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Title: Genomic and archaeological evidence suggest a dual origin of domestic dogs

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Abstract: The geographic and temporal origins of dogs remain controversial. Here, we generated genetic sequences from 59 ancient dogs and a complete (28x) genome of a late Neolithic dog (~4,800 calBP) from Ireland. Our analyses revealed a deep split separating modern East Asian and Western Eurasian dogs. Surprisingly, the date of this divergence (~14,000-6,400 years ago) occurs commensurate or several millennia after the first appearance of dogs in Europe and East Asia. Additional analyses of ancient and modern mitochondrial DNA revealed a sharp discontinuity in haplotype frequencies in Europe. Combined, these results suggest that dogs may have been domesticated independently in Eastern and Western Eurasia from distinct wolf populations. East Eurasia dogs were then possibly transported alongside people where they partially replaced European Palaeolithic dogs.

One Sentence Summary: Genomics and archaeology reveal both a possible dual origin of domestic dogs and a subsequent translocation of East Asian dogs into Europe.

Main Text: Dogs were the first domestic animal and the only animal domesticated prior to the advent of settled agriculture (*1*). Despite their importance in human history, no consensus has emerged with regard to their geographic and temporal origins, or whether dogs were domesticated just once or independently on more than one occasion. Though several claims have been made for an initial appearance of dogs in the early Upper Palaeolithic (~30,000 years ago; *e.g. 2*), the first remains confidently assigned to dogs appear in Europe ~15,000 years ago and in Far East Asia over 12,500 years ago (*1*, *3*). While archaeologists remain open to the idea that there was more than one geographic origin for dogs *(e.g.* (*4*, *5*), most genetic studies have concluded that dogs were likely domesticated just once (*6*) – disagreeing on whether this occurred in Europe (*7*), Central Asia (*8*), or East Asia (*9*).

Recent palaeogenetic studies have had a tremendous impact on our understanding of early human evolution (*e.g.* (*10*, *11*)). Here we apply a similar approach to reconstruct the evolutionary history of dogs. We generated 59 ancient mtDNA sequences from European dogs (from 14,000 to 3,000 years ago) as well as a high coverage nuclear genome (~28x) of an ancient dog ~4,800 calBP (*12*) from the Neolithic passage grave complex of Newgrange (*Sí an Bhrú*) in Ireland. We combined our ancient sample with 80 modern publically available full genome sequences and 605 modern dogs (including village dogs and 48 breeds) genotyped on the 170k HD SNP array (*12*).

We first assessed characteristics of the Newgrange dog by typing SNPs associated with specific phenotypic traits and by inferring its level of inbreeding, compared to other breed and village dogs (*12*). Our results suggest that the degree of artificial selection and controlled breeding during the Neolithic was similar to that observed in modern free-living dogs. In addition, the Newgrange dog did not possess variants associated with modern breed-defining traits including hair length or coat color. And though this dog was likely able to digest starch less efficiently than modern dogs, it was more efficient than wolves (*12*).

80   A phylogenetic analysis, based on 170k SNPs revealed a deep split separating the modern
81 Sarloos breed from other dogs (Fig. 1a). This breed - created in the 1930s in the Netherlands -
82 involved breeding German Shepherds with captive wolves (*13*), thus explaining the breed's
83 topological placement. Interestingly, the second deepest split (evident on the basis of both the
84 170K SNP panel – Fig 1a - and genome-wide SNPs - Fig. S4) separates modern East Asian and
85 Western Eurasian (Europe and the Middle East) dogs. Moreover, the Newgrange dog clusters
86 tightly with Western Eurasian dogs. We used Principal Component Analysis (PCA), D-statistics
87 and *TreeMix* (*12*) to further test this pattern. Each of these analyses unequivocally placed the
88 Newgrange dog with modern European dogs (Figs. S5, S6, S7). These findings demonstrate that
89 the node separating the East Asian and Western Eurasian clades is older than the Newgrange
90 individual; directly radiocarbon dated to ~4,800 years ago.

91   Other nodes leading to multiple dog populations and breeds (including the basal breeds
92 (*1*) such as Greenland Sledge dogs or Siberian Husky; Fig. 1a) are poorly supported, suggesting
93 that these breeds likely possess mixed ancestry from both Western Eurasian and East Asian dog
94 lineages. To further assess the robustness of the deep split and those nodes associated with the
95 potentially admixed lineages, we defined Western Eurasian and East Asian "core" groups (Fig.
96 1a) supported by the strength of the node leading to each cluster (*12*). We then used D-statistics
97 to assess the affinity of each population to either Western Eurasian or East Asian core groups
98 (*12*). The results of this analysis again revealed a clear East-West geographic pattern across
99 Eurasia associated with the deep phylogenetic split (Fig. 1b). Breeds such as the Eurasier,
100 Greenland Sledge dogs and Siberian Huskies (all basal breeds from Northern regions(*1*)),
101 however, possess strong signatures of admixture with the East Asian core samples (Fig. S11), as
102 do populations sampled in East Asia that clustered alongside Western Eurasian dogs (*e.g.* Papua
103 New Guinean village dog; Fig. 1a).

104   We used the Multiple Sequentially Markovian Coalescent (*MSMC*)(*12*, *14*) to reconstruct
105 the population history of East Asian and Western Eurasia dogs. An analysis of individual high
106 coverage genomes demonstrated a long, shared population history between the Newgrange dog
107 and modern dogs from both Western Eurasia and East Asia (Fig. S15). A reconstruction using
108 two genomes per group improved the resolution for recent time periods (Fig. 2a) and revealed a
109 bottleneck in the Western Eurasian population, following its divergence from the East Asian
110 core. A similar bottleneck observed in non-African human populations has been interpreted as a
111 signature of a migration out of Africa (*15*). We therefore speculate that the analogous bottleneck
112 observed in our dataset could be the result of a divergence and subsequent migration from east to
113 west; supporting suggestions drawn from recent analyses of modern dog genomes (*8*, *9*, *16*).

114   We then used *MSMC* to compute divergence times as a mean to assess the time frame of
115 the shared population history among dogs, and between dogs and wolves. To obtain reliable time
116 estimates, we used the radiocarbon age of the Newgrange dog to calibrate the mutation rate for
117 dogs (*12*)(Fig. S16). This resulted in a mutation rate estimate of between 0.3×10^{-8} and 0.45×10^{-8}
118 per generation - similar to that obtained with an ancient grey wolf genome (*17*). Using this
119 mutation rate, we calculated the divergence time between the two modern Russian wolves (*18*)
120 used in this study and the modern dogs to be 60,000-20,000 years ago (Fig. S17; Fig. 2b).
121 Importantly, this date should not be interpreted as a time frame for domestication, since the
122 wolves we examined may not have been closely related to the population that gave rise to dogs
123 (*6*).

124   These analyses also suggested that the divergence between the East Asian and Western
125   Eurasian core groups (~14,000-6,400 years ago) occurred commensurate, or several millennia
126   after the earliest known appearance of domestic dogs in both Europe (>15,000 years) and East
127   Asia (>12,500 years) (*1*) (Figs. S17, 2b). In addition, admixture signatures from wolves into
128   Western Eurasian dogs most likely pushed this estimated time of divergence deeper into the past
129   (*12*) meaning that the expected time of divergence between East and Western cores is likely
130   younger than our estimate. These results imply that indigenous populations of dogs were already
131   present in Europe and East Asia during the Palaeolithic (prior to this genomic divergence).
132   Under this hypothesis, this early indigenous dog population in Europe was replaced (at least
133   partially) by the arrival of East Eurasian dogs.

134   To investigate this potential replacement, we sequenced and analyzed 59 hyper-variable
135   mtDNA fragments from ancient dogs spread across Europe and combined those with 167
136   modern sequences (*12*). Each sequence was then assigned to one of four major well-supported
137   haplogroups (A-D) (*19*). While the majority of ancient European dogs belonged to either
138   haplogroup C or D (63% and 20%, respectively), most modern European dogs possess sequences
139   within haplogroups A and B (64 and 22% respectively) (Fig. 2c, d, e). Using simulations, we
140   showed that this finding cannot be explained by drift alone (*12*). Instead, this pattern arose from
141   clear turnover in the mitochondrial ancestry of European dogs, most likely as a result of an
142   arrival of East Asian dogs. This migration led to a partial replacement of ancient dog lineages in
143   Europe that were present by at least 15,000 years ago (*1*).

144   Though the mtDNA turnover is obvious, the nuclear signature reveals an apparent long-
145   term continuity. Assessments of ancestry in humans have demonstrated that major (nuclear)
146   turnovers can be difficult to detect without samples from the admixing population (*11*). A
147   genome-wide PCA analysis revealed that PC2 clearly discriminates the Newgrange dog from
148   other modern dogs (Fig. S8), suggesting that this individual possessed ancestry from an
149   unsampled population.

150   Our MSMC analysis reveals that the population split between the Newgrange dog and the
151   East Asian core (as measured by cross coalescence rate [CCR]) is older (on average) than the
152   split between modern Western Eurasian and East Asian lineages (Fig. 2b). Simulations suggest
153   that this pattern could be explained by a partial replacement model in which the Newgrange dog
154   retained a degree of ancestry from an outgroup population (Fig. S20a,b), that was different from
155   modern wolves (*12*). Alternatively, this pattern could also be explained by secondary gene flow
156   from Asian dogs into modern European dogs (Fig. S20c). Nevertheless, simulations show that
157   secondary gene flow has a smaller effect on CCR than the partial replacement model (Fig.
158   S20b,d). Moreover, secondary gene flow cannot explain the placement of the Newgrange dog on
159   our genome-wide PCA (Fig. S8). Overall, these observations are consistent with a scenario in
160   which the Newgrange dog retained a degree of ancestry from an ancient canid population that
161   falls outside of the variation of modern dogs, but that is also different from modern wolves. This
162   pattern also suggests that the replacement of European indigenous Palaeolithic dogs may not
163   have been complete.

164   To assess the consilience between our results and the archaeological record, we compiled
165   evidence for the earliest dog remains across Eurasia (Fig. 3a). We found that while dogs are
166   present at sites as old as 12,500 years in Eastern Eurasia (China, Kamchatka and East Siberia)
167   and 15,000 years in Western Eurasia (Europe and Near East) dog remains older than 8,000 years
168   have yet to be recovered in Central Eurasia (Fig. 3a; Table S7). Combined with our DNA

analyses, this observation suggests that two distinct populations of dogs were present in Eastern and Western Eurasia during the Palaeolithic.

The establishment of these populations is consistent with two scenarios: a single origin of Eurasian dogs followed by early transportation, founder effects, isolation and drift, or two independent domestication processes on either side of Eurasia. In the first scenario, the archaeological record should reveal a temporal cline of the first appearance of dogs across Eurasia stemming from a single source. Given the current lack of dog remains prior to 8,000 years ago in Central Eurasia, a scenario involving a single origin followed by an early transportation seems less likely.

Given our combined results, we suggest the following hypothesis: two genetically differentiated and potentially extinct wolf populations in Eastern (*8*, *9*) and Western Eurasia (*7*) may have been independently domesticated prior to the advent of settled agriculture (Fig. 3a). The eastern dog population then dispersed westward alongside humans, between 6,400 and 14,000 years ago, into Western Europe (*10*, *11*, *20*) whereupon they partially replaced an indigenous Palaeolithic dog population. Our hypothesis reconciles previous studies that have suggested domestic dogs originated in East Asia (*9*, *19*) and Europe (*7*). For numerous reasons, the null hypothesis should be that individual animal species were domesticated just once (*21*). The combined genetic and archaeological results presented here, however, suggest that dogs, like pigs (*22*), may have been domesticated twice. Nevertheless, given the complexity of the evolutionary history of dogs and uncertainties related to mutation rates, generation times and the incomplete nature of the archaeological record, our scenario remains hypothetical. Genome sequences derived from ancient Eurasian dogs and wolves will provide the necessary means to assess whether dog domestication occurred more than once.

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359 **Fig. 1: Deep split between East Asian and Western Eurasian dogs.*a.*** A neighbour-joining
360 tree (with bootstrap values) based on Identity by State (*12*) of 605 dogs. Red and yellow clades
361 represent the East Asian and Western Asian core groups respectively (*12*). ***b.*** A map showing the
362 location and relative proportion of ancestry (mean D-values) of dogs (Fig. S10). Positive values
363 (red) indicate that the population shares more derived alleles with the East Asian core while
364 negative values (yellow) indicate a closer association with the Western Eurasian core.

365 **Fig. 2: Effective population size, divergence times and mtDNA. *a.*** Effective population size
366 through time of East and Western Eurasian dogs and wolves with MSMC. ***b.*** Cross-coalescence
367 rate (CCR) per year for each population pair in Fig. 2a. The CCR represents the ratio of within
368 and between population coalescence rates (CR). The ratio measures the age and pace of
369 divergence between two populations. Values close to 1 indicate that both within and between CR
370 are equal meaning the two populations have not yet diverged. Values close to 0 indicate that the
371 populations have completely diverged. ***c.*** Bar plot representing the proportion of mtDNA
372 haplogroups at different time periods. ***d.*** Locations of archaeological sites with haplogroup
373 proportions. ***e.*** Location of modern samples with haplogroup proportions.

374 **Fig. 3: Archaeological evidence for the first appearance of dogs across Eurasia and a model
375 of dog domestication. *a.*** Map representing the geographic origin and age of the oldest
376 archaeological dog remains in Eurasia (*12*). ***b.*** A suggested model of dog domestication under
377 the dual origin hypothesis. An initial wolf population split into East and West Eurasian wolves
378 that were then domesticated independently before going extinct (as indicated by the † symbol).
379 The Western Eurasian dog population (European) was then partially replaced by a human-
380 mediated translocation of Asian dogs at least 6,400 years ago, a process that took place gradually
381 after the arrival of the eastern dog population.

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383 **Supplementary Materials:**

384 Materials and Methods

385 Figs. S1-S29

386 Tables S1-S7

387 References (23-110)