

ANTHROPOLOGY

# *A composite window into human history*

## Better integration of ancient DNA studies with archaeology promises deeper insights

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Over the past decade, the ability to recover whole genomes from ancient remains has emerged as a powerful tool for understanding the human past. From a strictly biological perspective, the sequencing of ancient genomes has resolved the dispute over our evolutionary relationship with Neandertals, revealed the extent of gene flow within and between modern and archaic humans, shed light on genetic and health consequences of this admixture, and uncovered genomic changes in recent human evolution (*1*). More generally, the results have made clear that over the course of human history, moving and mating have been more the rule than the exception. The possible benefits of ancient DNA (aDNA) research for archaeology are enormous. Why, then, have aDNA approaches to archaeological questions occasionally raised eyebrows among archaeologists (*2, 3*)?

Most obviously, there is far more to human history than our biology, especially over the past ~100,000 years, during which culture has played an increasingly dominant role in human evolution. Many of archaeology's "grand challenges" (*4*) concern the understanding of human cultures and cultural change. Although aDNA research can contribute to addressing these challenges, its potential has yet to be fully realized. The main obstacles are fourfold: the problem of scale; the challenge of aligning different analytical

PHOTO: JURAJ LIPTÁK/LANDESAMT FÜR DENKMALPFLEGE UND ARCHÄOLOGIE SACHSEN-ANHALT

Double burial of an adult woman and a juvenile male with rich grave goods, including hundreds of shell sequins. Late Neolithic Corded Ware culture, ca. 4760 to 4680 before present, Karsdorf, Germany.

units; the difficulty of discerning causal connections between population and cultural changes; and the frequent lack of genuine collaboration between fields.

Integration of aDNA and archaeology is arguably least complicated at the smallest spatial scale. aDNA analyses of individuals found at single archaeological sites, bolstered by high-resolution radiocarbon chronologies and careful attention to archaeological context, have successfully documented detailed genealogies. The results have revealed previously unseen hereditary relationships and elements of social structure and political hierarchy (*5*).

However, aDNA research has mainly addressed questions at much broader scales. These studies seek to examine demographic processes of migration, admixture, and population turnover (*6*), and their effects on cultures across regions and through time. aDNA studies that reveal ancestral affinities and demographic structure are valuable in ascertaining population origins and movements into continents and regions devoid of people (e.g., Australia, the Americas, islands of the Pacific) (*7*, *8*), as well as dispersals across already-occupied landscapes (e.g., in the past 10,000 years in Africa and Europe) (*9, 10*). But the explanatory value of identifying such broad spatiotemporal patterns in biological populations is limited by the difficulty of linking these to specific changes seen archaeologically in, for example, economic adaptations or material culture, or to the natural and social environments in which these changes took place (*3*).

A central problem is the methodological challenge of aligning very different types of evidence. On the one hand, past populations identified by ancient genomes are biological units whose members were related by degrees that can be precisely measured. These populations can be complex entities: Differences in class, religion, language, and culture may (or may not) limit mating and gene flow. On the other hand, archaeological cultures are classificatory labels based on material culture that can vary widely over space and time and even within cultural units (*2, 3*). We cannot assume that individuals who shared material culture traits were part of the same biological population: One can have similar traits without relatedness (owing to convergence or exchange) and relatedness without similarity in traits (owing to divergence).

Furthermore, in contrast to biological relatedness, there is no commonly accepted measure of cultural relatedness. Equally, language groups cannot necessarily be conflated with biological populations, material assemblages, or even social units (*11*). Geneticists who venture across disciplinary borders without local guides may treat these classificatory units as analytically comparable and coincident in scale. They are not (*2, 3*).

Geneticists are often keen to use aDNA to understand the causes and mechanisms of demographic and cultural change. But archaeologists long ago abandoned the idea that migrations or encounters between populations are a necessary or sufficient explanation of cultural change. aDNA evidence of admixture, and perhaps even migration, is important not because it provides an explanation of cultural change. Rather, it is important because it provokes additional, more significant questions, such as what processes may have triggered movements of people, how these movements unfolded, and what the broader social and economic consequences were for the populations involved.

Consider the Neolithic of western Eurasia, which has seen the greatest amount of aDNA research to date (*6*). aDNA research has confirmed large-scale population movements in the sixth millennium BCE in southeastern and central Europe, involving entire social groups that brought a package of early farming culture but that only admixed with local foraging populations to a limited extent (*12*). By contrast, the introduction of new genes from central Eurasia to Europe during the third millennium BCE unfolded in a markedly different way. This migration, more restricted in time and space, may have involved more men than women, resulting in high levels of admixture with local populations (*9*). In this case, dispersal was independent of any uniform economic transformation, and cultural changes were not homogeneous across regions (*2, 13*) (see the figure and photo).

In the above cases, aDNA evidence has pointed to a previously unknown diversity and interplay of demographic factors shaping specific episodes of human expansion. Yet, understanding the causes and consequences of these population movements requires a broader investigation of the many factors that may have played a role. These factors include the environmental and social contexts in which expansion occurred, the details of its timing and logistics, and how new resources and landscapes were managed and cultural knowledge transmitted. Hence, it requires evidence from archaeology, paleoecology, and other fields to supplement and complement aDNA data. And that entails effective collaboration, one that goes beyond archaeologists serving as passive sample providers.

In these dynamic early years of aDNA research, there are few illustrations of such a deeply integrated approach (*5*). One example is Le Roy *et al.*'s recent archaeological, osteological, and genetic study of 55 individuals at the fifth-millennium BCE cemetery of Gurgy, France (*14*). This study revealed a diversity of mitochondrial genomes, yet homogeneity in diet and grave goods. This evidence shows that different in-migrating farming populations mixed with local foragers. This process helped to maintain the demographic viability of the overall population. Further studies of settlements and land use in the area, as well as additional isotopic, genetic, and skeletal

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analyses, would help to more fully explore the cultural and biological mobility over time. These could explain the presence of DNA diversity despite cultural homogeneity.

Given the power of an integrated approach, we believe it is time for a deeper, more sustained collaboration between geneticists and archaeologists. aDNA is a valuable addition to the interdisciplinary toolbox for studying past human societies, but this research cannot be done in analytical isolation or inductively. An approach that produces hypotheses tested through analyses and integration of multiple lines of evidence, including aDNA, will result in far more robust conclusions.

In addition, hypothesis-driven collaboration has ethical implications. The archaeological record is a finite, common resource, and we must always aim to maximize information yields when we sample it. Also, analyses of ancient human remains are enhanced through systematic collaboration with descendant communities who are stakeholders in the outcome (*15*). Moreover, aDNA research produces data that are easily politicized (*3*). Although we cannot control misuse of evidence, we must make that evidence as robust and comprehensive as possible to minimize the possibility of misappropriation.

The days when virtually every aDNA study revealed facets of heretofore unknown population histories are ending. And by now, the finding that human history is a story of dispersal and admixture is no longer revelatory. We have an opportunity to jointly explore human history more deeply, and we should make the most of it. ■

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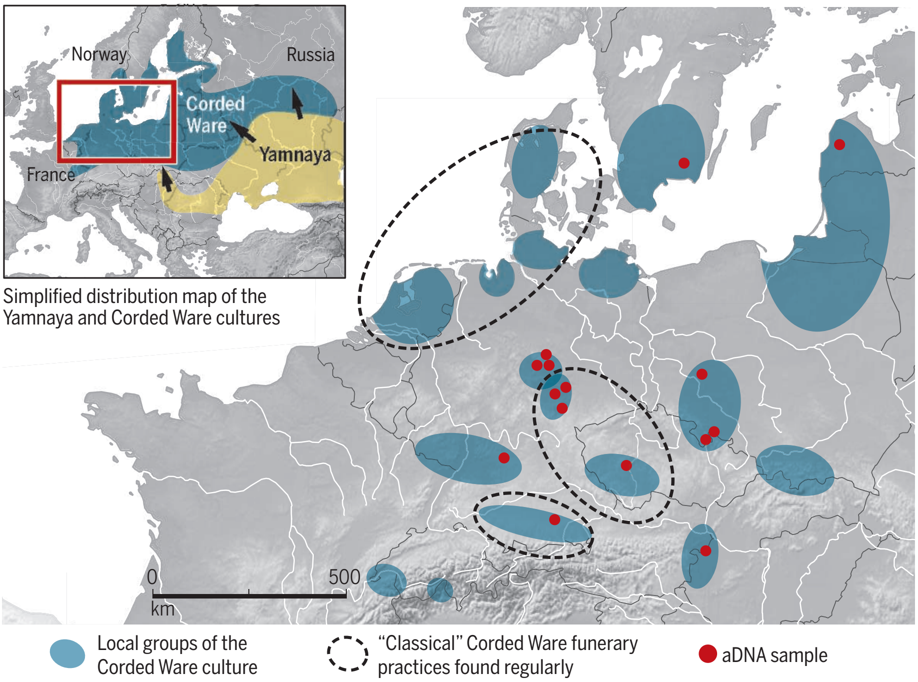
## Combining data from archaeology and aDNA research

During the third millennium BCE, groups scattered across central and northern Europe were part of the Corded Ware culture, which shared broad practices and artifacts, yet varied culturally by region. Limited aDNA sampling nonetheless emphasizes the biological homogeneity of these groups and their genetic affinity with groups of central Eurasia (the Yamnaya culture). Reconciling these differing lines of evidence will require greater collaboration between archaeologists and geneticists.




NANOMATERIALS

# Growing anisotropic crystals at the nanoscale

Single-nanoparticle imaging and theoretical modeling can guide synthesis strategies

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Technological prospects of metal nanoparticles (NPs) have stimulated intense research activities into their growth mechanisms to predict shape, size, and crystallinity. Of high interest are low-symmetry nanocrystals (NCs), which exhibit high-energy facets that are relevant in catalysis or plasmonic properties that are attractive for applications in areas such as biomedicine. Rodlike shapes are in principle most challenging because the high-symmetry face-centered cubic lattice of the metals of interest, such as gold, tends to form high-symmetry, compact NCs. To promote shape anisotropy, nucleation and growth are usually separated in the so-called seed-mediated growth, in which a metal precursor is reduced on preformed seeds in the presence of shape-directing additives. The growth of nanorods is a nonequilibrium process and remains poorly understood, which accounts for their limited reproducibility and yield. The required control over the crystal habit of the seeds and the effect of additives will necessitate insights from theoretical modeling as well as characterization, especially by state-of-the-art transmission electron microscopy (TEM).

In the early stages of growth, the 1- to 3-nm seeds grow to a critical diameter of 4 to 6 nm, which facilitates the emergence of well-defined crystal facets (see the figure, left panel). Shape bifurcation (symmetry breaking) can then take place, after which anisotropic products outnumber isotropic ones (*1*). As a rule of thumb, single-crystal seeds can evolve into either single-crystal


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