

widespread electrification, energy conservation and the removal of some CO₂ from the atmosphere.

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The author declares no competing interests.

Ancient DNA

Dogs have deep roots in ice-age Europe

Mikkel-Holger S. Sinding & Lauren M. Hennelly

Two studies report the oldest dog genomes ever to be sequenced, representing leaps in scientists' understanding of the animal's origins. See p.986 & p.995

Dogs have a special place in human history. They were the first animals to be domesticated and are commonly found in our homes today. But where did dogs come from? What were the earliest dogs like? Despite numerous resourceful studies across disciplines, the enigmatic origin of these animals is still unclear. Writing in *Nature*, Bergström *et al.*¹ and Marsh *et al.*² break this barrier, getting closer in time to the origin of dogs than ever before and charting their early evolution in western Eurasia.

Between roughly 10,000 and 4,000 years ago, agriculture spread across Europe. In an impressive effort, Bergström and colleagues (page 986) analysed and directly compared genome-wide data from more than 200 ancient canids, finding dozens of dogs (*Canis lupus familiaris*) that lived in Europe before and after this defining transition in human history. For humans, the shift to farming was accompanied by large-scale immigration from southwest Asia and, in many places, a major shift in human genetic groups^{3,4}. Remarkably, Bergström *et al.* find that this was not the case for early dogs: the ancestry of the ancient dogs that were associated with farmers can be traced back to dogs that lived more than 14,000 years ago and were linked to hunter-gatherer populations. This suggests that there was genetic continuity for dogs in ancient Europe, rather than a sharp population shift like that found in humans. In this fascinating case, human history and dog history differ; by contrast, in Asia⁵ and the Americas⁶, dog history mostly reflects the history of human mobility and cultural transitions. Although

there have clearly been genetic contributions from other dog populations over time, the oldest ancestry of modern European dogs can be traced to the earliest known dogs in western Eurasia.

In the second study, Marsh and colleagues (page 995) report the oldest dog genome that has been sequenced so far, dating to almost 16,000 years ago, from Anatolia in south-western Asia. Using this genome and a newly sequenced one from a dog that lived around 14,000 years ago in Great Britain, Marsh *et al.* illuminate the early history of dogs in Europe. These two ancient genomes belong to one of two major dog lineages – the western Eurasian lineage – suggesting that it can be traced back to almost 16,000 years ago. A stunning finding is that these two ancient dogs, separated by more than 3,000 kilometres, were closely related genetically. This suggests that the population from which they both originated had quickly expanded across vast distances, and that dogs must have been passed on among diverse cultures and groups of people.

Together, Marsh *et al.* and Bergström *et al.* provide insights into dog domestication by positioning the oldest dog genomes in place and time in human and dog history. In the past few years, analyses of numerous ancient genomes from Eurasia and North America have shown that, by around 10,000 years ago, dogs were already widely distributed and had diversified into distinct genetic groups^{7,8}. Evidently, dog domestication pre-dates this and probably originated in Eurasia, the centre of this diversification. Of modern dogs, those in eastern Asia have the greatest genetic diversity, so it was long assumed that this was where dogs originated⁹. However, no dog remains more than

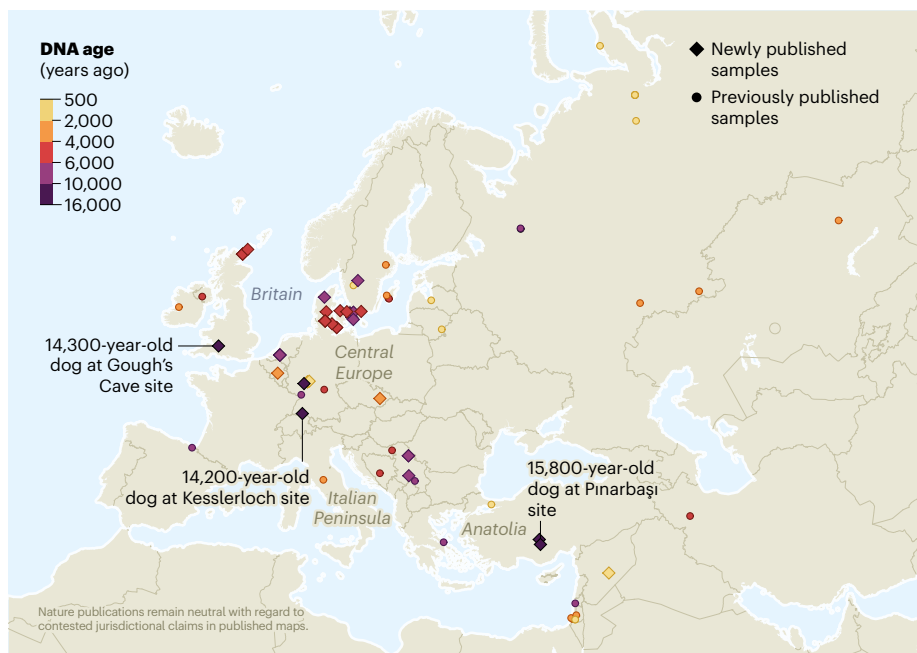


Figure 1 | Ancient dog genomes. The map of Eurasia shows the locations and ages of ancient dog (*Canis lupus familiaris*) genomes that were analysed by Bergström *et al.*¹ and Marsh *et al.*² (some sites have more than one sample). Among them are the oldest dog genomes ever to be sequenced, located in the region of Anatolia (around 15,800 years old), the island of Britain (around 14,300 years old) and present-day Switzerland (around 14,200 years old). Genetic analyses reveal that an ancient dog population was distributed widely across western Eurasia before the introduction of agriculture, and that much of the ancestry of modern western dogs can be traced to this population.

around 10,000 years old from eastern Eurasia have so far been genetically confirmed⁵. These two latest studies, which genetically confirm dogs in Europe and southwestern Asia that are between 14,000 and 16,000 years old (Fig. 1), put a fresh focus on western Eurasia in scientists' quest to understand dog origins.

So what lies next? So far, no one has identified the ancestral population of grey wolves (*Canis lupus*) that all dogs are descended from, or determined where or when this population lived. However, both studies point in the same direction, towards western Eurasia. For example, Bergström and colleagues' oldest dog, from around 14,000 years ago in what is now Switzerland, shares ancestry with modern-day European dogs, suggesting that this lineage has persisted in Europe for 14,000 years, rather than arriving later with other dog populations.

Finally, Marsh and colleagues put a spotlight on DNA from mitochondria, the cellular structures that carry a small amount of maternally inherited genetic material. The mitochondrial genomes of the oldest dogs enabled the authors to reassess previously published mitochondrial genomes of ancient canid remains that were suspected to be those of early dogs. Using this approach, the authors confirmed that other canid remains from around 14,000 years ago have mitochondrial genomes that are closely related to those of the two oldest dogs.

This further emphasizes the idea that dogs were already widely distributed 14,000 years ago in western Eurasia, ranging from Britain to central Europe, the Italian peninsula and into Anatolia. Together, these two studies reveal that modern Western dogs trace their roots back to the late Pleistocene period, before the end of the last ice age – a conclusion drawn from the earliest dogs that have ever been documented.

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The authors declare no competing interests.

Geoengineering

A process for storing CO₂ underground in dry places

Juliane Weber

Carbon dioxide has been turned into minerals in Earth's subsurface using recirculating water flow – a viable way to sequester this greenhouse gas in water-scarce areas. **See p.954**

Many countries agree that carbon dioxide will need to be stored deep underground in the next two to three decades to mitigate increases in atmospheric CO₂ levels. One method for doing this involves dissolving CO₂ in water and injecting the solution into porous rock in Earth's subsurface, where it reacts to form solid carbonate minerals. However, the amount of water used in previously tested processes is 20–50 times the mass of the CO₂ that is sequestered, limiting the feasibility of the process in regions that have limited water supplies. On page 954, Oelkers *et al.*¹ report the first pilot demonstration of an industrial process in which the injected water is recirculated – greatly reducing the water demand and opening up CO₂ storage as an environmentally feasible strategy for mitigating climate change, even in arid regions.

Two main methods for storing CO₂ underground through mineralization are currently under consideration: injection of water-dissolved CO₂; and injection of supercritical CO₂, a fluid phase of CO₂ that has both gas and liquid properties. The first method was tested in the 'CarbFix' pilot project² in Iceland between 2011 and 2014 (Fig. 1a), and a follow-up project (CarbFix2) that is testing larger injection volumes is under way. A pilot project³ of the second method was conducted near Wallula in Washington state between 2013 and 2015.

The difficulty with the second method is that supercritical CO₂ is buoyant, which means that it tends to rise back to the surface. A cap of impermeable rock above the storage site is therefore needed to prevent this from happening. By contrast, aqueous CO₂ solutions are more dense than water and are therefore not buoyant, which means that a cap is not needed. However, a disadvantage of sequestering dissolved CO₂ underground is the huge amount of water required to do so – for the original CarbFix project, 25 tonnes of water were needed for each tonne of CO₂ that was sequestered⁴.

This requirement is a problem because water is a precious resource that is in high demand

– especially freshwater, which makes up less than 3% of Earth's total available water. The main factors that are driving this scarcity are the increasing world population, improving living standards, changing consumption patterns and increases in irrigation for agriculture⁵. However, the problem is not that the overall volume of freshwater is too small to meet demands, but that the freshwater is not equally distributed around the world. Arid regions have therefore become particularly vulnerable to changes in water availability over the past two decades.

Oelkers *et al.* report a pilot study of underground CO₂ storage in which the water used to dissolve CO₂ is circulated back to the surface after injection. The water is then reused in subsequent injections, thereby reducing the amount that needs to be used (Fig. 1b). The test site is in western Saudi Arabia, an arid region with a historically strong petroleum-refining industry that emits large quantities of CO₂.

The authors' process makes use of two fundamental properties of aqueous CO₂: its acidity and its density. As many people with acid reflux know, sparkling water – which is a CO₂ solution – can make their symptoms worse, in part because of its acidity. In Oelkers and colleagues' study, acidic CO₂ solution that is injected into the local bedrock dissolves the surrounding silicate minerals. This releases magnesium and calcium ions, which react with the dissolved CO₂ to form carbonate minerals. These carbonates precipitate out of solution as solids, thereby locking CO₂ into the subsurface. After this, the resulting CO₂-lean water is pumped back to the surface. Because CO₂-rich water is denser than CO₂-lean water, it has a low propensity to rise to the surface, minimizing the risk of leakage that would return CO₂ to the atmosphere.

In Oelkers and colleagues' study, a drilled well (the injection well) was used to inject CO₂-rich water into the subsurface, and another (the production well) was used to remove CO₂-lean water. A connecting pipe transported water from the production well back to the