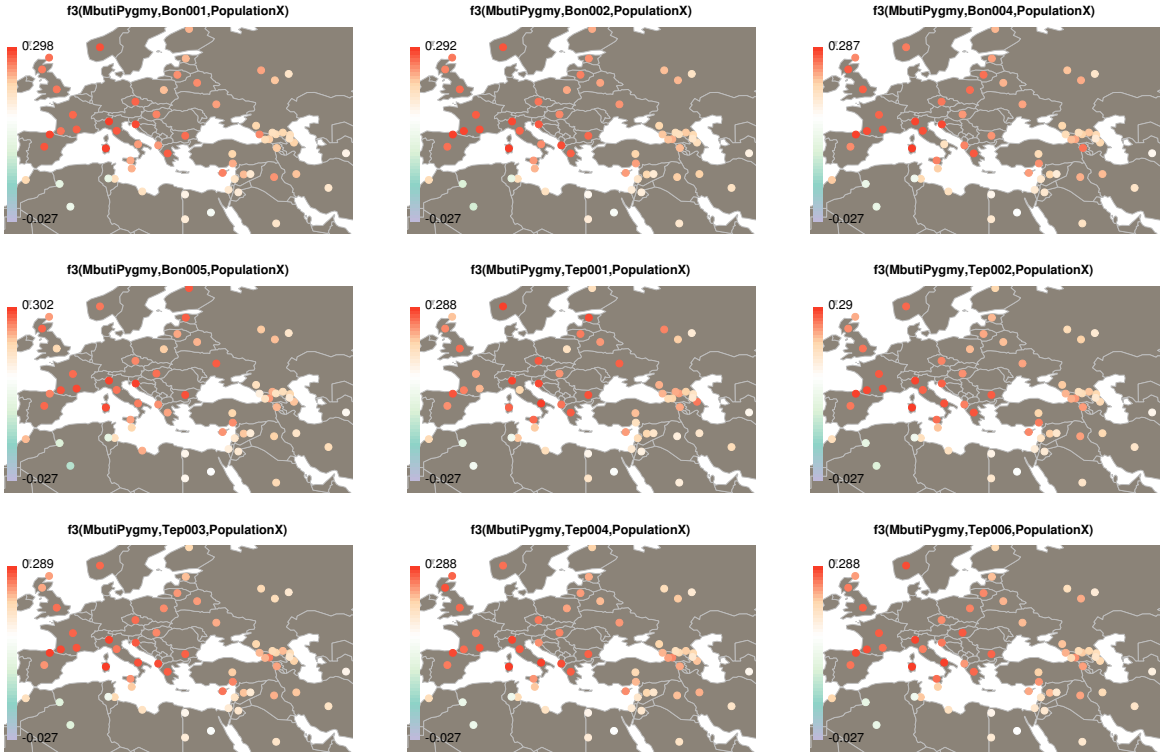

Figure S2. Shared genetic drift between ancient individuals and present-day populations. Outgroup f_3 statistics with topology of (MbutiPygmy; ancient individual, modern individual). (Related to Figure 2)

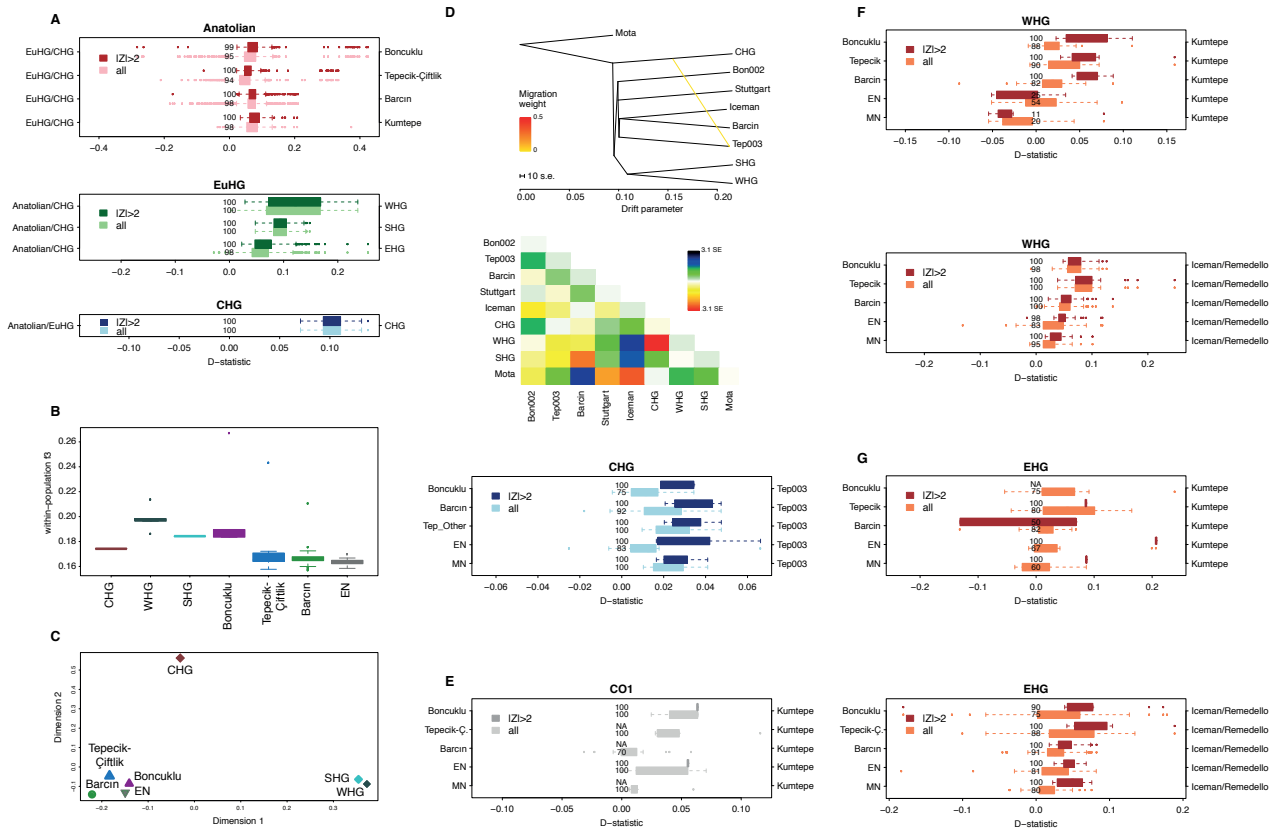

Figure S3. Genetic affinities between different populations (A) Boxplots of D-statistics for the topology *D(Denisova,Anatolian1;Anatolian2,Other)*, where Anatolian1 and Anatolian2 are two ancient Anatolian individuals and Other represents a European or Caucasus hunter-gatherer (CHG) individual; the topology *D(Denisova,EuHG1;EuHG2,Other)* where EuHG1 and EuHG2 are two European hunter-gatherer individuals, including Western European (WHG), Scandinavian (SHG), Eastern European hunter-gatherers (EHG), while Other represents a CHG or an ancient Anatolian individual; and the topology *D(Denisova,CHG1;CHG2,Other)* where CHG1 and CHG2 are two CHG individuals, while Other represents a European hunter-gatherer or an ancient Anatolian individual. In each comparison, boxplots show all D-statistics based on all available individuals in all populations (lighter colors), or only nominally significant D-statistics with $|Z|\geq 2$ (darker colors). The numbers in the middle indicate the percentage of comparisons where the test population resembles the population indicated on the right-hand y-axis. **(B)** Boxplots show within-population f_3-statistics for each population. Boncuklu had significantly higher within-population f_3 compared to both Tepecik-Çiftlik and Barcın (Mann-Whitney U test $p<0.01$ and 100% jackknife support). **(C)** Multidimensional scaling analysis based on mean f_3-statistics across populations. **(D)** TreeMix plot of the Tep003 with known migration from CHG model. **(E)** Boxplots of D statistics for the topology *D(Denisova,CO1;X,Kumtepe)* **(F)** Boxplots of D statistics for the topology *D(Denisova,WHG;X,Kumtepe)* and *D(Denisova,WHG;X,Iceman/Remedello)* **(G)** Boxplots of D statistics for the topology *D(Denisova,EHG;X,Kumtepe)* and *D(Denisova,EHG;X,Iceman/Remedello)*, where *X* stands for an ancient Anatolian or European early Neolithic (EN) or middle Neolithic (MN) individual, indicated on the left side y-axis. Results are plotted as in Panel A. (Related to Figure 2 and Figure3)

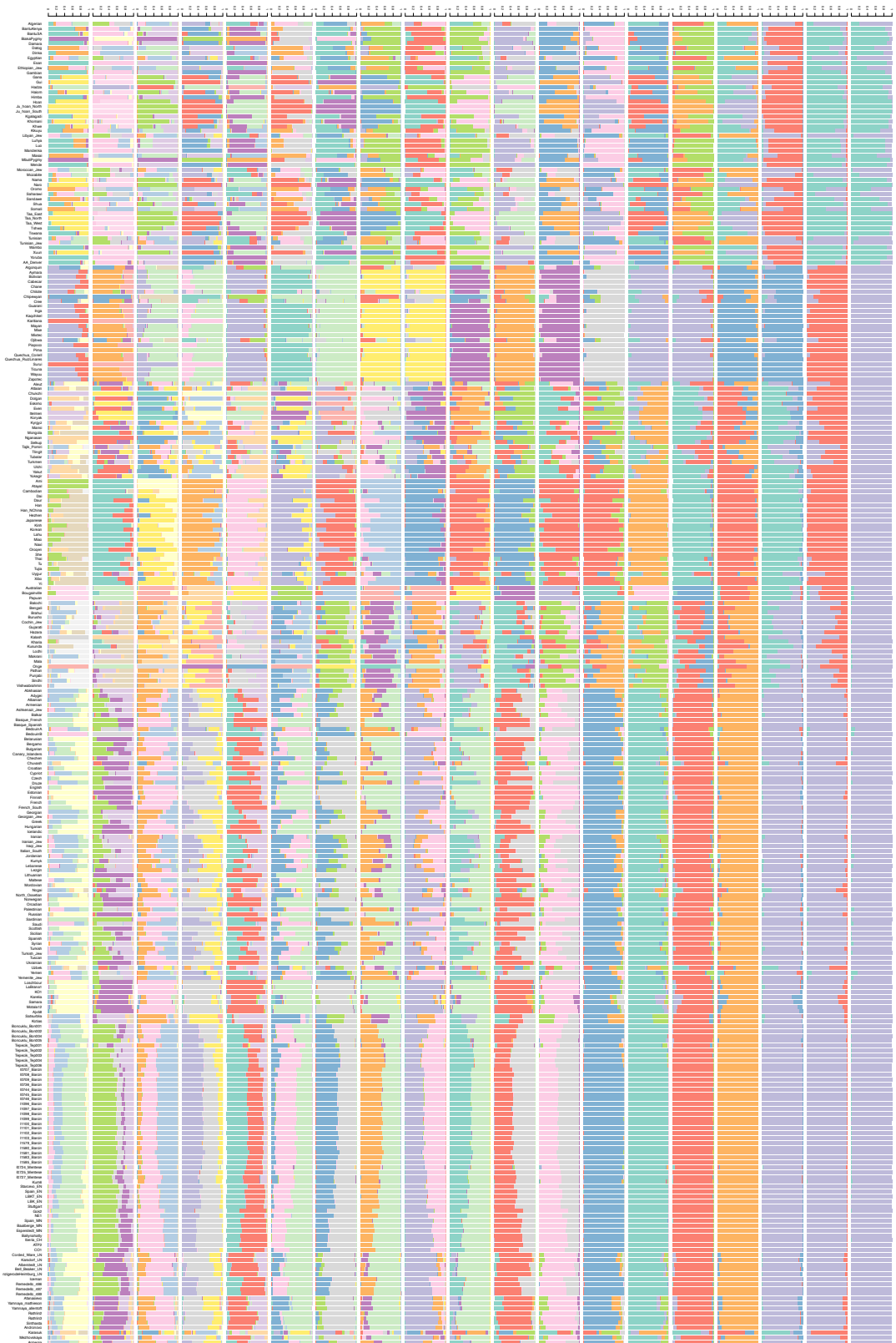

Figure S4. Admixture Analysis for K=2 to K=20. (Related to Figure 3)

Table S1: Number of SNPs of the ancient individuals used in this study, overlapping with reference datasets, either Human Origins ("HO") or the 1000 Genomes datasets. "Origin" refers to the population identity also used in Figure 2A. (*: this study). (Related to Figure 2)

Sample	Origin	HO	1000 Genomes	Source
Bon001	Boncuklu	24574	257166	*
Bon002	Boncuklu	356862	1750526	*
Bon004	Boncuklu	36263	353318	*
Bon005	Boncuklu	6459	70205	*
Tep001	Tepecik-Çiftlik	5193	45098	*
Tep002	Tepecik-Çiftlik	103179	765738	*
Tep003	Tepecik-Çiftlik	190517	872166	*
Tep004	Tepecik-Çiftlik	90488	582655	*
Tep006	Tepecik-Çiftlik	41142	393955	*
Denisova		389964	1845060	[S4]
Ust_Ishim		377273	1868221	[S5]
Oase1		75825	83498	[S6]
K14		244416	1037211	[S7]
MA1		132665	548352	[S8]
Bichon		379982	1827072	[S9]
Satsurblia		276697	1250908	[S9]
Kotias		378827	1812975	[S9]
Loschbour		378127	1869945	[S10]
LaBrana1		362114	1556281	[S11]
I0061	Karelia	353286	429688	[S12]
I0124	Samara	187268	111172	[S12]
KO1		257727	1125607	[S13]
Motala12		340648	1579528	[S10]
Ajv54		225442	1023721	[S14]
Ajv58		334932	1525594	[S14]
Bar8	Barcın	370414	1781411	[S15]
Bar31	Barcın	344306	1629480	[S15]
I0707	Barcın	352066	486817	[S12]
I0708	Barcın	343474	427669	[S12]
I0709	Barcın	348904	480918	[S12]
I0724	Mentese	22749	11743	[S12]
I0725	Mentese	14488	9037	[S12]
I0727	Mentese	15130	13826	[S12]
I0736	Barcın	305240	242288	[S12]
I0744	Barcın	314776	288254	[S12]
I0745	Barcın	351351	510681	[S12]
I0746	Barcın	352478	490715	[S12]
I1096	Barcın	262224	164676	[S12]
I1097	Barcın	260420	162100	[S12]
I1098	Barcın	274329	178294	[S12]
I1099	Barcın	186654	105584	[S12]
I1100	Barcın	99738	50128	[S12]
I1101	Barcın	228521	136845	[S12]
I1102	Barcın	138674	72212	[S12]

Sample	Origin	HO	1000 Genomes	Source
I1103	Barcın	208469	116473	[S12]
I1579	Barcın	279212	222938	[S12]
I1580	Barcın	312343	345227	[S12]
I1581	Barcın	280346	237593	[S12]
I1583	Barcın	335847	430493	[S12]
I1585	Barcın	283232	258647	[S12]
Kum6	Kum6	42069	179010	[S16]
I0174	Starcevo	93297	70796	[S12]
I0412	Spain	361180	670935	[S12]
I0176	LBKT	28641	21171	[S12]
I0100	LBK	351556	451996	[S12]
Stuttgart		377721	1849865	[S10]
Gok2		264828	959786	[S14]
ne7		234554	1026839	[S13]
ne1		375720	1850494	[S13]
I0408	Spain_MN	351352	498932	[S12]
I0560	Baalberge	141097	128812	[S12]
I0172	Esperstedt	371104	996699	[S12]
Ballynahatty		376668	1825174	[S17]
Iceman		373241	1528382	[S18]
I1300	Iberia	277445	196493	[S12]
ATP2		364082	1724404	[S19]
CO1		220323	967387	[S13]
I0103	Corded_Ware	368046	768507	[S12]
I0550	Karsdorf	62091	65070	[S12]
I0118	Alberstedt	367883	646574	[S12]
I0112	Bell_Beaker	343500	403502	[S12]
I0058	Benzigerode Heimburg	165158	56117	[S20]
RISE486	Remedello	60707	238049	[S21]
RISE487	Remedello	54117	234503	[S21]
RISE489	Remedello	150615	601768	[S21]
RISE508	Afanasievo	85966	252282	[S21]
I0231	Yamnaya_M	364439	667074	[S12]
RISE552	Yamnaya_A	327310	1208368	[S21]
Rathlin2		293436	1317947	[S17]
Rathlin3		206612	905407	[S17]
RISE395	Sinthasta	316486	1173415	[S21]
RISE505	Andronovo	367868	1611645	[S21]
RISE497	Karasuk	375986	1663555	[S21]
RISE523	Mezhovskaya	338921	1249961	[S21]
RISE423	Armenia	135554	508622	[S21]
RISE600	Iron Age	160309	720433	[S21]
Mota		384394	1831580	[S22]

Supplemental Experimental Procedures

Archaeological context of the samples

Neolithic on the Anatolian plateau

The Anatolian plateau, along with the Fertile Crescent, has been a major focus of Neolithic studies. The plateau can be divided into several geomorphological and cultural subregions: the Salt Lake region, the Konya Plain, Volcanic Cappadocia, and Sultansazlığı. The Epipalaeolithic of the plateau and its coastal fringes is poorly documented [S23]. However, one site on the plateau has been excavated at Pınarbaşı in the Konya Plain, where unlike the partially contemporary Levantine Early Natufian, there is no evidence of sedentary practices or intensive plant exploitation [S24]. The earliest sedentarising communities on the plateau appear in the 10th-9th millennia cal BC and are represented also by occupation at Pınarbaşı which lacks evidence of cultivation or herding [S25].

The Pre-Pottery Neolithic period (PPN) of the plateau is better understood. Among the human groups and cultures of the Konya Plain there are indications of highly diverse but indigenous communities during this phase of uptake of sedentism, of cultivation and of herding. Boncuklu and Aşıklı Höyük Level 4 [S26,27] have the earliest evidence of cereal and legume cultivation detected to date on the plateau. At both sites it was present by c. 8300 cal BC, presumably appearing somewhat earlier, but apparently post-dating the development of cultivation in the northerrn Levant, where cultivation appeared during the course of the10th and early 9th millennia cal BC. Substantial evidence of herding of morphologically wild sheep and goat (caprines) is present at Aşıklı also by 8300 cal BC [S28]. Sub-oval mud-brick houses characterise Boncuklu and early phases at Aşıklı Höyük in the second half of the 9th millennium cal BC. They are replaced by rectilinear closely packed house clusters in later phases at Aşıklı Höyük [S29] and Canhasan III [S30] in the 8th millennium cal BC. In the same period, the obsidian sources of Göllüdağ inVolcanic Cappadocia provide a focus for both settlement and those exploiting the sources for exchange, as obsidian from the region was exported to North Mesopotamia and the Levant, as well as Cilicia and Cyprus [S31]. There is thus substantial evidence for interactions between central Anatolia, the south coast of Turkey, the Levant and areas south-east of the Taurus from the Epipalaeolithic into the Pottery Neolithic [S32]. Several PPN sites have been discovered around and not far from the Göllüdağ obsidian beds and workshops. The variation in settlement types is remarkable; scattered site clusters like Yapılıpınar/Çakılbaşı, flat settlements with single period occupations, camp sites on scoria cones, rock shelters. The only stratified mound site Tepecik-Çiftlik has PPN levels in its lower strata [S33].

A diversity of cultures can be described in the Anatolian plateau during the subsequent Pottery Neolithic, considered to span from c.7000 to c.6000 cal BC. In Çatalhöyük in the Konya Plain [S34,35] we find rectilinear closely packed house clusters as at 8th millennium Aşıklı Höyük, and domestic organization that resembles 9th-8th millennium Boncuklu. In contrast, Tepecik-Çiftlik and Köşk Höyük in Volcanic Cappadocia have independent houses and open areas, pointing to cultural differences with the Konya plain. In the Pottery Neolithic, the Volcanic Cappadocia region still contains many workshops for obsidian tools and weapons. Recent work has detected many new settlements in the Volcanic Cappadocia region; these are thought to be related to migrating individuals and small groups, possibly moving over quite significant distances, attracted by the local obsidian sources [S32]. Finally, in the cultural/geomorphological region Sultansazlığı PPN and Pottery Neolithic sites are known only from surveys. The locations of the settlements on the dunes, hilltops and small valleys around the Holocene lake resembles those of Konya Plain.

Boncuklu

The site of Boncuklu is a small archaeological settlement mound in the northern part of the Çarşamba fan in the south-west Konya basin. The probable span of occupation was 8300-7500 cal BC. The site consists of a series of sub-oval structures with mudbrick superstructures; and extensive intervening open areas [S26]. Buildings have relatively standard domestic features and a highly structured use of domestic space, divided into ‘clean’ and ‘dirty’ areas. Buildings are also reconstructed over a number of generations in the same place, standing as a symbolic testament to the endurance, and social, economic and reproductive success of the household. At Boncuklu the evidence indicates adoption of cultivation by indigenous foragers, sometime before 8300 cal BC [S23]. This interpretation is based on continuities in very specific local technological practices and symbolism in the area and which are seen already c. 9500 cal BC and thus predate domestic plants in the Konya Plain by 1000 years [S26]. These plants were presumably introduced to the plain in the first instance as part of the far-reaching interactions in the 10^{th} and 9^{th} millennium, which have been documented at earlier and contemporary Pınarbaşı, as well as Boncuklu itself. Burials occur at Boncuklu under the ‘clean’ south-eastern areas in houses but in the open spaces between houses as well. All the burials under the houses are complete articulated inhumations, as are many of

those in the open areas. However, there is evidence of secondary mortuary practices on the site, with the burial of partial articulated remains and the circulation and deposition of skulls in the open areas [S26]. All of these human remains are thus well stratified within the settlement in relation to buildings, midden deposition and thus each other.

Tepecik-Çiftlik

Tepecik-Çiftlik is located in the Melendiz/Çiftlik Plain which is surrounded by the Melendiz Volcanic Mountains, lying along the southwest of the Volcanic Cappadocia region and the southern part of Central Anatolia [S33]. The occupation at the settlement probably continued uninterrupted from the Aceramic Neolithic Period until the early Chalcolithic Period, i.e. between 7500-5800 cal BC. The presence of yet unexcavated levels shows that the initial date of the settlement at the höyük predates 7500 BC. The Aceramic Neolithic levels do not contain architectural remains. In the Pottery Neolithic levels (5-4) the settlement layout consisted of wide open areas and single large structures but in the final Neolithic level (3) the settlement layout changed as the open areas were replaced by different types of structures. Utilization of domestic animals occurred in the Neolithic period at Tepecik-Çiftlik but hunting of wild fauna was still practiced and during the end of the Neolithic Period hunting, in fact, gained significance in the subsistence. During the Neolithic Period, alongside agriculture, intensive gathering also continued. The pottery at Tepecik-Çiftlik is the oldest in the region and of significant importance is its closeness to the Göllüdağ and other obsidian ore beds in the region. Obsidian as a raw material played a significant role in all of Near East and during the entire Neolithic Period for tools and arms production and there was a demand for obsidian tools and arms in many areas [S31]. Intensive obsidian tool production occurred at Tepecik-Çiftlik and also other Volcanic Cappadocia sites such as Yapılıpınar, Çakılbaşı, "Kayırlı Girişi/Sapağı", Bunuş and Nuzla. The obsidian tool and arms production "industry" in the region may have resembled "commodity" production [S33].

During archaeological fieldwork, a large number of human burials have been unearthed, beginning from the 5th level of the stratigraphy. The single and multiple burials dated to the Neolithic the number of the individuals is over 170. Beside primary and secondary burials, there are skull burials and also numerous individuals without skulls. Most of the graves contain single primary burials while most of the secondary burials contain bones of multiple individuals. A significant number of individuals were buried in hocker (crouched) positions, on their left or right sides with varying body orientations. The Neolithic graves are found in the courtyards, inside of the buildings and in open areas. However, a mass grave called BB was revealed in the 5th level. Among the individuals retrieved from this collective burial site are females and males of all age groups (i.e. infants, children, young adult) except for very young infants. The unique burial contains bones of at least 42 individuals. The general characteristics of the mortuary practices at Tepecik-Çiftlik are characteristic of the Aceramic Neolithic of the Near East [S36].

Sample description

Boncuklu individuals

The four individuals, subject to aDNA analysis in this paper, with context codes ZHF, ZHB, ZHBJ, ZHAF, (Data set 1) were all articulated single inhumations buried in oval cuts and stratified within the settlement sequence at the site. It should be noted that all four individuals were buried in one small part of the site, closely related to a sequence of buildings in that area. ZHB was directly dated to the last quarter of the 9th millennium cal BC by C14: range 8279-7977 cal BC (Oxcal) 2 sigma at 95.4% probability (lab number Wk29763). ZHF was dated to a similar time frame: range 8212-7952 cal BC (Oxcal) 2 sigma 95.4% probability (lab number BA120539). ZHAF was dated by C14 to 8300-8240 cal BC (Oxcal) 2 sigma 95.4% probability (lanb number WK43898). The other burial predates these directly dated individuals. Adult individuals were assigned to three age categories: young, middle and old. Young adults were individuals aged approx. 20-30, mature adults were aged approx. 30-50 and old adults were those over 50 years. Since adult age is dependent upon degenerative changes to the skeleton, these ages are approximate stages and should not be considered as exact numerical figures or directly comparable to calendar years.

ZHF Grave 14 (Bon001): A single inhumation of an adult individual. Key elements were not sufficiently preserved to estimate an age more precisely. Morphology was inconclusive, however the genetic analysis indicates it is a male. The individual was found lying on its left side in a tightly flexed position.

ZHB Grave 9 (Bon002): Single inhumation of a young to middle age category adult female. The individual was lying on their right side and partially prone, in a lightly flexed position. Genetic analysis confirms the assignation to sex made on morphological grounds.

ZHBJ Grave 30 (Bon004): A single inhumation of a middle-old age category adult male. The individual was found lying tightly flexed on their side. Genetic analysis confirms the assignation to sex made on morphological grounds.

ZHAF Grave 18 (Bon005): A middle age category adult female lying on her left side in a tightly flexed position. She was accompanied by a perinatal baby not analysed here. The arrangement of the skeletal remains was quite distinct with the perinatal child placed at one end of the grave. Genetic analysis confirms the assignation to sex made on morphological grounds.

Tepecik-Çiftlik individuals

TP'10 BB 4-23 (*Tep001*): This male individual is estimated to be a young adult (nearly 25-30 years old). The morphological sex assessment is in agreement with the genetic analysis. The individual comes from the 5th level of Tepecik-Çiftlik settlement and was obtained from BB collective burial. He is one of the few primary burials identified in BB collective burial. Whereas the upper side of this individual was laid down on his back in south-north direction, legs were positioned on his left side in crouched form.

TP'10 SK 40 (*Tep002*): The individual is represented by a mandible. Although the exact age could not be determined, it can be said that it belongs to an adult individual. Genetic analysis indicates that the individual was female. The burial SK 40 is located in fifth level of the settlement and was found at a very close location to BB collective burial. It is a secondary multiple burial and has different types of bones presenting at least four people.

TP'09 16 K (*Tep003*): The individual is presented by some parts of the skull. Although the exact age could not be determined, it can be said that it belongs to an adult individual. According to the genetic analysis the individual is male. The partial skull was found in 16 K sounding area of the settlement during the 2009 excavation season and it belongs to fifth level of the settlement.

TP'10 SK 37 (Tep004): The remains of this adult individual were in bad condition, so the exact age could not be determined. The sex of this individual estimated by osteological techniques is female which is in agreement with genetic data. The burial comes from the fourth level of the settlement. She is one of the individuals obtained from the western part of the AY room, part of the larger AK building complex. The individual has north-south direction, laid down on her left side and in a crouched position. In the grave there were various post-cranial disarticulated bones belonging to a different individual. The stratigraphy shows that SK37 is of earlier date than the other burials in room AY.

TP'10 SK 21 (Tep006): Osteological analysis indicates that this is an elderly individual (nearly 45-50 years old). According to osteological analysis the individual is male which was confirmed by genetic data. Antemortem tooth loss was observed for all the teeth together with various degrees of osteoarthritis in long bones and trunk bones. The burial comes from fourth level of the settlement in the eastern part of room AY, part of the larger building complex AK. The individual has a southeast-northwest direction, laid down on his right side and in a crouched position. In the grave there were various post-cranial disarticulated and articulated bones belonging to different individuals. Two potsherds were found as grave goods.

Sample preparation

Sample preparation, DNA extraction and library preparation from 4 Boncuklu and 5 Tepecik-Çiftlik samples were carried out in a laboratory dedicated to ancient DNA at the Middle East Technical University. Teeth and bone samples were decontaminated as in [S37]: The outer surface of the bone or teeth were removed using a single use blade. Teeth were wiped with 5% sodiumhypochlorite (NaClO) and then rinsed with nuclease free water. Each sample was placed in a petri dish and UV-irradiated (254 nm wavelength, 12 V and a distance of 5 cm from the UV source) in a cross-linker for 60 minutes from two sides. The bones were ground into fine powder using freezer mill.

DNA Extraction

Two different protocols were used for DNA isolations [S37,38]. In the first protocol, DNA extraction from 300 mg bone powder was performed with slight modifications based on [S37]. Bone powder was mixed with 1608 µl of lysis buffer (0.5 M EDTA pH 8, 20 mg/ml Proteinase K) and incubated in a shaker incubator first at 56 ^{0}C for 24 hours, then at 37 ^{0}C for 24 hours. DNA extraction was completed using silica spin columns, with a final elution of 104 µl. Two blank extractions were also carried out; for the grinding blank we used hydroxyapatite instead of bone powder. In the second protocol, 80-150 mg bone powder was mixed with extraction buffer (0.45 M EDTA pH8, 0.25 mg/ml Proteinase-K) and incubated for at least 18 hours at 37 ^{0}C in a shaker incubator and then centrifuged to obtain supernatant. 13 µl binding buffer (5 M Guanidine Hydrochloride, 40% (vol/vol) Isopropanol, 0.05% Tween-20, 90mM Sodium Acetate) was added to the supernatant. This mixture was filtered through Qiagen PCR Minelute spin columns to bind and wash the DNA, which was eluted with 48 µl of Qiagen Elution Buffer.

Library preparation

Double stranded DNA libraries were prepared using 20 µl of extract, with blunt-end ligation as described in [S39] with modifications as in [S19]. The initial nebulization step was omitted since aDNA is already fragmented. Each library was amplified in six replicates, each in a total volume of 25 µl. Two negative controls were included in each PCR batch. Each reaction contained 3 µl DNA library and the following in final concentrations; 1X AmpliTaqGold Buffer, 2.5 mM $MgCl_2$, 250 nM of each dNTP, 2.5U AmpliTaqGold (Life Technologies), and 200 nM each of the IS4 primer and an Indexed P7 primer. The cycling conditions were 94 C° for 10 min followed by 10-14 cycles of 94 C° for 30 sec, 60 C° for 30 sec, 72 C° for 45 sec, and a final extension at 72 C° for 10 min. Amplified libraries were pooled and purified with AMPure XP beads (Agencourt). The libraries were quantified on a 2100 Bioanalyzer using the High Sensitivity Kit (Agilent Technologies). None of the extraction blanks or PCR blanks showed presence of DNA and were therefore not further sequenced.

Initial sequencing

Libraries were pooled at equimolar concentrations for initial screening process. Sequencing was done on Illumina HiSeq 2500 and HiSeq X platforms at the SNP & SEQ Technology Platform at the Science for Life laboratory, Stockholm University. Each pool was sequenced with version 3 chemistry and 100 bp paired-end reads on one or several lanes. Libraries that yielded sufficient reads from the initial screening process were then selected and sequenced deeper in pools of four to six libraries per lane.

Whole genome in-solution capture and resequencing

In order to increase the depth of coverage, all the libraries built from the samples Bon001, Bon002, Bon004, Bon005, Tep001, Tep002, Tep003, Tep004, and Tep006 (Data set 2) were enriched using the MYbait Human Whole Genome Capture Kit from MYcroarray (Ann Arbor, MI). The libraries were captured following the manufacturer's instructions (http://www.mycroarray.com/pdf/MYbaits-manual-v3.pdf). The captured libraries were amplified for 10–19 cycles using primers IS5 (5' AATGATACGGCGACCACCGA) and IS6 (5' AAGCAGAAGACGGCATACGA) and Herculase II Fusion DNA Polymerase (Agilent Technologies). Subsequently, libraries were purified with AMPure XP beads and quantified by 2100 Bioanalyzer (Agilent Technologies). Purified libraries were pooled in equimolar amounts and sequenced on HiSeq 2500 and HiSeq X.

Processing of the ancient genome sequence data

We performed base calling using Illumina CASAVA software and de-multiplexed the sequences by requiring a complete match with the 6-nucleotide index sequences used in library preparation. Using MergeReadsFastQ_cc.py [S40], we removed the residual adapter sequences in FASTQ files and merged the paired-end sequencing reads with a requirement of minimum 11 bp overlap between the pairs. We mapped the merged reads to the human reference genome (version hs37d5 and hg18) using BWA [S41] version 0.7.12 in single-end mode with parameters -n 0.01 -o 2 and disabled the seed with –l 16500 as reported in [S10,14]. We merged the data from libraries of each individual and collapsed the PCR duplicates with identical start and end coordinates using FilterUniqueSAMCons.py [S40]. We filtered reads with length of less than 35 bp and required less than 10% mismatches to the human reference genome for each read. For comparative analysis, we re-mapped the published ancient data from individuals in Table S1, using the same procedure. We evaluated the success rate of using either teeth or petrous bone samples with respect to the endogenous DNA content (Figure S1A, Data set 2). We calculated the mean endogenous DNA content and clonality for each sample across libraries to compare the efficiency of sequencing in whole genome capture and non-capture libraries (Figure S1B).

Estimation of the contamination and authentication of data

To evaluate the authenticity of the genomes, we used a set of well-established approaches including the a) examination of ancient DNA specific damage patterns, b) X-chromosome-based contamination estimation in males, and c) mtDNA-based contamination estimation in all samples.

We first assessed the aDNA-specific DNA damage patterns that are not expected to be present in modern-day human DNA: high frequency of the cytosine to thymine (C to T) transitions at the 5' end of DNA due to cytosine deamination and short fragment length due to DNA strand breaks [S42,43]. We used PMDtools to evaluate the nucleotide misincorporation patterns at the first 30 positions at the 5' ends of the reads [S44]. All sequence data showed evidence of elevated C to T substitution frequencies at the ends of the DNA molecules (between 32%-24% at the first 5' base (Figure S1C). Mean read length of data ranged between 52-84 nucleotides.

We estimated the DNA contamination fractions using different approaches that are based on the examination of polymorphic positions in mitochondrial and X chromosomes in all samples and in males, respectively. In the first method, we obtained mitochondrial DNA contamination estimates using the approach adopted in [S16]. Here we first identified the private or near-private consensus alleles (<5 % in 311 modern mtDNA sequences) with minimum depth of 10X and minimum base quality of 30 in ancient individuals. We filtered positions where the consensus allele is C or G and a transition type substitution were detected, to prevent confounding with postmortem damage. We obtained the point estimate of mtDNA contamination by adding the counts of consensus and alternative nucleotides across all sites. For one of the nine samples (Tep001) we could not obtain the contamination estimates using this method, due to lack of informative sites with sufficient coverage. For the remaining 8 individuals average proportion of contamination ranged between 0.6% and 7.9% with a median of 1% (Data set 1). In the second method, we calculated the posterior probability of mtDNA contamination using a Bayesian approach described in [S1]. In brief, we called a consensus sequence for the samples using mpileup and vcfutils modules of the samtools [S45], and mapped the consensus sequences to a set of 311 modern human mtDNA sequences. Using contamMix, we calculated the probabilities of the authenticity for all samples (Data set 1). All individuals passed minimum one of the two mitochondrial DNA based contamination estimations. In the third method, for all male individuals in our study, we estimated the rate of contamination using a maximum likelihood method described in [S46] and implemented in the ANGSD (http://www.popgen.dk/angsd/) package (Data set 1). Given limitations in specificity and sensitivity of each of the above approaches, we assessed the results in combination, to ensure that none of the ancient individuals investigated here failed more than one contamination estimation method. Based on these results and post-mortem damage and read length analyses, we included all samples in further population genetics analysis.

Mitochondrial haplogroups

We obtained mtDNA sequence with mean coverage between 66- and 2,379-fold per individual. From this data, we called consensus mitochondrial sequences of each individual using the mpileup and vcfutils.pl (vcf2fq) tools in the samtools package with default parameters [S45]. We determined the mitochondrial DNA haplogroups of the individuals based on SNPs at informative nucleotide positions of the mitochondrial genome sequences (Data set 2). For this, we aligned mtDNA sequence of each individual to the RSRS [S47], identified the polymorphisms and analyzed these using HaploFind and PhyloTree [S48,49]. To prevent possible misinterpretation that might arise due to classification of missing sequences as deletions in HaploFind, we examined each consensus manually.

We observed haplogroup N1, the most abundant haplogroup in Neolithic farmer populations [S50], in five individuals from Central Anatolia. Four belonged to subtypes of N1a (N1a1a1) and one, from Tepecik-Çiftlik, belonged to N1b (N1b1a). One individual from Boncuklu belonged to U3. The remaining three individuals from Central Anatolia belonged to another common haplogroup in Neolithic farmer populations, K (K1a, K1a and K1a12a).

The Bon001 mitochondrial genome has 46 mutations classifying it as haplogroup U3 (Data set 2). 19 additional mutations were found in the consensus sequence, and 14 of these were C to T or G to A transitions attributable to post-mortem damage [S51]. The Bon002 mitochondrial genome has 50 mutations classifying it as haplogroup K1a (Data set 2). Six additional mutations (5 of these C to T or G to A) were found in the consensus sequence. The Bon004 mitochondrial genome has 49 mutations classifying it as haplogroup N1a1a1 (Data set 2). 20 additional mutations (16 of these C to T or G to A) were found in the consensus sequence. The Bon005 mitochondrial genome has 48 mutations classifying it as haplogroup N1a1a1 (Data set 2). 34 additional mutations (33 of these C to T or G to A) were found in the consensus sequence. The Tep001 mitochondrial genome has 48 mutations classifying it as haplogroup K1a (Data set 2). 36 additional mutations (35 of these C to T or G to A) were found in the consensus

sequence. The Tep002 mitochondrial genome has 53 mutations classifying it as haplogroup K1a12a (Data set 2). Eleven additional mutations (9 of these C to T or G to A) were found in the consensus sequence. The Tep003 mitochondrial genome has 52 mutations classifying it as haplogroup N1b1a (Data set 2). 16 additional mutations (15 of these C to T or G to A) were found in the consensus sequence. The Tep004 mitochondrial genome has 51 mutations classifying it as haplogroup N1a1a1 (Data set 2). 23 additional mutations (20 of these C to T or G to A) were found in the consensus sequence. The Tep006 mitochondrial genome has 52 mutations classifying it as haplogroup N1a1a1 (Data set 2). 14 additional mutations (12 of these C to T or G to A) were found in the consensus sequence.

Haplogroup N1a is typical of early European farmer from the Linearbandkeramik (LBK) culture of Central Europe. Haplogroups K and N1a are characterized as Early and Middle Neolithic [S50]. Both of these haplogroups were frequently observed in Barcın, LBK, LBKT (Linearbandkeramik culture in Transdanubia, 5800–4900 BC), STA (Early Neolithic Starčevo culture, 6000–5400 BC) populations including four Central European Neolithic groups (RSC, SCG, BAC and SMC) [S12,50,52]. K1a is common in present day Near East (Levant) and in Europe [S53], while N1 is described to be common in modern-day West Eurasia [S54]. The European hunter-gatherers mostly carried haplogroup U lineages including U, U2, U4, U5 and U8 [S2,50,55]. Meanwhile, U3 was not detected among Mesolithic individuals, and it is unclear whether there was a Mesolithic or a Neolithic emergence of haplogroup U3 in Central Europe [S50,56]. We constructed an mtDNA haplogroup network for 9 individuals using Network v5 (http://www.fluxus-engineering.com) (Figure S1D).

Biological sex determination

To determine the biological sex of all individuals, we used the R_y method as described in [S57,58]. In short, we used reads with mapping quality of minimum 30 and calculated the ratio of reads mapping to the Y chromosome to those mapping to both X and Y chromosomes. 5 individuals were assigned as males and 4 individuals were assigned as females (Data set 1).

Population genetics analysis datasets

We prepared two different datasets (to be used in different population genetics analyses) by merging the ancient sequence data produced in this study with ancient genome data from previous studies (Table S1) and with two different genotype datasets of contemporary individuals including i) Human Origins SNP Array and ii) 1000 Genomes whole genome sequencing datasets.

Human Origins SNP Array dataset

We obtained a curated version of Human Origins SNP Array dataset which includes 594,924 autosomal SNP genotype calls for 2,730 modern-day individuals from 203 different populations and 14 ancient individuals from [S10,59]. To merge ancient individuals with this dataset, we identified all reads with base quality and mapping quality of 30 or higher, and with overlapping positions with the Human Origins dataset. Whenever multiple reads overlapped with the same position, we randomly selected one read, and thus haploidized our data as in [S19]. We discarded all sites where an ancient individual carried an allele not found in the reference data, as well as all transitions and indels.

1000 Genomes dataset

We downloaded VCF and BAM files of African Yoruba individuals (n=108) from phase 3 of the 1000 genomes project from ftp.1000genomes.ebi.ac.uk [S60]. We used Yorubans as ascertainment population, for which we have good quality genomic data and who are known to be essentially isolated from Eurasian populations [S14]. We filtered the dataset by extracting all transversion SNPs with a minor allele frequency of 10% in African Yoruba population using vcftools [S61]. A total of 1,938,919 SNPs remained. We merged ancient genomes with these SNPs as described above.

Principal component analysis

We conducted principal component analysis (PCA) using a subset of individuals from the Human Origins SNP Array dataset. For PCA, we used a total of 55 modern West Eurasian populations and 85 ancient individuals (76 previously published and 9 reported here). We haploidized the dataset by randomly selecting a single allele at each heterozygous site for all the modern-day individuals, as in [S16,19]. We performed PCA of the modern-day

individuals using the smartpca program of EIGENSOFT [S62] with numoutlieriter: 0 and lsqproject: YES options, and projected the ancient individuals onto the first two principal components inferred from modern individuals. We plotted the result using the ploteig program of EIGENSOFT [S62].

ADMIXTURE analysis

We carried out unsupervised clustering using the algorithm ADMIXTURE [S63], where we estimated ancestry components using contemporary Eurasian, African, Asian, and American groups from the Human Origins dataset [S10,59], and used these components to cluster the ancient genomes. Prior to ADMIXTURE analysis, we filtered the Human Origins Array dataset for linkage disequilibrium using PLINK [S64], with parameters --indep-pairwise 200 25 0.4. This filtering resulted in a total of 293,404 SNPs. We conducted ADMIXTURE analysis as described in [S65]. In brief, we determined ancestral clusters for modern-day populations using ADMIXTURE and inferred the cluster memberships of each ancient individual using the ancestral allele frequencies. Therefore, ancient samples did not have influence on ancestral clusters and the difference in number of overlapping SNPs across samples did not interfere with the results.

We determined the cluster memberships of each ancient individual through maximization of the following log-likelihood function, an adapted version of Eqn2 in [S63]:

$$L(Q,F) = \sum_i g_i \ln\left(\sum_k (q_k f_{ik})\right) + (2-g_i)\ln\left(\sum_k q_k(1-f_{ik})\right)$$

where;

g_i : genotype at the position *i*

q_k : contribution of population *k* to a sample

f_{ik} : frequency of a variant at position *i* in population *k*. These values are obtained from the output of ADMIXTURE that was run on modern individuals.

The optimization was implemented through the following formula which was defined as a part of FRAPPE EM algorithm in [S63]:

$$q_k^{n+1} = \frac{1}{2I}\sum_i g_i a_{ik}^n + (2-g_i) b_{ik}^n$$

$$a_{ik}^n = \frac{q_k^n f_{ik}^n}{\sum_m q_m^n f_{im}^n} \text{ and } b_{ik}^n = \frac{q_k^n (1-f_{ik}^n)}{\sum_m q_m^n (1-f_{im}^n)}$$

$$L(Q^{n+1}, F^{n+1}) - L(Q^n, F^n) < \epsilon$$

$\epsilon = 10^{-4}$ was used as the convergence criteria, as implemented in the original ADMIXTURE software.

We performed clustering of the modern individuals as well as the ancient individuals between K=2 and K=20 (Figure S4). For each K, we carried out 50 replicate runs with different random seeds for each modern individual and determined the clusters of each ancient individual. We identified common signals between different replicates for each K using LargeKGreedy algorithm of CLUMPP [S66]. We compared cluster proportions between ancient populations using one-sided Mann-Whitney U tests in R.

Outgroup-*f3* statistics

We used outgroup-*f3* statistic to evaluate the genetic relationship between two populations regarding the shared genetic drift between them since their divergence from a common ancestral population. This statistic is not affected by an excess of drift in either of the populations [S59]. We calculated the statistic as in the formula:

$$f3(O;A,B) = \frac{\Sigma(p_o - p_A)(p_o - p_B) - (p_o - p_O^2)/(n_O - 1)}{\Sigma 2 p_O (1 - p_O)}$$

where;

p_O: allele frequency of the reference allele.

n_O: number of chromosomes in outgroup populatin (O) at locus i.

We used Mbuti Pygmy (in comparisons with modern populations in the Human Origins dataset) or Yoruba (in comparisons with ancient individuals, to maximize the number of overlapping SNPs) as outgroup. A positive value of this statistic indicates the shared genetic drift between populations A and B. For Figure S3C, we converted f3 statistics into a distance measure by subtracting all values from 1, and summarized these values by multidimenstional scaling (MDS) using the *cmdscale* function of R.

D-statistics

We carried out formal tests of admixture using D-statistics to investigate relationships between ancient individuals. We tested deviations from a tree-like population topology by computing D-statistics implemented in ADMIXTOOLS qpDstat program [S59], based on:

$$D(A,B;X,Y) = \frac{\sum_{i=1}^{n}[S(p_{iA}-p_{iB})(p_{iX}-p_{iY})]}{\sum_{i=1}^{n}[S(p_{iA}+p_{iB}-2p_{iA}p_{iB})(p_{iX}+p_{iY}-2p_{iX}p_{iY})]}$$

where;

p_{iA}: frequency of a randomly chosen allele at marker *i* in population A.

n: total number of markers

We tested the significance of each test by computing standard errors using a block jackknife of 5cM in size. Significant deviations from zero indicates deviation from the proposed tree with topology (*A*,*B*)(*X*,*Y*). When A is the outgroup, positive values indicate that the population B is closer to population Y; while negative values shows that the population B is closer to population X. We used the high-coverage Denisovan genome [S4] as outgroup in this analysis.

Conditional nucleotide diversity

We assessed within-population diversity by computing conditional nucleotide diversity as described in [S14,19]. In brief, the method is based on estimating the average number of mismatches for all sites between two individuals. Here we used two ancient contemporaneous individuals for each ancient population: Bon001 and Bon002 for Boncuklu; Tep002 and Tep003 for Tepecik-Çiftlik (both from level 5); Bar8 and Bar31 for Barcın [S15]; ne1 and ne7 (from Hungary) for European early Neolithics (EN) [S13]; Loschbour [S10] and LaBrana [S11] for western European hunter-gatherers (WHG); Kotias and Satsurblia for Caucasus hunter-gatherers (CHG) [S9]; Ajv58 and Ajv54 for Swedish hunter-gatherers (SHG) [S14]. We chose individual pairs to be close to each other with respect to their ages and have the highest number of SNPs. We restricted our calculation to transversion SNPs identified in Yorubans to prevent the possible effects of ascertainment bias as well as post-mortem damage. We tested the significance of results by calculating standard errors using block jackknife over blocks of 500 SNPs.

Weir and Cockerham's Fst estimation

We computed F_{st} as in [S14], using Weir and Cockerham's estimator, implemented in 'popstats' program (https://github.com/pontussk/popstats). We used transversion polymorphisms identified in Yorubans as described earlier. F_{st} estimates for all populations were computed with two ancient individuals – same with those used in diversity estimates. We conducted MDS analysis based on F_{st}, using *cmdscale* function of R.

Admixture graph inference

We inferred the relationships amongst ancient populations in the form of a bifurcating tree, using a statistical framework implemented in TreeMix [S67]. Treemix builds a maximum likelihood tree of populations and fit admixture edges to given populations using the covariance matrix of allele frequencies. We applied TreeMix to Bon002, Tep003, I0745 (Barcın), Stuttgart, Iceman, Loschbour (WHG), Kotias (CHG), Motala12 (SHG) and Mota. Since we used a single individual as representative of each population, we turned off the correction for low sample size using "–noss" option. We rooted the tree with high coverage ancient Ethiopian Mota [S22] individual. We restricted the analysis to a total of 210,973 transversion SNPs genotyped in all ancient individuals, which were ascertained in African Yoruba individuals from the 1000 Genomes project. We fitted an admixture graph by modeling gene flow from CHG to Tepecik-Çiftlik population (observed in ADMIXTURE analysis and D tests), using the –cor-mig option of TreeMix. We determined the starting proportion of admixture as 0.0 to allow the 0% possibility of gene flow. We estimated the standard errors using blocks of 500 SNPs. We ran TreeMix in this setting with 50 different random seeds. Each of the runs supported the observed result. We plotted the resulting tree and residuals using the plotting functions provided Treemix.

Permutation test for population differentiation using f_3-statistics

We used a permutation scheme to test differentiation between two populations based on pairwise f_3 statistics, using the R environment. We first calculated all pairwise f_3 values of the type $f_3(Outgroup, IPop_1, IPop_2)$, where $IPop_1$ and $IPop_2$ stand for the n_1 and n_2 members of Pop_1 and Pop_2, respectively. We used the mean of these n_1*n_2 f_3 values as a measure of observed genetic similarity between Pop_1 and Pop_2. Next, for 10,000 times, we randomized group memberships, creating two groups again with n_1 and n_2 members and calculating mean f_3 for the randomized groups. These mean f_3 values represent the null distribution for no difference. Finally, we calculated a one-sided permutation test p-value for population differentiation by determining the number of times the observed mean f_3 is equal to or lower than the null expectation.

Jackknife resampling for comparing homozygosities using f_3-statistics

To confirm population homozygosity differences estimated using conditional nucleotide diversity, we used mean within-population pairwise f_3 values. We first tested difference in mean within-population pairwise f_3 values using the Mann-Whitney U test. To ensure that this result is not influenced by single individuals, we repeated the analysis leaving out one individual at a time, creating n=20 jackknife resamplings for Boncuklu vs. Tepecik-Çiftlik and n=80 jackknife resamplings for Boncuklu vs. Barcın comparisons.

Estimation of the runs of homozygosity

We analyzed four high coverage ancient genomes (Bon002, Barcın8, Loschbour and Stuttgart) for runs of homozygosity (ROH). The diploid genotype calling was performed using autosomal transversions from Yorubans in the 1000 Genomes phase 3 dataset [S60] with samtools mpileup [S45], which generated between 1,789,956 and 1,891,896 transversion SNPs for these four samples. We identified ROH as in [S17] using PLINK [S64] version 1.90 with parameters (--homozyg , --homozyg-window-snp 50, --homozyg-window-het 1, --homozyg-window-threshold 0.05, --homozyg-snp 50, --homozyg-kb 500, --homozyg-density 50, --homozyg-gap 100).

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