from their data that phosphates are indeed abundant in Enceladus's ocean, consistent with the high concentrations of carbonate and bicarbonate ions in the water.

The researchers also carried out laboratory experiments in which material from a chondrite (used as an analogue of Enceladus's rocky core) was exposed to sodium carbonate solution, and observed that the levels of dissolved phosphate increased with the carbonate content. These experiments, together with theoretical considerations put forward by Postberg and colleagues, confirmed that substantial sequestration of dissolved calcium ions into carbonate minerals favours the release of phosphate ions from calcium phosphate minerals. The results are consistent with earlier predictions of elevated dissolved phosphate levels based on modelling of the geochemistry of soda lakes on Earth[4] and of the ocean on Enceladus[9].

One factor that is not considered in Postberg and colleagues' analysis, or in the previous modelling studies[9], is whether the abundance of dissolved phosphates on Enceladus is increased by the incorporation of calcium ions into organic complexes – as has been suggested to happen in soils[11]. Another unconsidered factor is that the sodium carbonate in the ocean water would promote the desorption of phosphate ions from organic and other ocean-floor materials. This type of effect is helpful in the laboratory, where sodium carbonate solutions are used to extract soluble phosphates from soils[12]. Other limitations of the new study are that only nine phosphorus-containing icy grains have been identified in the Cassini CDA data set, and the authors had to make assumptions in their modelling to determine the composition and abundances of the phosphorus compounds. Future *in situ* investigations of the plume, or of plume materials returned to Earth, should therefore probe the details of Enceladean ocean chemistry and the identities of the phosphorus compounds.

Postberg and co-workers' discovery of phosphates in the plume of Enceladus supports the idea[5,7,9] that a soda ocean is sandwiched between the moon's icy shell and a core of rock that contains phosphate and carbonate minerals (Fig. 1). In turn, the presence of a soda ocean implies that Enceladus formed from CO_2–H_2O ices that are common in comets in the outer Solar System. If Enceladus did originate in the outer Solar System, that would suggest that, as is the case for comets[13], up to around 50% of the interior mass of the satellite is organic matter – consistent with the presence of organic compounds in the plume[10]. The new results also imply that aqueous phosphates could be abundant on other ice-covered bodies in the outer Solar System thought to have subsurface oceans, increasing the prospects of their habitability.

The discovery of sodium phosphates in the Enceladean plume lends weight to the idea that any sodium phosphates found in other extraterrestrial settings would have precipitated from soda solutions. The presence of sodium-bearing phosphates and abundant carbonates in samples returned from the asteroid Ryugu indicates that iron phosphides in the asteroid material have undergone aqueous oxidation to form phosphates[14]. Perhaps these sodium phosphates precipitated from a sodium-rich solution within Ryugu's parent body, which had formed in the outer Solar System from CO_2–H_2O ices and other materials[1,14].

Similarly, if sodium phosphates or carbonates were found in rock samples from Venus, this would suggest that soda lakes or seas once existed on the currently dry planet. This would be interesting because the sodium carbonate in such reservoirs could have formed through the sequestration of an early CO_2-rich atmosphere – and would thus provide crucial information about the enigmatic history of our sister planet. In turn, the apparent lack of sodium phosphates in rock samples from Mars does not support the idea[3] that an early dense, CO_2-rich atmosphere[15] was consumed to form soda solutions and corresponding salts.

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Ancient DNA

Onset of farming in northwest Africa traced

Louise Humphrey & Abdeljalil Bouzouggar

Genomic data from bones and teeth found at archaeological sites across Morocco paint a picture of how Neolithic farmers and pastoralists spread into northwest Africa that is more complex than previously thought. **See p.550**

The shift in human cultures from hunter-gatherer lifestyles to those based on the cultivation and husbandry of domesticated plants and animals is known as the Neolithic or agricultural transition. How Neolithic lifestyles spread into northwest Africa has been unclear, with archaeological findings providing conflicting evidence for both the migration of farmers into the area (demic diffusion) and the adoption of a Neolithic lifestyle by local foraging groups (cultural diffusion)[1]. Ancient human DNA could help to settle the debate. On page 550, Simões *et al.*[2] describe human genomic data from three previously unsampled archaeological sites in Morocco, dated to between 7,600 and 5,700 years ago – around the time when farming became established in the region[3]. The data provide an opportunity to refine and expand previous perspectives on the arrival and spread of Neolithic and pastoralist lifestyles in Morocco.

Previously, genomic data had been recovered only from three prehistoric sites in Morocco[4,5]. The oldest site, Taforalt – a cave in northeastern Morocco that houses an ancient cemetery – dates to close to the end of the last glacial period, about 14,500 years ago[4]. The DNA obtained at this site came from seven people belonging to a group called Iberomaurusian hunter-gatherers. The analysis revealed ancestry related to both sub-Saharan African groups and hunter-gatherer populations from the Levant (an area bordering the eastern Mediterranean that encompasses the land bridge between western Africa and Eurasia).

The second site, Ifri n'Amr o'Moussa in western Morocco, yielded DNA dating to about 7,000 years ago[5]. These early Neolithic

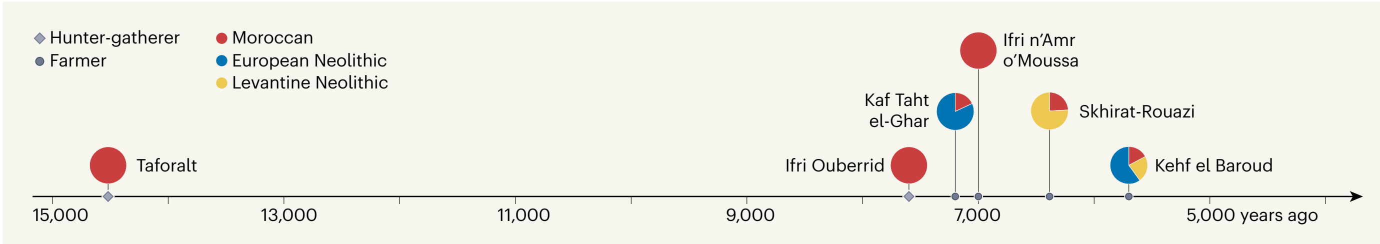

Figure 1 | Genomic data from the Neolithic transition in northwest Africa. Analysis of ancient DNA can help to reveal how people in Morocco transitioned from hunter-gatherer lifestyles to Neolithic farming culture. Simões *et al.*[2] extracted and profiled DNA from human bones and teeth found at four archaeological sites across Morocco, adding to existing genomic data for one of these sites and two others. The pie charts along this timeline indicate the ancestry of the people whose DNA was profiled at each site. The data suggest a long period of population continuity and isolation in hunter-gatherer groups between 14,500 and about 7,000 years ago. Neolithic lifestyles were introduced by farmers from Europe (as seen at Kaf Taht el-Ghar) and subsequently adopted by local communities (as seen at Ifri n'Amr o'Moussa). The arrival of more-recent ancestry from the Levant coincided with the spread of cattle pastoralists into the region.

farmers had a genetic profile similar to that of the Taforalt group, demonstrating population continuity in northwest Africa for a period of at least 7,000 years and suggesting that the onset of the Neolithic transition in Morocco involved the adoption of agricultural innovations by local hunter-gatherers, rather than demic diffusion. By contrast, DNA from a 5,700-year-old farming community from Kehf el Baroud in northern Morocco presented a strikingly different genetic profile, consistent with migration of farmers into the region during the Early or Middle Neolithic[5].

Simões *et al.* retrieved genetic data from the bones and teeth of one individual found at Ifri n'Amr o'Moussa and eight more from three previously unsampled sites: the Ifri Ouberrid cave; the early Neolithic site of Kaf Taht el-Ghar; and a Middle Neolithic necropolis at Skhirat-Rouazi (Fig. 1). Importantly, all of the bones and teeth were either dated directly by radiocarbon analysis or located in well-dated archaeological deposits, ensuring a direct link between the genomic evidence and cultural context.

The authors extracted DNA from a small human bone from Ifri Ouberrid cave that was directly dated to about 7,600 years ago — the period immediately preceding the first evidence for farming in Morocco. This bone yielded a genomic profile similar to those gathered from Taforalt and Ifri n'Amr o'Moussa (including the new profile from this site generated by Simões and colleagues), providing further evidence for long-term genetic continuity and population isolation in the region.

This finding is consistent with archaeological evidence, which indicates persistent cultural behaviours over a similar period in northwest Africa. These behaviours include stone-tool industries based on bladelets[6] and cultural modification of the dentition — Iberomaurusian hunter-gatherers practised deliberate removal of two central teeth in the upper jaw, and this highly visible signal of social identity spread across northwest Africa into the Sahara, continuing in a modified form in some Neolithic groups[7].

The Kaf Taht el-Ghar site pre-dates Ifri n'Amr o'Moussa by at least 100 years, and has yielded archaeological evidence for cultivation of domestic cereals, animal husbandry and Cardial-impressed pottery, which are all hallmarks of the Neolithic period. Simões and colleagues found that four individuals from Kaf Taht el-Ghar derived about three-quarters of their genetic ancestry from European Neolithic populations. The genetic make-up of the individuals from Kaf Taht el-Ghar provides direct evidence for the migration of European farmers to Morocco, most probably using contact routes across the western Mediterranean established shortly before the start of the Neolithic transition[3]. The individuals also derived between 15% and 27% of their genetic ancestry from pre-Neolithic groups in Morocco, and their mitochondrial DNA (a type of DNA housed in cellular organelles and passed down the maternal line) represented both local and incoming groups. Together, these data demonstrate genetic mixing between the local population and the incoming Neolithic farmers.

The authors' analysis of three individuals from Skhirat-Rouazi, dated to about 6,400 years ago, reveals ancestry derived from Neolithic groups from the Levant — potentially associated with the arrival of cattle pastoralists from the Sahara. Ceramics found in the burials at Skhirat-Rouazi display features that echo ceramic traditions from the Sahara, supporting this premise[8]. The spread of pastoralist groups within the Sahara and migration into new areas occurred during periods of increasing dryness towards the end of the most-recent African humid period[9], which ended around 5,500 years ago. Finally, the authors demonstrated that the genetic ancestry of the Late Neolithic population from Kehf el Baroud incorporates both pre-Neolithic populations from the region and incoming Neolithic groups from Europe and the Levant, demonstrating genetic mixing of all three groups in this part of Morocco by 5,700 years ago.

This research points to a more complex and dynamic pattern of human migration and admixture than previously recognized in Morocco. After a prolonged period of at least 7,000 years of continuity and isolation, the genetic and cultural landscape of Morocco changed drastically between 7,500 and 5,700 years ago, with the arrival of Neolithic groups and lifestyles from both Europe and the Levant. Human burials and isolated human bones and teeth from the past 15,000 years are well documented in archaeological sites across North Africa, and so the picture might become yet-more nuanced as further genomic data are retrieved and analysed.

The success of recent studies[4–6] and continued improvements in recovery of ancient DNA raise hopes for the retrieval of even older human DNA in this region. There are currently few well-dated human fossils that pre-date the Taforalt population, but the many active multinational interdisciplinary archaeological projects led by scientists in Morocco, Algeria and Tunisia provide potential for ancient human discoveries and further insights.

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