To curate the molecular past, museums need a carefully considered set of best practices

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Biomolecular research has sparked a methodological revolution in the field of anthropology, and museums are now faced with the curatorial challenge of conserving and evaluating materials for these new methods. Since 2010, hundreds of genome-wide datasets from ancient human samples have been published, and thousands more have been generated; doubling the amount of data in the field of paleogenomics now requires less time than the publication of a single article (1). Technological advances in laboratory and bioinformatic approaches have also led to a new era in paleomicrobiology, in which entire ancient microbial communities can be recovered from various substrates, such as calcified dental calculus (2). Increasingly, large-scale datasets for other biomolecules, such as proteins and metabolites, are generated and

Fig. 1. Museum collections staff stand among the anthropological collections at the Smithsonian's National Museum of Natural History. Museums are responsible for preserving collections and the information they contain for future generations. But in recent years, they've been given the increasingly challenging task of curating and conserving biomolecular data. Image credit: Chip Clark (Smithsonian Institution, Washington, DC).

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The authors declare no conflict of interest.

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integrated into multi-omic understandings of the human past (2).

Anthropological collections are important for science and society for reasons that include their potential applications for biomolecular research (3, 4). Ethical issues are central in the changing circumstances for ancient biomolecular information. Potential negative impacts on indigenous communities (such as when paleogenomic studies contradict traditional histories and undermine territorial or repatriation claims) have magnified the importance of community-based practices (5). Competition among ancient-DNA laboratories for museum samples has been likened to "the Wild West" (6), and more strictly regulating access to samples has been advocated to prevent "hoarding" (7). As stewards of collections that contain ancient biomolecules (e.g., isotopes, proteins, DNA, and metabolites), museums play a critical role among stakeholders in biomolecular research and should be responsive to such concerns (Fig. 1).

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Museums are also being inundated with destructive-sampling requests, underscoring the notion that collections and their biomolecules are finite resources. Anthropological collections, including ethnographic, archaeobotanical, and zooarchaeological, as well as human remains, are a source of unique insights into the history of our species, and it is an ethical imperative to preserve this information for future generations (8). Tasked with ensuring the scientific and societal longevity of their collections, museums consider a variety of criteria in making sampling decisions. Representing a unique perspective and a rich specimen repository, the position of museums in protecting, preserving, and providing materials for research should be included in biomolecular discussions.

Symposia such as our recent one at the 2018 meeting of the Society for American Archaeology suggest that an open dialogue about museum practices and policies is beneficial for all stakeholders. By drawing on examples from the Department of Anthropology at the Smithsonian Institution's National Museum of Natural History (NMNH), we hope to see more take part in this conversation. Researchers and curators need to better address the challenges of curating ancient biomolecules, and we should, as a professional community, work toward the development and dissemination of best practices.

Laws and Consultation

Although laws concerning human remains in museum collections have had the positive effect of increasing communication between researchers and indigenous communities, they specify only a minimum course of action for community engagement that often falls short of what is ethically appropriate (9). Paleogenomic researchers, whose studies may destructively sample bone, teeth, dental calculus, hair, soft tissues, and/or feces, have been encouraged to consult with descendant communities at the earliest stage of project design (5). Museums can be instrumental in facilitating these efforts, especially in cases in which it is unclear how or with whom researchers should engage.

At the NMNH, which is subject to the National Museum of the American Indian Act—the Smithsonian-specific counterpart to the Native American Graves Protection and Repatriation Act—the Department of Anthropology's Repatriation Office is represented on the destructive-sampling committee for requests that involve—or may involve—Native American remains. Culturally affiliated remains require consultation and support from the community. For remains that have not been culturally affiliated under NMNH's repatriation process, there is a longstanding practice of encouraging researchers to consult with representatives of the likely affiliated tribes. Additionally, NMNH provides a letter from the Smithsonian Institution's Native American Repatriation Review Committee encouraging researchers to consult with Native American communities, whether or not their research involves destructive sampling, and provides guidance of whom to contact in these communities.

Seeking Preservation

With each proposal for destructive sampling, a committee weighs the likely gain in scientific knowledge against the unquestionable loss of priceless and irreplaceable material. It is important to consider that one residue or substrate can be subjected to several different techniques to address very different questions. The petrous bone, for instance, has become the preferred sampling site for paleogenomic studies of ancient population history because of optimal preservation of endogenous, organismal DNA (10), but the bone can also be useful for stable isotope analysis as a supplement or proxy for teeth in reconstructing diet during early life (11), and it carries important morphological signals of population histories (12). If the entire inner ear is used for DNA extraction, this information is lost, and if sampling involves removal of a large part of the petrous bone, morphological information about sex and childhood disease may be lost as well (13). Likewise, well-preserved teeth can perform as well as petrous bones for paleogenomic research in some cases, but with a potential tradeoff in limiting their suitability for replicative or other types of analysis after destructive sampling (13).

Although the amount of sample needed for multi-omic analysis can be just a few milligrams, it may still represent a large proportion of the well-preserved biomolecules for that individual or even an entire collection. Our ongoing survey of NMNH's human skeletal remains, consisting of a cross-regional sample from North America, Europe, and Africa and encompassing

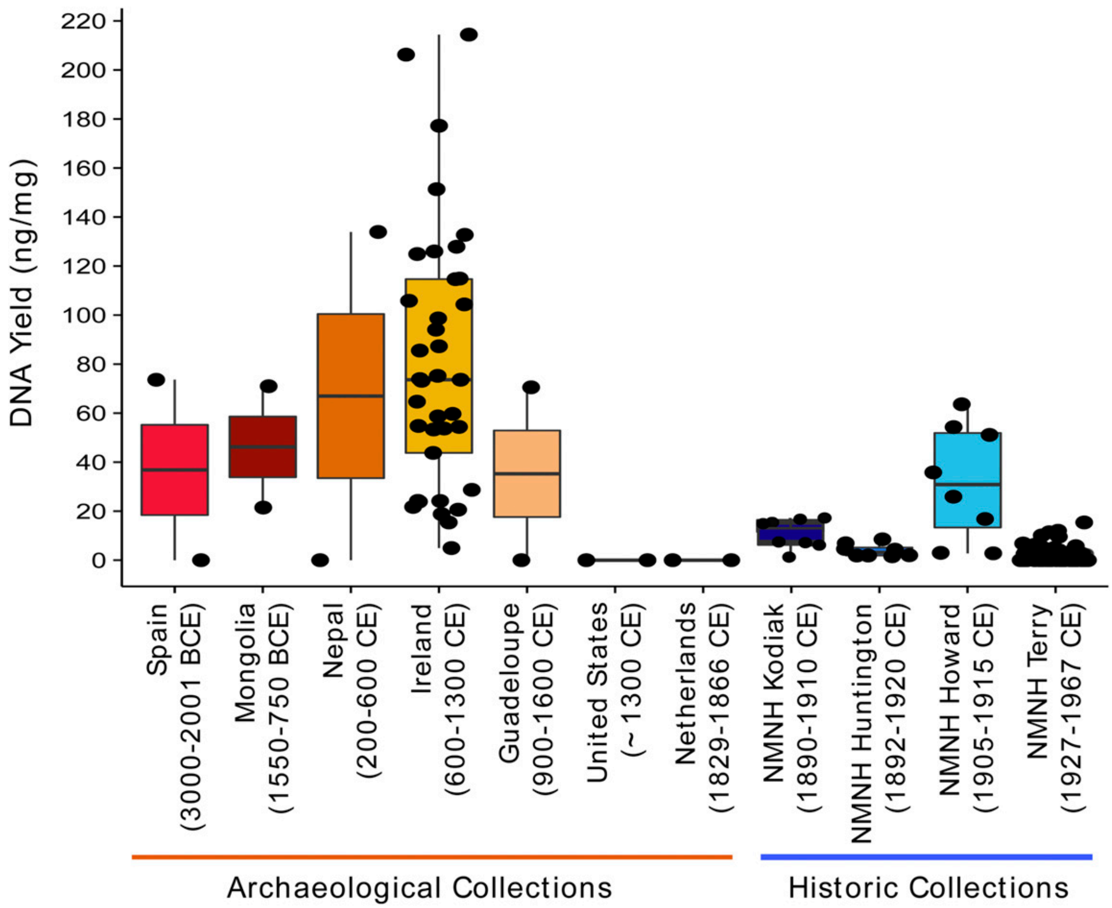

Fig. 2. The graph shows variation in calculus preservation by collection, illustrating DNA yields (nanograms per milligrams) for four 19th- to 20th-century NMNH anatomical collections and archaeological data (14) ranging from 3,000 BCE to the 19th century CE. All DNA samples were extracted with a widely used ancient DNA protocol (16) and quantified using a Qubit fluorometer. The DNA yields for archaeological collections were generally high with a more varied range of values whereas three of the four historic NMNH anatomical collections have consistently low amounts of DNA.

29 collections, highlights the disparate substrate availability within collections. Among 2,793 individuals, only about 11% have at least 5 mg of preserved dental calculus. Postmortem loss of calculus, due to intentional curatorial cleaning or accidental damage, was evident in roughly 50% of assessed individuals (n = 1,552). However, about 92% of individuals with calculus also have at least one intact petrous bone. Factors such as substrate availability and postmortem treatment are important to consider during study design, particularly for population-level investigations because collections may not contain sufficient dental calculus, petrous bone, or another substrate for representative analyses.

Moreover, knowledge about the curatorial conditions of collections, as well as historic and modern collection conservation practices (e.g., use of arsenic, glue, shellac, and pesticides) is important for assessing substrate-specific biomolecular yields and for interpreting the resulting data. Although dental calculus has proven to be a reservoir rich in endogenous human, microbial, pathogen, and dietary biomolecules, our analyses have shown considerable variation in DNA preservation between archaeological (14) and NMNH anatomical collections (Fig. 2). The latter collections are more recent than the former (i.e., 100 versus several thousands of years old), yet yielded very low quantities of DNA, which may be because of postmortem preparation techniques, such as heat and chemical maceration with boiling water and benzene vapors.

As more is learned about factors of ancient DNA decay (15), it's becoming increasingly evident that assumptions should not be made about biomolecule preservation based solely on the age of remains or their provenience. Because the treatment of remains can cause unexpected taphonomic variation in ancient biomolecules, successful molecular recovery from one anatomical and/or archaeological locality does not guarantee comparable success from another. For this reason, researchers may encounter hurdles in obtaining approval for the destructive sampling of collections for which biomolecular preservation is unknown.

In the Department of Anthropology at NMNH, decisions about destructive sampling are based, in part, on the likelihood that the proposed analytical methods will yield the intended results and gain the most possible information from sampled collections. To safeguard these collections for studies in the near or distant future—when improved techniques may be available—the destructive-sampling committee may approve a pilot test on a small subset of a larger request. The idea is to garner proof that biomolecular preservation is suitable for the proposed research before more extensive sampling can proceed.

Data Dissemination and Retention

A high likelihood of receiving analytical results from the requestor is a common criterion for destructive-sampling approval. Most museums have longstanding policies that require copies of documentation and publications from destructive sampling be kept as permanent records. However, many museums have yet to join with academic institutions, funding bodies, and scientific journals in adopting policies for proactive data archiving, maintenance, and sharing.

There is particular interest in paleogenomic data sharing for empirical investigations because of high experimental reliability and reproducibility standards (9) and museums have the ability to implement policies supporting the open science movement. For sampling requests to analyze nucleic acids (DNA, RNA, and epigenetic markers) from anthropological collections, NMNH has recently introduced requirements about the subsequent accessibility of raw data to ensure complete replicability of research and stable, open access to data deriving from collections. Requestors must now submit a Data Management Plan with their proposal that includes a specific strategy and timeline of data collection, management, backup, and release to field-standard genomic data repositories (https://naturalhistory.si.edu/sites/default/files/media/file/Anthro-SamplingPoliciesProcedures_0.pdf).

Like many institutions and organizations, museums are keen to adapt to changes in science and society. With respect to anthropological collections, museums everywhere face challenges to balance scientific interests, descendant concerns, and the need to preserve collections for future generations. Biomolecular techniques offer new avenues to understand the past, and curating specifically for biomolecules can increase their research applicability and continuing relevance. Although museums may differ in their views and policies toward destructive sampling, active discussion and consultation with stakeholders continue to be critical for preserving collections and developing innovative research partnerships. Museum collections are unique resources, and adjustments to these policies promise the sort of scientific and social benefits that only museums can provide.

Acknowledgments

We thank Siobain Duffy, Tanvi Honap, David Hunt, Dave Jacobson, Allison Mann, Susanna Sabin, Krithivasan Sankaranarayanan, Christina Warinner, and Molly Zuckerman for thought-provoking conversations; Nihan Kilic and Samuel Carreon for data-generation contributions; and William Billeck for thoughtful feedback on the manuscript. Finally, we thank all the participants from the 2018 Society for American Archaeology Biomolecules and Museums Collections: Challenges and Best Practices for Destructive Sampling session for contributing a range of perspectives related to museums and ancient biomolecules. This research was supported by grants from the Smithsonian Institution Graduate Fellowship Program; Department of Ecology, Evolution and Natural Resources, Rutgers, The State University of New Jersey; the Center for Human Evolutionary Studies, Rutgers, The State University of New Jersey; the University of Oklahoma; and the National Science Foundation (BCS-1643318 and BCS-1826220).

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