Science in Archaeology: A Review

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The inaugural appearance of yet another “newsletter” of recent archaeological discoveries, reflecting AJA’s historic and ongoing commitment to such reviews, is both auspicious and somewhat daunting.1 Late 20th-century science—here viewed in its more narrow sense as the natural sciences—is now making its share of discoveries in Old World archaeology, a field that some consider a rather esoteric pursuit, divorced from the modern world. A review of this kind might then simply be seen as a long-overdue response to our headlong plunge into a technological present and future. Computers and other “black boxes” are no longer just the province of a few scientific wizards, but are now part of everyone’s life, including the archaeologist’s, whether we like it or not and whether it produces worthwhile results in our research or not. Since there is no turning back, we all need advice on how best to cope with this revolution and perhaps even come to enjoy it a little more.

Such a review can be as daunting to its author as to its readers. How does one launch an endeavor that has few if any precedents,2 and which even its practitioners cannot decide among themselves what to call? A roundtable discussion on “Future Directions in Archaeometry,”3 held in conjunction with the 1981 Archaeometry symposium at Brookhaven National Laboratory, highlighted the fact that “archaeometry” had no precise definition (it has yet to be made an entry in Webster’s or the Oxford unabridged dictionary), and that it was too narrowly focused on the physical sciences and connoted too great a concern for precise measurements (“-metry”). Archaeologists might justifiably claim that their measurements, if not so precise, are at least better suited to cultural interpretation and broader issues of why things developed the way they did, how these developments are expressed in the modern world, and whether any predictive value can be attached to such findings.

The phrase “archaeological science” has fared somewhat better,4 but raises the hackles of both archaeologists (archaeology itself being viewed by many as a social science) and natural scientists, who do not view this as a well-developed discipline. Since “Science and Archaeology” is a similarly infelicitous juxtaposition, I have settled on “Science in Archaeology” as the title for this review. This phrase implies that science of whatever variety (social, biological, physical, etc.) has found its way into archaeology, and it is for us to decide whether it is producing worthwhile results.

This review is not intended, however, to cover every scientific approach or application in archaeology, but rather, to present a selected range of viewpoints of some of the latest developments is the “Archaeometric Clearinghouse” in JEA. C.W. Beck, who assiduously saw this review through 26 installments, retired last year, and the editorial reins have now been passed to J. Henderson of Sheffield University. More specialized newsletters are also published on a regular basis—e.g., La Toma, which deals with archaeoceramics and is edited by J.E. Corbin (Box 13047, SEA Station, Nacogdoches, Texas 75962-3047), and the series of reviews on archaeometallurgy in the Journal of Metals, edited by V.C. Pigott (MASCA, University Museum, University of Pennsylvania, Philadelphia, Pennsylvania 19104). Rather than duplicate what can already be found in these and other more eclectic newsletters, this overview attempts to take stock of the “field” and develop guidelines for effective research and discussion among archaeologists and natural scientists.

1 Publication of this review has been made possible in part by a generous subvention from the Frederick R. and Margaret B. Matson Fund, established specifically to encourage publication of technological studies in AJA. Fred S. Kleiner and Frederick R. Matson are to be especially thanked for first proposing the idea of such a review to me, and then helping to make it a reality by their suggestions, moral support, and, in the case of Fred Matson, contributing an essay of his own on ceramic ecology. Tracey Cullen also provided very thoughtful and practical advice on goals and possible contributors.


2 In the United States, the Society for Archaeological Sciences publishes the SAS Bulletin, which is a very useful “newsletter” that provides up-to-date information on advances in the field, meetings, publications, and funding opportunities. A series of textbooks on the archaeological sciences is also currently being prepared by members of this society in collaboration with Plenum Press, New York. Another newsletter that has kept archaeologists abreast

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and examples of how natural science functions within an archaeological framework. Future reviews, assuming that this one is well received, will expand into areas not covered here and, it is hoped, will lead to more fruitful theoretical perspectives on how best to integrate science with archaeology.

The terminological debate is largely a symptom of how poorly defined and amorphous the “field” is at present, as well as disillusionment with methods or approaches that promised more than they delivered. If an academic discipline constitutes an autonomous body of knowledge, with recognized practitioners, places where research is carried out, and appropriate journals, publications, professional groups, and conferences to disseminate the findings, then the “archaeological sciences” are still very poorly developed. National, museum, and private laboratories do exist in the United States, Europe, and elsewhere, providing a context for specific applications of science to archaeology, but these facilities primarily play a support role, either focusing their efforts on individual collections and in-house projects or providing a commercial service to archaeologists (especially dating and geophysical prospecting). Academic programs, which might serve to foster research and develop a tradition of scholarship, are virtually nonexistent. Public and private funding is difficult to obtain, because such research is too “interdisciplinary”—it does not fit squarely into any established discipline. With the all-too-common cutbacks in budgets generally, science in archaeology will probably continue, for the foreseeable future, to be carried out by widely scattered individuals and the occasional research group, approaching the subject from various scientific or archaeological perspectives. Science in archaeology truly suffers from C.P. Snow’s “two culture” split personality. It may seem exciting to explore a borderline discipline (where serendipitous discoveries so often occur) and become a polyglot interpreter of sorts, yet the would-be practitioner must be prepared to be misunderstood and certainly underfunded.

To be fair, the sheer dimensions of possible interactions between archaeology and the natural sciences, ranging from the subatomic to the astrophysical level, preclude any simple definitions and hence a more systematic approach. Some may choose to divide up the field by physicochemical techniques (whether neutron activation analysis, mass spectrometry, or optical microscopy), others may opt for a materials science approach (ceramics, metallurgy, etc.), while still others will argue for a general problem approach (such as establishing trade networks, reconstructing palaeoecologies, or elucidating demonstrate the desirability and need of coupling archaeology and natural sciences. See J. Riederer ("Teaching Archaeometry as a Basis of Archaeometric Research") and S.E. Warren ("The Education of the Archaeological Scientist") in Olin (supra n. 3) 34–35 and 36–38, respectively, and the discussion session 34–46; also see J.A. Sabloff, "Toward a Future Archaeological Ceramic Science: Brief Observations from a Conference," in Bishop and Lange (supra n. 4) 394–99.


6 Olin (supra n. 3) 109–45 (section on the “Roles of Museum, University, Government, and Industrial Laboratories”) and van Zeist (supra n. 4). A recent British Museum publication, S. Bowman ed., Science and the Past (Toronto 1991), provides an excellent overview of interdisciplinary research in the Department of Scientific Research of the British Museum that will be readily comprehensible to the nonspecialist.

7 New and Old World archaeology, incorporating natural scientific training to some extent, are taught in the same academic department (Archaeology) at Boston University. Several programs are also attached to materials science and/or anthropology departments in the United States (e.g., the Massachusetts Institute of Technology and the University of Arizona) and Canada (University of Toronto). In England and Germany, separate departments of archaeological sciences (e.g., the University of Bradford and the Institute of Archaeology at the University of London) exist or have integrated natural scientific studies effectively into their archaeological curricula. Conservation programs (e.g., at the Institute of Fine Arts in New York or the Institute of Archaeology at the University of London), although having more pragmatic goals, clearly
cognitive processes of ancient humans). Each approach has its advantages and disadvantages, and may seem relatively more interesting or boring to the archaeologist or natural scientist, but all share the premise that information made available only by the natural sciences can be used to shed light on issues ranging from the most fundamental—for example, dating an archaeological site or artifact—to the most ambitious and potentially important, viz., the origins and development of humans and their cultures.

It is not difficult to understand why science should play an important role in archaeology. The general principles and empirical procedures of stratigraphic excavation and record-keeping, as well as site survey and landscape archaeology, themselves embody the empirical observation and systematization that characterize science. Unlike chemistry and physics (the "hard sciences"), experiments in archaeology cannot be repeated, but, like geology or astronomy, archaeology is concerned with evidence of past events (during the relatively short span of Earth history over the past several million years) and the interpretation of that evidence within a more general theoretical context. In the historical natural sciences, a limited range of materials is subjected to a battery of analyses (material, imaging, and statistical), and interpretations are based on general scientific "laws" (uniformitarianism, the structure and mutation rates of DNA strands, the speed of light, and so forth). Even with their sophisticated tools (like the Hubble space telescope), there is room for disagreement on how the data should be interpreted. As just one example, not all scientists agree that the dinosaurs were warm-blooded, social creatures, or that they became extinct when an asteroid collided with the earth.

Archaeologists also aspire to generalized and detailed reconstructions in time and space, as well as establishing cause and effect relationships, based on an analysis of its restricted data base. Unfortunately, because of the disciplinary schizophrenia already mentioned, most archaeologists are not trained in how to extract natural scientific information from their sites and the artifacts that they recover. Lacking a basic knowledge of the natural sciences, archaeologists are at a disadvantage in properly recovering and interpreting materials from sites that have certainly been altered by geological and biological processes and of which now mostly inorganic materials remain. Some archaeologists, recognizing the deficiency in their training, have the good sense to enlist the help of natural scientists in a multidisciplinary effort, which is the hallmark of most modern scientific projects. Unless the natural scientist's role is to be no more than "window-dressing," however, there has to be a very serious attempt by all involved, archaeologist and natural scientist alike, to articulate the goals of the project in their respective "languages" and develop an effective research design for answering some significant cultural questions. Placing specialist studies with little if any relationship to the archaeological interpretations at the end of an excavation report illustrates how not to do interdisciplinary research. Equally reprehensible is a scientific study of unprovenienced, possibly fake, archaeological material parading masses of data that may have been generated by the most sophisticated analytical tools available but which are archaeologically meaningless.

The communication gap between natural scientists and archaeologists is exacerbated by the human dimension, which cannot be easily factored into an

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13 Such studies are interdisciplinary almost by definition. For example, a recent conference on "The Origins and Ancient History of Wine" (in press, under the same title, and edited by P.E. McGovern, S.J. Fleming, and S.H. Katz) brought together specialists in palaeoethnobotany, archaeology, genetics, enology, art, food science, chemistry, textual analysis, and history. Besides reviewing and debating the available evidence for viticulture and viniculture, participants were encouraged to look at this beverage, which played an important role in the diet, economy, social structure, and religion of ancient societies, from a variety of perspectives and develop innovative approaches to answer culturally significant questions. As just one example, many centuries of experimentation in plant domestication and crossbreeding, wine making itself, and in pottery technology (to produce relatively airtight, stoppered vessels of dense fabrics) were presumably required to reach the level of expertise that is evident by ca. 3000 B.C. in Egypt and Mesopotamia—but where is the evidence for these developments, and how is it to be recovered from excavations and scientifically verified? By attempting to tailor our survey, excavation, and analytical strategies to specific research objectives, the advantages of collaborative research, despite the specialization and fragmentation of modern knowledge, will become apparent.

14 F. Widemann, "Why Is Archaeometry So Boring for Archaeologists?" in Olin (supra n. 3) 29–36.


interpretative schema and which makes archaeology a very "soft" science. Archaeological remains often appear to be an extension of the natural world, simply needing to be subjected to thorough physical and chemical investigation for their significance to be elucidated. In some instances, this may be true. The microstructure of a ceramic or metallurgical artifact may reveal how it was made, and by the cautious use of ethnographic analogy, even some facets of the organization of the industry. Certainly, the radiocarbon reservoir in the oceans and atmosphere was little affected by human intervention before the industrial revolution, so that one can have confidence in dates based on this technique (assuming adequate tree-ring calibration, elimination of contaminants, and statistical evaluation). On the other hand, what may appear to be the result of natural processes (e.g., pollen rain, a soil lens, or patination on glass) might also have been affected by human activity, and cannot be explained solely by physicochemical factors.

Archaeologists understandably seek cultural interpretations that even the natural scientist should be willing to admit are at a higher level of abstraction than, for example, the reconstruction of an ancient regional environment or the significance of some group of artifacts for the history of science. Anthropologists, as social scientists, may seek to make generalized statements about social and economic structures, religious ideology, or cross-cultural interactions that are derived from their archaeological data bases. Historians may attempt to interrelate archaeological findings to information—whether psychological, social, or environmental—gleaned from contemporaneous and noncontemporaneous documents that have been subjected to critical study. Art historians in evaluating specific objects may emphasize aesthetic canons of judgment. Each kind of interpretation has its place, with the proviso that they should be inferred from as careful and thorough an appraisal of the field and laboratory data as possible.

Lacking most of the material evidence that once existed, especially the organics that comprised humans themselves, their personal belongings and buildings, food, etc., archaeological interpretations are per force extremely weak. A deficiency of data, however, should not be taken as an excuse for fuzzy thinking. The consequences of an interpretation based on the available data should be deduced; if borne out, the hypothesis gains in credibility. Tests that demand a tangible outcome, such as a certain microstructure in a metal or a specific artifact distribution, can provide extremely powerful support for a hypothesis, because archaeological evidence is unintentional and contemporaneous (with the rare exception, e.g., conspicuous consumption in a burial). Thus, it was not "planted" to achieve some ulterior purpose in the distant future nor to rewrite history after the fact.

Archaeological interpretations will never achieve the same level of confidence as those in the natural sciences—there are far too many interacting and unknowable factors to assess—but by making testing procedures explicit, archaeologists and natural scientists can share a common ground and language of scientific inquiry. Fuzzy archaeological thinking, of course, may continue to thrive, because its effects are not as immediately obvious as in the natural sciences where, for example, bridges fall and rockets explode if a theory or its application is incorrect. Moreover, for some people, rhetoric and politically correct paradigms, serving to preserve disciplinary power structures and financial support, are more persuasive than probabilistic statements. Well-thought-out and tested ideas, which have profound implications for how we define ourselves and our cultures, are often lost in the process.

Clearly, a middle way needs to be found—what in the parlance of anthropological archaeology is called middle-range research—to bridge the practical and theoretical divide between natural scientists and archaeologists. The essays that follow are

17 W.D. Kingery, "Possible Inferences from Ceramic Artifacts," in Olin and Franklin (supra n. 5) 37–45.
18 Smith (supra n. 10).
22 Kingery (supra n. 17).
Remote Sensing

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New windows on the past are being opened through the use of remote sensing technology.\(^24\) Remote sensing is based upon the fact that all materials emit energy along the electromagnetic spectrum. Archaeologically relevant information, most of which cannot be seen with the naked eye, can be recorded by detectors along this spectrum and processed for view on a computer. Sensors are mounted on satellites, space shuttles, airplanes, and balloons, dragged on the ground, or simply manipulated by hand.

Beginning at the turn of the century, archaeology was one of the first disciplines to employ remote sensing. Using black-and-white aerial photography, archaeologists recorded ancient features that could not be seen or understood from ground level. During World War I, for example, British archaeologists described aerial photographic “features of long-obliterated structures in the terrain, soil formations, and vegetative cover . . . that are either invisible or easily overlooked in surface reconnaissance.”\(^25\) This capability subsequently led to the discoveries of ancient Roman villas and roadways in Europe, sites in the Middle East, and earthworks in the Mississippi River valley.

SATELLITE IMAGERY

The launch of the first land satellite (Landsat) in 1972 ushered in a new era in remote sensing. Computers were now required to handle the digital data format and convert the information into photograph-like products. The multispectral capability of satellite imagery enabled several regions of the electromagnetic spectrum to be recorded simultaneously. Since archaeological features show up through soil variations, moisture differences, plant stress, etc., multispectral information can be used to detect subtle features. No part of the spectrum is necessarily


any better than any other part for detecting archaeological features, since the material comprising the feature, atmospheric conditions, and the time of the year result in different energy outputs.

Although the first Landsat satellites recorded information at only 80-m resolution, current foreign and domestic satellite systems can record information ranging from 30-m down to 1-m resolutions (e.g., using French SPOT satellite imagery). New advances in airborne remote sensing instrumentation allow multispectral acquisition at resolutions of one foot or less. Remote sensing analysis used to require huge mainframe computers and expensive software; today, data can be processed on a personal computer using inexpensive and readily understandable software.

As one example of the new high-tech view from space, the possible remains of the ancient city of Ubar were recently located through faint traces of caravan trails. Researchers could see various parts of these trails on Landsat, SPOT satellite, and shuttle imaging radar data. By excavating at a spot where these trails converged, archaeologists uncovered an eight-sided fortress surrounded by smaller sites used by caravans.

Satellite data have been used in western Greece to locate a variety of physical features, including stone quarries, coal mines, oak and silver fir forests, and clay beds used for pottery-making. This information provided greater insight into ancient fortifications, hydraulic systems, and settlement patterns. On the other side of the globe, satellite data are currently revealing unmapped Mayan pyramids and roads in the Peten region of northern Guatemala.

Remote-sensing instruments can be flown in Lear jets or Cessna aircraft to provide greater resolution. Aircraft data at 5-m resolution were able to detect ancient Anasazi roads in Chaco Canyon, New Mexico. The same six-band thermal instrument was also flown at 5-m resolution over the jungles of northern Costa Rica to detect the oldest confirmed footpaths. Despite the environmental differences between New Mexico and Costa Rica, both the desert roads and jungle paths, invisible to the human eye from the air and ground level, were detected due to minute differences in heat retention.

GLOBAL POSITIONING SYSTEM (GPS)

GPS technology is revolutionizing archaeology and enhancing the effectiveness of remote sensing research because it enables ground positions to be determined to centimeter accuracy. The GPS system consists of 24 satellites orbiting 11,000 miles above the earth. GPS signals can be received directly with a hand-held receiver. Besides being extremely useful in remote, poorly mapped regions, GPS locates archaeological features that have been detected in remote-sensing imagery but are invisible on the ground.

CONCLUSION

Although archaeologists pioneered the use of remote sensing, most mainstream archaeologists of the late 1970s and '80s were reluctant to invest in the technology. By then remote sensing had evolved into an expensive enterprise, requiring knowledge of optical physics, advanced computer analysis, and multivariate statistics—disciplines generally outside the purview and funding of archaeological research programs. Today, however, the technology is becoming increasingly affordable and understandable. It is a nondestructive technology that protects our human legacy by allowing archaeologists to map entire regions and prioritize areas for excavation while simultaneously preserving cultural resources for future research.

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BEGINNINGS

The first systematic use of a tethered photographic balloon to record an ongoing excavation was made in 1931 at Megiddo, site of biblical Armageddon, by Philip Guy (fig. 1). Operating out of the Oriental Institute at the University of Chicago, field director Guy used a single-shot 8 x 10" cut-film camera and a spherical hydrogen balloon to assemble detailed mosaics at successive stratigraphic levels. This bird's-eye view, he reported, allowed him to see continuities and patterns that went unobserved on the ground. Guy used these vertical photographs, which included points of his surveyed grid, to eliminate much measuring on the ground and make lighter work of the drawings. But his single-shot camera had to be pulled down and reloaded for each new exposure—a tiring process that used up the short precious time in the morning when the angle of the sun was right and the air quiet. In fact, a Megiddo colleague later told us that the balloon did not handle well in the wind, and Guy quietly abandoned the method as impractical at the season's end when a sudden gust crashed his camera.

We learned firsthand about balloon site recording in Greece in 1973 while working with Michael Jameson at his excavation of the underwater sanctuary of Apollo at Haliac, where Julian Whittlesey brought his spherical balloon.34 Invited to help him, we became interested ourselves in the process, seeing that much time was saved with a modern radio-controlled motor-driven camera. Our own 20 years of aerial archaeology in the Mediterranean started then and has since taken us to over 150 sites and area surveys in Italy, Sicily, mainland Greece, Crete, Yugoslavia, Israel, Turkey, and most recently Jordan. Though much of the coverage has been scattered, carried out at the request of individual excavators, it has also been possible to fund work on a regional basis, producing a site atlas for reference and comparative study.35

APPLICATIONS AND ADVANTAGES

For exploration, salvage work, comparing successive levels of excavation, and preservation of visual information for future study, vertical photographs provide an expeditious unique perspective, constituting a permanent record. In the raking light of early morning, even the slightest contours, as traced by their highlights and shadows, stand out in high relief. One is able to spot relationships not easily seen at ground level. Over a level site, vertical aerial photographs are the dimensional equivalent of a drawn plan.

The obvious advantage of a balloon or blimp over a plane is that it can come low to capture details, such as a single house or a mosaic floor. Helicopters can fly lower than planes, but the powerful downwash of their rotors can damage fragile remains and disturb the water over submerged sites.

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EQUIPMENT AND METHODS

Through much experimenting, we have gradually settled on methods and equipment that are most suitable. Problems with a spherical balloon had suggested that a blimp might be easier to handle in the wind. Working with design engineers at Raven Industries of Sioux Falls, South Dakota, we had a blimp made that meets our requirements (fig. 2). It is 10 m long, with four fins that keep its streamlined shape headed into a breeze, offering less drag area than a spherical counterpart. Inflated with 35 m³ of hydrogen or helium, the blimp lifts 8 lb of cameras to 800 m—the altitude from which a square kilometer can be photographed. Above 800 m, air photographs from a plane would be more efficient.

Equipped with an elastic dilation panel, the blimp expands without bursting as it rises into thinner air, and contracts again, holding its aerodynamic shape, when lowered. A still larger blimp, though more stable in the wind, would require heavy winching equipment and restrict movement. The hand-held system allows us to move quickly through shifting positions at a large site, while some remote sites can only be reached on foot.

Twin cameras allow us to make both black-and-white negatives and colored slides at the same instant. The medium format Hasselblad ELM/500 produces 55 mm negatives, best for journal publication (fig. 3), while the 35 mm camera, a Canon AE-1 or a Nikon 2020, makes slides. The cameras are mounted in a precision gimbal—like that which holds the compass level on a heeling ship—thus stabilizing them vertically and eliminating the distortions in scale that appear in oblique views. The tethers of ¼” braided polyester cord are carried on light backpack reels designed for taking up the slack as crew members haul down the balloon.

The altitude at which the cameras are positioned is determined by the dimensions of the target on the ground. Given the focal length of the lens and size of the film, the proper altitude is derived from a ratio (fig. 4): focal length is to film size as altitude is to the size of target. For shots below 200 m, two tethers are generally used, angled down from opposite sides of the gimbal to keep both cords and backpacks just outside the photograph. Thus, the frame of the photograph is closely fitted to the shape of the target. Simple calculations made on a working plan are used to decide exactly where each reel must be positioned and how much tether line let out. Above 200 m, two tethers would be difficult to control and might tangle in a tricky breeze. With a single tether, the altitude of the camera is judged by patches of colored yarn tied to the tether line at calibrated intervals. For the higher shots, the necessary framing is done by cropping in the darkroom. With wide-angle lenses, 60 mm for the Hasselblad and 28 mm for the smaller camera, the focusing distance can safely be set on infinity.

Accessory equipment has also proven useful in the field: a surveyor’s tape and prismatic compass for making a working plan of unrecorded sites; a small turbine anemometer to help us decide whether a slight breeze is increasing and might cancel a planned inflation; heavy canvas ground cloths on which to unroll and inflate the easily punctured balloon fabric; a set of walkie-talkie radios, allowing crew members at widely separated tether positions to communicate with each other and with the operator controlling the camera; a portable light table.

Fig. 3. A Hasselblad medium-format vertical photograph of the little theater in the Sanctuary of Asklepios at Messene, Greece.
for studying the day's negatives with magnifiers; and, where remote sites are not easily located on maps, a miniature global positioning device to measure and record latitude, longitude, and altitude.

CAUTIONARY NOTES AND PROBLEMS

We described above Guy's problems with the wind at Megiddo. Even with an aerodynamic blimp, one must be careful. Because it may take 20 minutes to haul down the equipment from 800 m, it is important not to have the blimp caught aloft in a rising wind. At a certain wind velocity, even a blimp will begin to veer off to the side, its fins less and less able to head into the wind, and finally broach, turning broadside to the wind and heading straight for the ground, all lift lost to the weight of the cameras and the horizontal force of drag. Recovery here is possible only if the ground crew can run toward a sinking blimp fast enough to slacken tether and allow it to rise again. Even then, the balloon can be pulled down gradually only when the wind lulls a bit. It is best to avoid these panic situations by hauling down as soon as one feels an increasing pull on the tether.

Delays in the photographic schedule are best avoided by learning early what permissions a country requires from civil air or military authorities or what advance notice to authorities would be prudent and courteous. Sources of hydrogen or helium should be located and arrangements made early for prompt commercial delivery.

OTHER BALLOON SYSTEMS

We have regularly responded to requests for information from others who would like to start their own balloon systems and increasingly hear of successful recording. Good examples of balloon photography appear regularly in AJA. A very simple and inexpensive 35 mm system, with a servo-motor to incline the camera, but limited in altitude to 100 m, is described by Dieter Noli. G.D. Summers reports flights of a tethered blimp as high as 850 m to record a site in Turkey. Andrew Heafitz has developed an ingenious radio-controlled servo-system that can incline and rotate the balloon camera in any direction. A video camera, mounted together with a still-camera that monitors the coverage, transmits the image to the ground, allowing the operator to see exactly what the still-camera will record.

There is little doubt that archaeologists of the future will use increasingly sophisticated methods to record and examine sites in minute detail at low altitude. The whole range of remote-sensing equipment, operating in the infrared to radar ranges and now used for sophisticated regional surveys by plane or satellite, may one day be miniaturized for low-altitude suspension over archaeological sites. Much subsurface investigation might then be conducted without the traditional digging that has been described with cautionary irony as the systematic destruction of evidence.

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A successful geophysical survey will allow a prediction of the location of sites or the location of features within sites. This should help to minimize the cost of excavation and enable a wide variety of features to be examined.

While remote sensing usually does not allow the detection of a feature deeper than about 1 m, geophysical exploration can detect a feature at any depth, although its maximum dimension must typically exceed its depth.

THE INSTRUMENTS AND THEIR LIMITATIONS

One of the first instruments to be applied to archaeological geophysics was the magnetometer. A magnetometer measures slight changes in the earth's magnetic field; a commonly used instrument has a sensor mounted on a vertical staff and connected with a wire to a small console where the measurements are displayed. Point-by-point measurements, spaced 1–2 m apart, create a magnetic map of the area of interest. The magnetometer is excellent for locating iron artifacts as well as fired earth in the form of brick, roof tiles, kilns, or furnaces. Surveys with a magnetometer are generally more rapid than those with other geophysical instruments, and are also more easily done in brushy, wooded, or rocky areas. They are less suitable for urban areas and regions with igneous rock.

Resistivity surveys are relatively easy to carry out. Wires connect a small resistivity meter to four electrodes driven into the earth; the meter indicates how readily electrical current flows through the soil. Resistivity surveys are ideal for locating concentrations of stone in the soil (e.g., walls) and also for mapping filled-in pits and trenches. Because of the electrodes and wires, resistivity surveys are difficult to carry out in rocky or brushy areas.

Conductivity surveys are performed with instruments that operate somewhat like very sensitive metal detectors. They will locate the same types of features that a resistivity survey will, but conductivity surveys are faster since no contact is made with the ground. Conductivity surveys are difficult to carry out near cities and in areas with metal trash in the soil, but wooded or rocky areas do not cause major difficulties.

Ground-penetrating radar is the most elaborate of the commonly used geophysical instruments, and will detect a wider variety of features than the other instruments. Radar generates an approximate cross-sectional image of the earth; while these images are similar to sonar records, the radar emits a radio rather than a sound pulse. Radar is generally not suitable for sites where the soil is saline or quite clayey; it also cannot be used if there are many large boulders or much brush on the surface.

For special applications, seismic and gravity instruments can also be employed. Seismic equipment measures the speed of sound in the soil, while a gravity meter measures the density of materials that are underground. Surveys with these two instruments, however, are quite slow.

CAPABILITIES FOR LOCATING DIFFERENT FEATURES

The ancient ground surface may be buried below a layer of modern soil. The depth of this deposit can be estimated with a resistivity, ground-penetrating radar, or seismic survey. The entrances to rock shelters, caves, mines, and quarries may be hidden by soil, and can sometimes be detected with any of the geophysical instruments. Tunnels or chambers that are air-filled cavities can be readily detected with ground-penetrating radar and, in special circumstances, with a gravity survey.

The former channels of rivers, buried roads, or filled-in ditches can be mapped with any of these geophysical instruments. Because of the large size of these features, aerial or satellite reconnaissance may be most suitable.

Tells and tumuli often have stratigraphy that is too complex for geophysical surveys to resolve. While structures in the upper few meters can be mapped as at any other site, small and deep features cannot be detected. General mound stratigraphy, however,

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particularly on the sides of the mound, can be approximated, and resistivity surveys are generally the most appropriate technique. The stratigraphy of burial mounds is usually simpler and, if the burial chamber is at least as large as its depth underground, it might be detected.

Building remnants can be detected under ground or under water. If a buried wall is surrounded by rubble from the wall, it will generally be impossible to isolate the intact wall with geophysical exploration. Brick walls or concentrations of rooftiles will usually be easier to delineate than stone walls. Mud-brick or adobe walls may be detectable in sandy soil and limestone walls may be detectable in clayey soil.

If kilns, furnaces, or iron objects are sought, a magnetic survey is recommended. In some cases, concentrations of pottery or other fired ceramic materials can be located.

Isolated artifacts will generally be difficult to locate with any geophysical survey. A large object such as a statue can be detected if it is close to the surface; it would be easier to detect if carved in igneous stone rather than marble or some other nonmagnetic stone.

Conductivity surveys can locate artifacts made of any metal. For example, lead pipes can be traced with this technique.

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44 E.K. Ralph, "Comparison of Proton and Rubidium Magnetometer for Archaeological Prospecting," *Archaeome-*

THE GEOPHYSICAL SURVEYS OF
ELIZABETH K. RALPH

Elizabeth K. Ralph, who passed away in 1993, was a pioneer in the application of geophysical surveying to archaeology and an inspiration to this writer. Her excellent success in locating buried features at many archaeological sites in the Mediterranean region is particularly appropriate to detail in this review, since she received the AIA's Pomerance Award in 1986 for her contributions to archaeological science and her work is frequently referred to in *AJA*.

During the period from 1962 to 1976, Ralph did geophysical surveys at over 49 sites in 13 countries. Her principal and favorite geophysical instrument was the magnetometer (fig. 5), and her application of the cesium magnetometer showed how speed and precision could be combined for a successful survey.44 Her sheer output—about 750,000 magnetic measurements that were plotted and contoured by hand—has never been equaled. She also carried out many surveys with resistivity meters and a seismograph.

The largest single survey that Ralph undertook was at the site of ancient Sybaris, in Italy, where the Greeks established a colony renowned for its "sybaritic" lifestyle. Over the period from 1962 to

*try* 7 (1964) 20–27.
1967, she worked on site in Italy for a total of about two years. She made between 300,000 and 400,000 magnetic measurements, which enabled the Archaic rooftiles of Sybaris to be located at a depth of 4 m beneath the alluvium that had accumulated over 2,500 years.\(^4\)

Because of the huge area of search, the great depth of the structures, and the presence of shallower and more recent Roman structures, the survey at Sybaris was extremely difficult. The mapping of ancient Elis, a contemporaneous site in Greece, was easier and required fewer measurements (only 100,000).\(^5\)

Ralph was able to show the plan of this city, for the brick and reused rooftiles used to construct the walls here were clearly delineated. While the written measurements look like a mass of dots, the contour lines of the magnetic maps trace the lines of underground walls.

Ralph did magnetic surveys at many other sites. In the former Yugoslavia in 1969, burnt Neolithic house floors were located.\(^6\) At Malkata, Amenhotep III’s palace in western Thebes, she located mudbrick structures buried in the sand (fig. 5). While these bricks had not been fired, the alluvial clay from the Nile River is quite magnetic and the bricks made from it were detectable in the nonmagnetic sand.\(^7\)

At the ancient Elamite capital of Tall-i Malyan, Iran, Ralph’s magnetic survey was remarkably successful in locating significant archaeological remains in every area that was followed up by test soundings (fig. 6). Unfortunately, the Iranian revolution intervened to prevent further work at this site.

Although carried out 20–30 years ago, Ralph’s geophysical surveys have never been surpassed in terms of their success or quality. Recent improvements in magnetometers enable surveys to be completed more quickly, but no significant increase in the accuracy of the measurements has been possible. Conductivity meters and ground-penetrating radar have been developed since Ralph did her surveys, and with these instruments, geophysical surveys can be carried out at a wider range of archaeological sites.


Palaeoethnobotany (or the shorter term, archaeobotany) is the study of the "direct interrelationships between humans and plants for whatever purpose as manifested in the archaeological record." No matter what the time period or geographical area, plants played an important role in human culture. As primary data about the natural environment, land-use practices, diet, architecture, and trade in exotic plant materials, plant remains also reflect many aspects of society, including social practices, such as eating, the organization of labor, and status differentiation.

The three major categories of archaeobotanical materials are macroremains, pollen, and phytoliths. Macromeries are relatively large items that generally comprise the bulk of plant remains recovered from archaeological sites. They include seeds and seed-like plant structures, fruits, wood, leaves, tubers, etc. Typically, macroremains are recovered manually, by screening, and by flotation (fig. 7). Flotation enables the archaeologist to concentrate macroremains dispersed in the site matrix, usually by dissolving a soil sample in water.52

No single category of remains provides a full picture of ancient plant use. When one considers the total amount of plant material intentionally brought to a site by ancient people (for food, fuel, fodder, construction, tools, and other artifacts), plus material unintentionally incorporated in the archaeobotanical record, one realizes that it is ordinarily the discards and residues of plant use that get deposited initially, a subset of which is eventually preserved (usually through carbonization, but sometimes under dry or waterlogged conditions).53 Texts, too, are an important source of information that describe many aspects of the relationships between people and plants (e.g., agricultural treatises, receipts, recipes, and medical prescriptions). Yet such sources are often too limited or too general to provide more than a narrow window onto agricultural practices, the effects of land clearance, fuel-gathering, and irrigation, and all the other ways in which plants were integrated into the daily lives of ancient peoples. Thus, especially for the later periods, the information gleaned from texts complements, but does not supplant, that gained from detailed archaeobotanical studies.

Although archaeologists have been saving plant remains from archaeological sites since the mid-19th century, the systematic sampling of archaeological sediments by means of flotation is a relatively recent development. Prior to the pioneering work of Hans Helbaek54 at Jarmo in Iraq, and later at Ali Kosh in southwestern Iran, botanists were brought in to identify obvious concentrations of plant remains, usually crops. It was not until the late 1960s that flotation techniques were brought to the attention of archaeologists in the Old and New Worlds, and

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51 Palynology is discussed in the next section of this review.
52 Paleoethnobotany: A Handbook of Procedures (San Diego 1989) by D.M. Pearsall is a comprehensive, practical introduction to palaeoethnobotany.
through the 1970s, flotation was not routinely practiced. Most of archaeobotanical work concentrated on the origins of agriculture, the major problem as defined in the United States by anthropologically trained archaeologists and in Europe by prehistorians. Now, in the 1990s, the aceramic Neolithic is increasingly well understood, but comprehensive syntheses of the later Neolithic and beyond have yet to be written. Even the early civilizations of the third millennium B.C., which have been given a fair amount of archaeobotanical attention, are poorly known. Later historical periods have been particularly neglected, probably because of undue reliance on written records.55

Several reviews of research in the Near East and Europe summarize decades of work on plant remains from sites dating between Palaеolithiс and medieval times.56 A detailed example from recent work at Gordion, a site that culturally straddled the classical world and the ancient Near East, illustrates the kinds of questions one can ask of archaeobotanical data.

RECENT RESEARCH AT GORDION

Gordion, located on the Sakarya River in central Turkey, was the capital of ancient Phrygia. Excavations early in this century and more recent research directed by Rodney S. Young between 1950 and 1973 were completed before the systematic search for plant remains became standard practice. Plant remains recovered by Young's team were primarily construction material and food remains from the massive Early Phrygian destruction level, the log structures at the base of the "Midas Mound" (Tumulus MM), other burial mounds, and tomb furniture, also from the Early Phrygian period (ca. 700 B.C.).57 Renewed excavations in 1988 and 1989 and archaeobotanical study have begun to fill out the picture of ancient plant and land-use practices at Gordion between the Late Bronze Age and medieval times.58

Reconstructing Ancient Vegetation and Human Influence

Over the past 3000 years, human activities have had a more profound influence on the vegetation of the Sakarya valley than climate.59 Land clearance for fuel and agriculture, the grazing of domesticated animals, and, in the Phrygian period, construction seem to have had the cumulative but gradual effect of reducing whatever natural tree cover there was. Gordion lies at the edge of the central Anatolian steppe, where remnants of oak and juniper woodland and pine forest still exist. Based on the modern distribution of trees, we infer that the impressive juniper and pine timbers found in Phrygian burial mounds and the settlement probably originated in woodland 20–50 km away.

To trace the history of ancient vegetation in more detail, less dramatic evidence from occupation debris must be gathered and analyzed. This plant material, nearly all of which is carbonized, comes primarily from the remains of fuel (wood, brush, and dung) and consists of wood charcoal and charred seeds. Many species are found that are unknown from the tombs or from the constructional and food remains of the burnt buildings. Since fuel is rarely transported from far away, fuel remains enable one to monitor the vegetation growing relatively close to a settlement. At Gordion, the analysis showed a decline in juniper relative to oak. The virtual absence of juniper fuel in contemporary Phrygian deposits suggests that juniper timber had already become a fairly rare material, reserved for or limited to use in the royal tombs. Trees that characteristically replace the climax vegetation of oak, juniper, or pine, along with components of riparian forest, show a gradual increase between the Late Bronze Age and the medieval period, though they never surpass 20% by weight of the assemblage.

Brush and dung fuel are potential sources of seeds in the archaeobotanical record, and the charred seed...
assemblage is a useful indicator of these alternative fuel sources; an increase in the ratio of seeds to charcoal suggests a decline in the use (i.e., availability) of tree wood. At Gordion, there is no dramatic shift in this ratio, which suggests that fuel use practices were relatively stable, despite some long-term disturbance in the tree cover.

Reconstructing Ancient Agricultural Practices

The seeds provide more than just evidence of fuel use. In the absence of cess deposits, seeds from burnt domestic structures provide the strongest evidence that a crop plant was grown for food, though fiber and fodder can usually not be ruled out.

Six-row barley and bread wheat dominate the crop seed assemblage in all periods. Einkorn wheat is a minor cereal, and rice occurs in only one medieval deposit. Lentils and bitter vetch comprise the bulk of the pulses. A burnt early Iron Age house had what appears to be baskets of barley, wheat, and bitter vetch on the floor. A small jar of tiny flax seeds found in the destruction level of Terrace Building 2A might be seed stock for the fiber plant, but the same room yielded small jars of other food crops, wheat, barley, and lentils, so the flax might have been human food. Grapes (a few seeds) were also found as were nutshell, perhaps from wild-growing almonds.

Plant remains may point to changes in irrigation practices, as indicated by crop choice, seed size/shape, and characteristic weeds. At Gordion, despite the unpredictable climate, very little “progress” is visible in the archaeobotanical record. For example, barley is more drought-tolerant than wheat, yet the proportion of these two crop plants remains constant through time. Irrigated grains tend to be plumper than unirrigated ones of the same species; at Gordion, size and shape of both wheat and barley are remarkably stable throughout the occupation. The expansion of a moist habitat—irrigation ditches or riverside vegetation—may be indicated by the apparent increase in the proportion of sedge seeds, which is consistent with the evidence of increased use of riparian vegetation. As trees by the river were cut, a sunny riverbank habitat would have opened up.

Stability characterizes Gordion crop choice. Small shifts in the proportion of einkorn wheat relative to six-row barley and bread wheat are therefore particularly intriguing. Einkorn was one of the earliest domesticated plants, but by 2000 B.C. it had dropped out of favor as an important cereal in the Near East.60 In southern Europe, the presumed homeland of the Phrygians, it seems to have retained its value well into the Iron Age.61 Thus, the apparent slight increase in einkorn coincidental with construction and ceramic shifts, suggestive of the Phrygian culture, may be further evidence of the arrival of these newcomers from Europe.62

CONCLUSION

Despite several decades of research, the full potential of archaeobotany for the investigation of ancient culture is yet to be realized. For both prehistoric and historical periods, plant remains enable us to assess human impact on the environment. As direct, site-specific evidence of agricultural and culinary activities, they can enrich our understanding of how people lived. Archaeobotanical research at Gordion is meant to show both skeptics and the converted how bits and fragments of charred remains help create a picture of the lives of ancient people and the landscape they shaped and inhabited.

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Ancient Palynology

S. BOTTEMA

The study of micro- and macrofossils (including agricultural products such as carbonized hard grains—see the preceding section on Archaeobotany) in the Near East was stimulated by Robert J. Braid wood of the University of Chicago in the early 1960s. He sought to integrate archaeology and the natural sciences in his work on early prehistoric sites in Iran and Turkey. The botanical investigations of this proj-

60 Miller (supra n. 55) 146–48.
Swamps incorporate enormous numbers of pollen, which can be well preserved if kept constantly wet. Yet, these pollen need not correlate with the activities of ancient peoples, whose settlements and encampments can be located away from such bodies of water. Samples from the archaeological site itself, on the other hand, have the disadvantage that they are dominated by Liguliflorae, mostly yellow flowering composites, which comprise a relatively small percentage of the total pollen rain. Furthermore, the accumulation of debris in a Near Eastern tell is often the result of the disintegration and leveling of mudbrick houses. Such mudbrick is made from clay that has its own history, i.e., it may contain pollen that derives from a time preceding the structure in which it was used and which therefore cannot be used to reconstruct the contemporaneous palaeoenvironment.

Pollen samples from water sediments usually enable the general vegetational development of a region to be reconstructed. The best sequences occur where rainfall exceeds 300 mm per year. This iso-hyet appears to be the minimum for the formation of pollen-bearing sediments. An exception is a pollen core from the salt flats of Bouara on the Syrian-Iraqi border, where precipitation amounts to only about 150 mm. The Bouara salt flats form part of the Khabur valley, a region that was densely inhabited during Assyrian times. The Assyrians, who dry-farmed and irrigated the fields elsewhere in the Khabur, evidently used the Bouara exclusively for salt-winning.

The collection of pollen samples is done by manually coring the sediments. The samples are identified in the laboratory, using a light microscope, generally under 400× magnification.

PALAEOENVIRONMENTS IN PRE- AND POSTGLACIAL TIMES

Near Eastern pollen sequences or profiles (e.g., fig. 9) show a marked contrast in palaeoenvironmental development from the glacial period (Pleistocene) to postglacial (Holocene) times, i.e., pre- and post-10,000 B.P. (uncalibrated radiocarbon years). As dated by radiocarbon or by correlation with other

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65 See Küthe (supra n. 64).
dated pollen profiles, the general picture for lower elevations (e.g., the Ghab valley of northwest Syria or Yenisehir in the Bursa area of western Turkey), as well as the higher Anatolian plateau of Turkey and the Zagros Mountains of western Iran, is that of a steppe landscape giving way to forest. This climatically induced change is locally influenced by developing farming communities, but the general trend of steppe herb pollen gradually being replaced by tree pollen has been demonstrated.

The process starts as early as 15,000 B.P. in northern Israel where relatively dense Tabor oak forests established themselves, only to decrease abruptly around 11,500 B.P. A climatic belt of rain that encouraged tree growth apparently moved farther north and east, leaving Israel much drier after this time. The moist zone arrived in the Pisidian Lake district of southwestern Anatolia around 9000 B.P. In eastern Turkey, the Van district shows some increase in deciduous oaks at about 7000 B.P. In northwestern Iran, optimal conditions for tree growth were established around 5500 B.P. The forest development of the Pontic part of Turkey is very similar to that of northern Greece and large areas of Europe. If such vegetational patterns are translated into climatic terms, two main systems can be observed: a general European pattern that is uniform over a large area, and a shifting system that moves from the southern part of the Near East to the north and northeast. The latter moisture belt might have been caused by the gradual retreat of the large ice cap in northern Europe. This retreat, which started in the west and south, is likely to have caused a shift in the polar front that contributed to a moving moisture belt in the Near East.

**EARLY AGRICULTURE**

The pollen record also informs us about the impact of ancient man on the vegetation of a region, as well as the kinds of agriculture that were initiated during the Holocene period. In what kind of landscape did ancient agriculture develop, and what were the consequences for the environment? Pollen analysis provides answers to such questions if so-called indicator types (pollen that can be ascribed to human activity), which derive either from crops (pri-

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Faunal Analysis with a Focus on Anatolia

HITOMI HONGO AND RICHARD H. MEADOW

INTRODUCTION

Analysis of animal bones (faunal analysis) has become increasingly common in Near Eastern archaeology. Much of the first research focused on identifying animals exploited by Palaeolithic hunters and on the beginnings of animal domestication during the Neolithic. Recently, however, increasing numbers of faunal studies have been carried out on sites later than the Neolithic. Because analysis of animal bones began as early as the 1930s in Anatolia, that area provides a useful source of examples to underline some of the possibilities and problems of research that have changed over time.

CONCLUSIONS

An important focus of future palynological research in the Near East will be to define the specific constraints for human settlement, especially in the forest-steppe regions. In general, the pollen evidence needs to be integrated with other disciplines (e.g., archaeobotany) and the available archaeological data to draw well-based conclusions.

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vestigators who approach the field in this fashion often call themselves “zooarchaeologists.” There is a parallel continuum in the ways that faunal analysts are related to excavation projects. Some have tended to work as technicians/specialists who identify bones and present the results to archaeologists. Others try to be an integral part of projects and employ a more holistic approach to analysis and interpretation.69

In faunal studies, recovery techniques and archaeological context are crucial (fig. 10). Animal bones themselves, unlike potsherds and other artifacts, generally do not contain intrinsic clues to dating or social/cultural affiliation (unless they can be characterized isotopically). Therefore faunal remains from mixed or disturbed contexts are best avoided, because the data may be misleading if they are interpreted uncritically. In addition, there are various cultural practices and postdepositional factors that can affect the distribution of animal bones across an archaeological site. Careful recovery incorporating a program of sampling and sieving combined with detailed information about archaeological context of the material will help the investigator to evaluate the biases involved. Ideally, the faunal analyst should be brought into a project during the research design stage to help develop an effective sampling method while taking into consideration time, budget constraints, and the overall goals of the project. At whatever stage an analyst becomes involved in a project, however, it is important that he or she be fully informed about the stratigraphy of the site, the details of archaeological context, and the sampling methods employed.70

What can be classed under the rubrics of “experimental” or “actualistic” studies form important aspects of faunal research. These include preparing a modern comparative collection to assist in identification of the archaeological fauna, carrying out studies on modern animal keeping and hunting or fishing practices in the local area in order to understand possibilities and limitations, and testing the efficacy of recovery techniques. An example of significant work in these areas has been that of Sebastian Payne in Anatolia and southeastern Europe. In a study of sampling methods, he demonstrated that bones of medium and small animals can be significantly underrepresented in a hand-picked faunal assemblage when compared to a sieved assemblage.71

For the material from Aşyan Kale, he developed a technique for recording tooth wear in sheep and

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69 S.J.M. Davis, The Archaeology of Animals (London 1987) provides a good introduction to some of what has been accomplished in the field as well as a useful bibliography. For an introduction to the basic techniques for identifying mammal bones and teeth, see S. Hillson, Mammal Bones and Teeth (London 1992), note, however, the author’s warning on the cover of the book that “it should be used in conjunction with a reference collection of bones and teeth and with the help of an experienced zooarchaeologist.” This is true of all published guides to bone identification


goats and, subsequently, studied tooth wear patterns in hundreds of living Angora goats in order to be better able to determine age at death of animals represented in the archaeological record. From aging data such as these, it is possible to describe a "kill-off pattern" that reflects hunting or husbandry practices employed in the past.

**ANATOLIAN FAUNAL STUDIES**

In Anatolia, modern faunal research can be said to have begun in the late 1960s with the work at Çayönü, Suberde, and Can Hasan. At each of these Neolithic sites, study of the animal remains was closely coordinated with other aspects of the projects, and faunal analysts were present on site for at least part of the excavation. Such work has shown that the transition from hunting to husbandry in Anatolia took place between about 7000 and 6000 B.C. in the context of settled agricultural villages. The keeping of domestic animals was not immediately accepted everywhere, however. At a number of contemporary sites (e.g., Aşıklı and Cafer Höyük), the faunal remains came from wild relatives of the stock that was already being kept and bred in captivity elsewhere.

At sites of later periods where faunal remains are dominated by domestic forms, research focus is on husbandry practices and the nature of animal economies. Topics include selective breeding, site provisioning, exchange of animal products, and animal use by different social groups. Investigators recognize that ethnicity, social hierarchy, and differences in accumulation of wealth can affect the distribution and consumption of meat and other animal products, and that they have even employed faunal remains to monitor the course of state formation.

Unfortunately, faunal remains often have been ignored at sites of the Bronze Age and later. Research at such sites traditionally has focused on texts, architecture, and objects of art and on the establishment of chronology, and little attention has been paid to questions of subsistence. There is the tendency to think that we are already well informed about the kinds of animals and their uses in early historical times, because trade in livestock and animal products and aspects of animal sacrifice are described in ancient texts. In reality, however, very little is known about practices of animal keeping and consumption, especially the practices of the general public as opposed to those of the elites.

For Anatolia, most studies of animal bones of the protohistoric and historical periods have been archaeozoologically oriented. During the 1970s and 1980s, German researchers published data on large assemblages of animal bones from Boğazköy, Fikirtepe, Hassek-Höyük, Korucutepe, Lidar Höyük, Norsun Tepe, and Demircihöyük. They usually presented species lists and skeletal part frequencies, discussed kill-off patterns for domestic animals and changes in animal husbandry through time, and used measurement data to characterize animal size and proportions. There was little discussion, however, of variability in the distribution of faunal remains across a site, with the archaeological period being the principal unit for defining an assemblage. In addition, as excavation and recovery techniques were seldom mentioned, intersite comparisons required assumptions of comparability that may not be justified.

Faunal research is even rarer in later periods, such as the Hellenistic, Roman, and Islamic periods in Anatolia. Although there is an exceptional study of the "Sacrificial Layer" at Halikarnassos, the practice of animal husbandry during the Iron Age and medieval period at the site remains largely unknown.

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RESEARCH POTENTIAL

The Middle East has always been a crossroads for peoples and cultures that are sometimes documented in the texts, but are usually difficult to trace archaeologically. Faunal remains can be an effective tool in this respect, because people belonging to all social groups, and not just the elites, discard bones; and how people raise animals, as well as what they eat, can reflect ethnic and social differences. The following kinds of observations are useful in documenting culture-specific practices of animal keeping:

1) The use of domestic animals, for traction or for their various products (meat, milk, wool, hides), and their contribution to the pastoral economy can be seen in the range of animal species used, their relative importance, and the kill-off pattern employed. The presence or absence of certain species (e.g., pigs) can indicate ethnic differences.

2) Season of slaughter can be determined by examining incremental structures in the cementum of teeth through the preparation of microscopic thin-sections. Since animals often appear in association with gods in season-specific ritual contexts in ancient texts and art, it may be possible in some instances to identify the remains from sacrifices or other periodic events through seasonality studies and perhaps even identify the sacrificial occasion.

3) The presence of foreign species may reflect trade or alliances between geographically distant places and even the migration of peoples. The introduction of the domestic horse into Anatolia, perhaps through the Caucasus, is a good example.

4) Change in size and body proportions of domestic animals through time can show whether different breeds of animals were developed or introduced. Similar observations on wild animals can help identify human pressure on the environment.

5) Frequencies of different body parts and butchery techniques can be related to ethnic differences and to different types of provisioning.

6) Intrasite distributions can provide information on social and functional differences. Animals associated with higher status (e.g., horses) or particular activities (e.g., camels) may only be found at specific locations.

Thus, there is great potential in the study of animal bones from archaeological sites of all periods, to shed light not only on animal exploitation patterns but on social/cultural practices that other archaeological materials cannot reveal. It is particularly regrettable that there is general indifference to animal bone studies among many archaeologists working at early historic and medieval sites in the Middle East. We hope that in the next decade faunal analyses will become more common and better integrated into research strategies developed to investigate the nature of complex societies.

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Dendrochronology

PETER IAN KUNIHOLM

Over 6000 years of tree-ring chronologies covering much of the period back to about 7500 B.C. have been developed over the past 20 years for the Aegean, Balkans, and Near East. The goal is to construct an unbroken chronology from the Neolithic to the present against which archaeologists, art historians, and anthropologists may date finds of wood or charcoal, theoretically to within one year.

METHOD

Tree-ring sequences from trees that grow in a seasonal climate, i.e., with one growth increment per

81 One exception is the excavations of the Middle East Cultural Center in Japan at Kaman Kalehöyük where the field director, Sachihiro Omura, has been particularly sup-

portive of all kinds of bioarchaeology. We wish to thank Dr. Omura and the MECCJ for supporting our own participation in the project.
81 The professional society for Archaeozoology/Zooarchaeology is the International Council for Archaeozoology (ICAZ), which can be contacted c/o Dr. A.J. Clason, General Secretary, Biologisch-Archaeologisch Instituut, Poststraat 6, 9712 ER Groningen, The Netherlands. Bibliographies are compiled each year and published in the journal of ICZ, ArcheoZoologia (Grenoble, France).
year, with the size of that growth dependent upon some climatic stimulus such as cold in the polar regions, drought in the Aegean, and various combinations of the two stimuli in regions in between, can be compared so that these increments, more popularly known as “rings,” can be dated to the calendar year in which they were formed. Crossdating, matching patterns of ring growth from one tree to another and assigning rings to specific years, is possible only among trees growing in the same general climatic region. Crossdating can sometimes be achieved in spite of human interference to ring growth by thinning of stands, resin gathering, fire damage, and other traumas such as severe weather effects, pollution, lightning damage, etc., not to mention shaping of the wood at the time of construction and decay afterward. Both visual and statistical techniques are employed to guarantee the accuracy of the matches. In addition to simple ring-width analysis, X-ray densitometric methods are used to reconstruct past environmental conditions. Wood or charcoal samples taken from standing buildings or excavated from archaeological sites can be crossdated with each other and with wood from living trees to extend the tree-ring chronology beyond the date of the oldest ring of the oldest living tree in the region. Dendrochronology is the only archaeometric technique for which determination of absolute dates accurate to the year is either theoretically or practically possible. For a thorough treatment of recent progress in dendrochronological and dendroclimatological work worldwide, see F.H. Schweingruber, Tree Rings: Basics and Applications of Dendrochronology (Boston 1988).

DENDROCHRONOLOGY IN THE AMERICAN SOUTHWEST AND IN EUROPE

Tree-ring studies have been a staple of anthropological investigation in the American Southwest since the early decades of this century and in Europe since World War II. The bristlecone pine chronology of the American Southwest now exceeds 8,500 years with the possibility that up to 3,000 floating years will be added in the reasonably near future. The European oak and pine chronology, a composite of work done in Germany and Northern Ireland, is now over 11,000 years long. Of particular interest to many A\textit{J}.A readers is the recent development of a 1,000-year oak chronology in Poland, which has demonstrated that panel paintings in Western collections, signed by artists such as Rubens, Rembrandt, etc., were painted on oak boards imported from Gdansk in the eastern Baltic.

Significant work, but outside the scope of this report, is going on elsewhere: some archaeological, some climatological, and some palaeoclimatological. Notable progress has been made in recent years in South America with the development of long chronologies from \textit{Fitzroya cupressoides} in the vicinity of the Patagonian glaciers, in China with attempts to link the tree-ring record with the Chinese archival records, in Russia with the study of tree growth at the northern timberline, and in Spain with the study of medieval monuments.

DENDROCHRONOLOGY IN THE AEGEAN

My own work has been focused on the Aegean for the last 20 years. Progress as of spring 1993 is shown in figure 11. We have about 6,000 years of chronologies spread out over the last 9,500 years in a region bounded by the Turkish-Georgian frontier in the east, the mountains of northern Lebanon in the south, including all of Turkey, Cyprus, Greece, parts of Bulgaria and the former Yugoslavia, and extending to the instep of the Italian boot at Mt. Pollino in Calabria. Whether we can push northward into the Crimea, northeastward into the Caucasus, and southward into northern Syria and other Near Eastern countries remains to be seen. Mesopotamia and Iran are for the moment inaccessible, but may some day yield useful information. We expect imported cedar and juniper from the Lebanon, found in Egypt, to crossdate with Anatolian chronologies.


Absolute chronologies for several genera of trees extend back for a millennium. Our oak sequence ends in A.D. 927. An eighth/ninth-century gap in the oak chronology may be filled by timbers from Amorium that were collected during the summer of 1993. A post-Justinianic gap exists just after the primary timbers from St. Sophia in Istanbul were cut. Another gap exists around the time of Constantine. Indeed, the millennium from roughly 500 B.C. to A.D. 500 is the most problematic of the last 4,200 years, although the first half may have been sorted out by the recent construction of a 513-year ring sequence from boxwood timbers in the Comacchio (Ferrara) shipwreck. The sequence, with which a number of other ring chronologies crossdate, is dated to the last decades B.C. by three and a half tons of lead ingots stamped with the name AGRIPIA. A 1,761-year continuous ring sequence from around 2259 B.C. to around 498 B.C. is the longest we have. Early Bronze Age sequences are still under construction (see Studia Troica III, Tübingen 1993). For the prehistoric period, the most notable advance in the last year has been the development of almost 700 years of chronologies for the Neolithic site of Çatal Hüyük.

**PRACTICAL MATTERS**

For the dendrochronological method to succeed, long ring sequences are needed. We have measured junipers with as many as 918 annual rings. Çatal Hüyük charcoal fragments no larger than a half-golfball have as many as 250 rings preserved. Crossdating material like this is relatively easy. Trying to date samples with fewer than 100 rings, on the other hand, is generally not worth doing. Quantities are important. A set of 100 samples is vastly preferable to a set of 10, and single samples are to be avoided except in desperation. One cannot tell from internal evidence whether a single sample has been reused from an earlier construction, cut particularly for the purpose to which it was finally put, or is some later repair. Species are important. Oak, pine, juniper,

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chronology for the Roman Ship at Comacchio (Ferrara),” forthcoming.
Radiocarbon calibration: Current Issues

S.G.E. Bowman and M.N. Leese

Radiocarbon dating has made a major contribution to archaeology for more than 40 years. For at least the last decade and a half, an immense amount of effort has been invested in providing calibration curves, in ensuring and evaluating data quality, and in interpreting results. The sheer volume of information is bewildering and much of it is seemingly complex, especially as new data are often presented without reference to the implications for archaeological application. In this review we are concerned only with the calibration of radiocarbon dating results and particularly with the status of recent calibration data and the emergent use of Bayesian statistics.

It must be stressed that calibration is often viewed as a final step, requiring thought only after the radiocarbon results have been supplied by the laboratory. On the contrary, the need for, and effect of, calibration are essential considerations in the sampling strategy. They may even influence the choice of laboratory, for example, if high precision proves necessary. Discussion among the archaeologist, radiocarbon scientist, and statistician is needed virtually from the moment the excavation is mooted. Only then can the correct type, size, and number of samples be dated for key contexts having well-understood sample-context-event associations. The archaeologist can also assess the funding needed, the support he or she will receive in the interpretation of the radiocarbon chronology, and the quality of work produced by a given laboratory.

The need for accurate results (i.e., those with no systematic bias) is self-evident, and every laboratory ought to be able to provide evidence for its accuracy. Equally important is the need to estimate realistically the precision (i.e., the random variability) of the results, since an assessment of this, together with the error on and shape of the calibration curve in the region of interest, determines the calendar age range(s). Use of an error multiplier is often suggested because of concern that the quoted error, which may be based only on counting statistics, does not fully reflect true variability (assessed by replication experiments or intercomparisons between laboratories). As an alternative, the current update of the program CALIB suggests the incorporation of ad-

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ditional laboratory error terms. Somewhat inexplicably, however, the values suggested are the errors on a long superseded calibration curve; thus, we strongly recommend against this procedure. While it may seem better to over- rather than underestimate precision, in fact, this may not be erring on the side of caution. For example, a \( \chi^2 \)-test (a statistical test of "agreement") could give an entirely erroneous confirmation of assumed contemporaneity. Again, only the laboratory itself can give the necessary information on the reliability of its error estimates and should be requested to do so.

CALIBRATION DATA

The publication in 1986 of a calibration issue of Radiocarbon (vol. 28:2B) and recommendation of the consensus curves of the Belfast and Seattle laboratories for the period 2500 B.C.–A.D. 1950 was a considerable breakthrough. This provided a much-needed single, and seemingly definitive, calibration curve with the promise of its extension to earlier periods. The picture presented in the 1993 Radiocarbon calibration issue (vol. 35:1), however, appears considerably more complex. Figure 12 summarizes which assumes a priori evidence for contemporaneity, is relevant. "Case II" is unrealistic, as it does not take account of "wiggles" in the calibration curve.


some of the 1993 curves based on dendrochronology. At least three of the data sets contain revisions of previous data, the maximum correction being about 30 radiocarbon years. Regrettably though the need for these changes may be, they illustrate the extreme care taken by the high-precision laboratories to check and recheck their experimental procedures and resultant data. Neither the revision of data nor the apparent proliferation of calibration curves should be taken as an excuse, as was previously prevalent, not to calibrate.

In choosing a calibration curve, it is best to match the age span of the sample to the time interval between points on the curve. Curves based on single-year samples are limited, but it has been shown that calibration of a single-year sample against decadal or bidecadal curves can lead to an underestimate of the calendar age range. For long-life samples, having an age span of, e.g., 100 years, a moving average of the calibration data is needed and some computer programs provide this option, but extreme care obviously needs to be taken in interpreting what archaeological event such long-life samples represent. The decadal or bidecadal curves, however, are the most suitable for many of the more archaeologically appropriate radiocarbon samples such as bone and round-wood. In the absence of a recommended consensus calibration data set, currently available calibration programs use different ones, ranging from the 1986 recommended curves to a combination of curves largely based on those summarized in figure 12.

CALIBRATION METHODS

Like calibration data, methods of calibration are under review. A consensus is emerging, however, that calibrated dates can be faithfully represented only by probability distributions that fully take account of both the error term on the radiocarbon result and the effect of the wiggles in the curve; the wiggles indicate that any one radiocarbon result can correspond to more than one calendar age range. Unfortunately the simplest method of calibration, the “intercept method,” does not properly represent those probabilities that can be calculated only with a computer program. Several such programs are available for dealing with dates individually, most of which, explicitly or implicitly, use the Bayesian methodology. Their underlying model assumes a priori that dates on the calendar scale are equally probable, which seems eminently reasonable in the absence of any information to the contrary. When combined with a radiocarbon result using Bayes’s theorem, this model gives rise to the probability distributions produced by programs such as CAL15, CalibETH, and CALIB. In contrast, those programs that “divide” radiocarbon probabilities before transferring them to the calendar scale are, in effect, assuming a priori that the true radiocarbon values rather than the calendar dates are equiprobable.

In the interpretation of groups of radiocarbon results, the simplest approach is to use charts of confidence bars or probability distributions for the individual sample, but these provide only a “by eye” indication of trends. Ideally, one should be able to combine all of the available data, both radiocarbon and archaeological, into a single statistical model. Bayesian methodology is particularly suited to this aim and can deal with, for example, calibration of a single result combined with an archaeological or historical terminus (post or ante quem), or calibration of groups of dates with stratigraphic ordering or phasing. The end product consists of, i.e., probability distributions similar to those already

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99 Van der Plicht and Mook (CAL15) and Nicklaus et al. (CalibETH) (supra n. 94); Stuiver and Reimer (supra n. 90) 215–30.
100 In such programs, the probability (p) associated with a given radiocarbon result is divided by the number (n) of calendar dates corresponding to that result before converting to the calendar scale. By contrast, programs that do not divide probabilities assign the whole probability (p) to each of the n calendar dates. For the former programs, the accumulated probabilities on the calendar scale sum to unity; for the latter, they must be standardized to do so.
102 Several examples illustrating the types of problem with which Bayesian methods can deal are described by C.E. Buck, J. Kenworthy, C.D. Litton, and A.F.M. Smith, “Combining Archaeological and Radiocarbon Information: A Bayesian Approach to Calibration,” Antiquity 65 (1991) 808–21; also see C.E. Buck, C.D. Litton, and A.F.M. Smith,
Radiocarbon Dating by Accelerator Mass Spectrometry

R.E.M. HEDGES

The technique of measuring radiocarbon using Accelerator Mass Spectrometry (AMS) has been in existence for nearly 15 years, and radiocarbon dates have been produced by this method for over a decade. Although only about a quarter of these are archaeological, I estimate that well over 10,000 AMS archaeological dates have been produced. This short review attempts to draw some very general trends and conclusions from such abundance. I apologize in advance for drawing so frequently on the experience gained by others about the principles of radiocarbon dating. This is a rapidly evolving field, and my understanding is based on a more limited exposure than is that of more experienced archaeologists.


103 E.g., CALIB and CAL15 (supra ns. 90, 94, and 99) provide an option that simply sums calibrated probability dis-

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rience of the Oxford Laboratory, but I know its work best, it has published the most archaeological dates, and it is the most specialized of the AMS laboratories in archaeological dating.

THE BASIS AND SIGNIFICANCE OF THE AMS TECHNIQUE

To obtain a radiocarbon date, it is necessary and sufficient to measure the relative abundance of the carbon isotopes $^{12}$C, $^{13}$C, and $^{14}$C in a suitable sample. The measurements must have an accuracy approaching 0.5% to hope to achieve a dating accuracy of 50 years. The main difficulty is the extremely small amount of $^{14}$C, which is therefore hard to detect, and especially so in the quantities necessary to give the statistical precision required for an accurate date. The "conventional" method detects $^{14}$C from its own radioactivity, but since it has a half-life of 5,730 years, only a tiny fraction of $^{14}$C atoms is detected in a reasonable time, and even samples containing as much as 1 g of carbon are barely sufficient for a measurement. This sets a limit of sample size, and thereby of sample selection and sample chemical treatment procedures. The AMS method detects $^{14}$C atoms independently of whether they radioactively disintegrate, measuring about 1% of all $^{14}$C atoms and requiring samples of only 1 mg of carbon (and often less).

The main outcome is that archaeologists now have far more possibilities as to what samples can be dated. Therefore, the value of the technique depends very much on how well this choice is exercised. In other respects, the AMS method does not differ greatly from the conventional method. The cost is somewhat higher, the measurement error similar (though the results are more reliable due to better selection), and the age range much the same (though again, older dates are undoubtedly more reliable because samples have been better freed from modern contamination). Both methods are subject to calibration.

Making samples smaller by 1,000 times, however, broadens the scope for many new approaches.

104 I would like to thank all the members of the Oxford Radiocarbon Accelerator Unit for their enthusiasm and support, and in particular Rupert Housley for reading a draft of this review. The Unit is partially supported by the Science and Engineering Research Council. Archæometry Date lists 1–16 appear in Archæometry 26–34 (1984–1992).


ADVANTAGES OF GREATER SELECTIVITY

The advantages of much greater selectivity generally fall into two categories: an increase in the archaeological reliability of the date (nos. 1–4), and the generation of new chronological information (nos. 5–6).

1) Rechecking dates. If a laboratory date seems questionable, for whatever reason, sufficient sample is often available for a second measurement, which might help to confirm that the original measurement was not in error. Notoriously problematic dates, e.g., those of the Thera volcanic eruption\textsuperscript{106} and the (Pleistocene) "Red Lady of Paviland,"\textsuperscript{107} can thus be checked.

2) Improved chemical "pre-treatment." When only 1 mg of carbon is required for analysis, it is relatively easy to find material that can be better chemically characterized and/or be subjected to more stringent chemical procedures. Therefore, reasonably well preserved bone has turned out to be the sample material of preference, because it contains the chemically well defined protein collagen.\textsuperscript{108} Poorly preserved bone, all too frequent on hot and arid sites,\textsuperscript{109} remains problematic. The question of chemical treatment becomes especially important for dates beyond 30,000 years, and only consistent stratigraphic sequences can demonstrate its effectiveness.

3) Comparison of different fractions. Related to the above is the ability to compare different fractions (chemical or otherwise) from the same sample. Different sources of carbon in sediments can be sorted out using this approach. Of particular interest has been the comparison of the "charcoal" and "humic" fractions in charred carbonaceous material.\textsuperscript{110} Their agreement obviously strengthens the reliability of the date obtained. This approach has been used in several situations, including the rather controversial issue of contamination in the Theran seed material. In many ways, it is one of the most powerful methods available for establishing reliability, although, of course, the cost of dating is thereby increased.
A useful spin-off is that more is learned at the same time about the processes of environmental contamination.

4) Selecting more directly relevant material. Small charcoal samples generally enable short-term growth material to be selected, avoiding mistakes due to reuse, or differences between heartwood growth and felling times. On the other hand, small charcoal fragments (or seeds) are fragile and all too mobile, and can be used only with great caution to date the strata from which they have been excavated. The dating of the late Upper Palaeolithic (Tjongerian) site of Rekem (Belgium), whose sandy deposits contained charcoal fragments loosely associated with fires, as well as microliths (one with attached arrow shaft adhesive), is an interesting case. The charcoal dates all proved to be stratigraphically incoherent and archaeologically useless, while the adhesive was able to supply a clear and useful date. In general, larger samples (e.g., bone) are found to be stratigraphically more static. We have found that finely disseminated charcoal, often collected into sedimentary lenses, is an especially difficult sample material from which to obtain consistent dates. For the dating of sediments, preserved terrestrial macrofossils are of increasing importance in establishing the regional and ecological context of an archaeological site.

5) New or better datings. Since AMS enables more samples to be dated, despite smaller sample size, many sites can be dated, either de novo, or else much more thoroughly than before. This is arguably the category with the greatest general benefit to archaeological dating. In particular, open sites with limited stratigraphy, such as the French Upper Palaeolithic sites of Pincevent, Etiolles, and Marsangy, have been able to be dated.

One site that has benefitted from a sustained and intensive AMS dating program is Abu Hureyra in Syria, which was occupied during the Epipalaeolithic and Neolithic periods. The dating of the stratigraphy, as well as specific seeds and burnt animal bones, has helped greatly in piecing together the evidence for the development of early agriculture. Jeitun in Turkestan, for which the only material available for dating was carbonized seeds, is another example of an early agricultural site that could be dated by AMS.

6) Directly datable samples. Many archaeological finds are precious, due to their inherent information content. Often they may still be dated by AMS if a small sample can be taken. Another dimension is thus added to the chronological framework inferred for the sample’s archaeological context. As one clear example, direct dating by AMS has shown that many human inhumations (in caves, for instance) are intrusive, and of later date than the cultural remains, which are often stratigraphically indistinguishable.

In general, the more information attached to the sample, the better. For example, dating a snowshoe hare bone bearing cut-marks not only dates the depositional stratum, but also dates a human presence, and the dating refers both to human cultural practice and also to the ecological and climatic setting. Typically about 200 mg of bone is sufficient for such a date. Evidence for animal domestication or changes in plant morphology due to cultivation may also be directly dated through measuring a single charred seed or a pig tooth. Such dates, however, can turn out to be later than expected because of problems of sample movement and stratigraphic uncertainty.

We have dated two grape pips found on different Neolithic sites. One was from the excavators’ lunch, and the other is the first occurrence of Vitis vinifera in Great Britain.

One of the most important information-bearing artifactual materials in archaeology is pottery. The dating of pottery is reliable only if it contains definite traces of food residues, or if any of the original carbonaceous temper survives and can be extracted. AMS dating has identified the earliest pottery so far found in the Americas, and confirmed early Neolithic dates in China.

Artifacts with virtually no context have also been dated. For example, the Oxford Laboratory has dated numerous bone points and harpoons of uncertain provenience, in order to establish a general typological sequence, particularly through the Mesolithic.
and Neolithic periods of northern Europe. More spectacular is the dating of rock paintings, which seldom contain sufficient carbon or well-characterized organic materials. Several French Upper Palaeolithic cave paintings have been dated from their charcoal content by the French AMS Laboratory at Gif.\textsuperscript{117} More controversial is the dating of what are believed to be blood proteins from Australian rock paintings.\textsuperscript{118} Here, reliability is again the crucial issue, for the chemical “pre-treatment” is being asked to perform at, or perhaps beyond, its limits. It is, however, an indication of the direction of future research.

CONCLUSIONS

The full archaeological potential of radiocarbon dating by AMS depends on a comprehensive grasp of how its selectivity may best be exploited. On the technical side, selectivity can be increased as smaller and smaller samples are able to be analyzed and as our understanding of the processes of organic degradation and environmental contamination improves. With deepening understanding, reliable dating beyond 50,000 years may eventually prove possible. To date, AMS’s chief contributions have been to provide much greater reliability in radiocarbon dates and to forge a closer relationship between specifically archaeological information and chronological data.

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Ceramic Ecology

FREDERICK R. MATSON

Archaeologists are increasingly including consideration of ecological aspects in their studies of Near Eastern, Mediterranean, and European ceramics, but perhaps not as much as in other parts of the world. In addition to shape and decoration, long reported in detail, pottery can be examined in terms of mineral and chemical composition, variations in methods of production and firing, and, of course, stratigraphic and regional distributions. Such data, together with cautiously used knowledge of the practices of present-day village potters, can at times be of use in better understanding the social, economic, and political aspects of past cultures. The potters and the pottery they produced were insignificant in the broad cultural perspective, but the almost indestructible nature of fired ceramics, and the subtle record potsherds and vessels retain when most other material remains have long vanished, make it essential that they be carefully excavated and studied in many ways.

“Ceramic ecology may be considered as one facet of cultural ecology, that which attempts to relate the raw materials and technologies that the local potter has available to the functions in his culture of the products he fashions.”\textsuperscript{119} This characterization of the field has met with approval, and been recently discussed in some detail by Rice, who also comments on the potential value of a ceramic ecological approach in archaeological research:

The final step of a ceramic ecological investigation is relating the accumulated data on the environmental and socio-technological factors of pottery making to the broader role of pottery in a culture. This includes such features as economic organization (local and long-distance trade arrangements), kinship structure, settlement patterns, demographic factors, ceremonial or ritual activities, and so forth.

Pottery manufacture, like any other productive technology, represents a point where a cultural system interacts directly with the environmental system. . . . Ceramic ecology can be linked with ceramic technology to show pottery production as one of the many patterned ways of exploiting particular environments and as one of a variety of economic adjustments in a network of productive relations in a society. Ceramic ecology emphasizes the potter’s role


\textsuperscript{118} T.H. Loy, R. Jones, D.E. Nelson, B. Meehan, J. Vogel, J. Southon, and R. Cosgrove, “Accelerator Radiocarbon Dat-

as an active and controlling agent in the procedures of pottery manufacture (resource selection, forming techniques, firing strategies) as these are revealed through technological analyses of both ancient and modern pottery.\textsuperscript{120}

Publications on ceramic ecology are scattered widely in the literature, and few of them until recently have dealt with Old World pottery. This may be because many archaeologists interested in the subject have an anthropological background that has been more directed toward New World studies. The range of non-Old World studies that appear in the materials cited here should provide a basis for selective approaches that can be applied anywhere in the world.

A volume edited by van der Leeuw and Pritchard contains several papers related to Near Eastern ceramic ecology. In their preface, they state: “The conference which resulted in this volume . . . held in 1982 . . . was deliberately planned as a sequel to an earlier symposium entitled ‘Ceramics and Man’ in 1962. . . . The primary aim of the 1982 conference was to attempt to elicit an assessment of what had been achieved in the field of ceramic research since 1962, both in archaeology and anthropology, and also to suggest new directions for further research.”\textsuperscript{121} Ceramic ecology has been the topic of at least four symposia at successive annual meetings of the American Anthropological Association from 1986 through 1989, and the papers presented at the first three have been published.\textsuperscript{122} New World ceramics are highlighted in these publications. Technological studies of Old World ceramics in their social contexts, however, appear frequently in the five volumes published between 1986 and 1990 by the American Ceramic Society in the series \textit{Ceramics and Civilization}, edited by W.D. Kingery and P.E. McGovern. Ceramic technology was the general subject of an entire issue of \textit{World Archaeology} (vol. 21:1, 1989). Many of the papers in this issue are pertinent for the Old World, specifically Near Eastern ceramic ecological studies. \textit{Art and Archaeology Technical Abstracts}, which are now published by the Getty Conservation Institute, often include abstracts of ceramic research in which one or more aspects of an ecological approach appear.

Examples of ceramic ecological concerns dealing with the Near Eastern and Mediterranean regions can be subsumed under the following topics, to which others might well be added.

\textbf{ENVIRONMENT}

J.N. Postgate makes specific use of the voluminous historical records found on cuneiform tablets in discussing Mesopotamia from 3000 to 1500 B.C.\textsuperscript{123} His discussions help to place potters in their ecosystem, and aid in the more effective initial study of the raw materials that the potters had available and of the markets that they supplied. Similarly, in synthesizing the archaeological evidence for the early cultures of western Iran, Hole and his colleagues relied on a detailed knowledge of the landscape and of the excavated pottery and architectural remains; in the final chapter of the book, G.A. Johnson provides an excellent example of the selective synthesis of field data to delineate a broad picture of change, including developments in ceramic production.\textsuperscript{124} This is a far different approach from the disdainful or perhaps puckish characterization of abundant potsherds on Near Eastern sites as “fairly durable rubbish,” which was made by a distinguished anthropologist over 50 years ago.

\textbf{TECHNOLOGICAL STUDIES}

Detailed laboratory analyses of ceramics are welcome and necessary aspects of archaeological reports, but their results too seldom are integrated into substantive discussions. Several well-illustrated reports on the Scarlet ware of the Early Dynastic period found at Uch Tepe in the Hamrin Basin of the Upper Diyala River in northeastern Iraq show, in addition to the technological data presented, a knowledge of the social or cultural aspects of the problems.\textsuperscript{125} Results from the several analytical techniques used, while complementing one another, also provide unique perspectives on the pottery together with the cultural and natural landscape in which it was produced. As an example of a very different approach, abundant kiln wasters and finished ceramic ware were found and carefully documented at Tell Leilan in northeastern Syria, an important urban center dur-


\textsuperscript{121} S.E. van der Leeuw and A.C. Pritchard eds., \textit{The Many Dimensions of Pottery: Ceramics in Archaeology and Anthropology} (Amsterdam 1984) xv.


ing the third millennium B.C. On the basis of compositional analyses and measurements of the vessel dimensions, together with statistical studies using several indices of standardization, it was shown that, with careful spatial and chronological controls, "one can use the standardization hypothesis as an effective methodology in reconstructing the productive organization of complex societies."126

CERAMICALLY DEFINED CULTURES

A sampling of recent publications concerned with ecological aspects of ceramics indicates, to some extent, the wide range of existing interests. The 'Ubaid period in lowland Mesopotamia with its well-known ceramics is the connecting link in time between the earliest farming communities and the more complex, regionally organized societies of the Uruk period, which were the forerunners of the Sumerian city-states. A recently published group of papers on the 'Ubaid127 relies greatly on the ceramic evidence in discussing trade and incipient state formation. One diagnostic vessel type of the Uruk period is the bevel rim bowl, which occurs in great abundance at many sites. There are many suggestions concerning the use of these bowls, but few that are convincing. Is it possible that the bowls were used to tightly bake bread, which in turn was used in the production of beer, a staple food product? Chazan and Lehner make a cogent argument for this hypothesis, summarizing previous studies and citing pottery parallels, especially as illustrated in tomb drawings in Egypt.128

The pottery of medieval Nubia has been thoroughly studied by Adams,129 who discusses the detailed information he has obtained from both archaeological and ethnographic materials. The trade of widely distributed Egyptian water jars, made for the most part at Ballas in Upper Egypt, is one facet of a detailed study of pottery manufacture at this site.130

The ecological aspects of the early phases of Neolithic ceramic production in the Aegean world are briefly considered in Vitelli's exceptionally thorough report131 on the pottery excavated at Franchthi Cave in southeastern Greece. In her concluding chapters, she comments on cooking pots that were probably used for other purposes, specialist potters who produced Urfinis ware, potters who may have been shamans, and pots as markers of social change.

CERAMIC ETHNOARCHAEOLOGY

Kramer's thorough survey and discussion of ceramic ethnoarchaeology132 focuses on studies "which explicitly consider contemporary pots and potters in terms of particular problems with which archaeologists frequently struggle." Her discussions of ceramic production, use, disposal, and change help place Near Eastern pottery studies in a world perspective, broadening the range of possible areas of ceramic inquiry for the Near East and the Mediterranean regions. Longacre's broad-ranging compilation of papers from an advanced seminar at the School of American Research in 1985 includes only one article that pertains to our present areas of discussion.133 His authors, all archaeologists, concern themselves with identifying social and behavioral sources of ceramic variation in societies all over the world. The bibliography in this volume is exceptionally thorough.

Village potters in Pakistan, and until recently in Afghanistan, continue to produce their wares unimpeded by modern technical practices. They provide current examples of long-standing techniques of pottery making. Rye and Evans's detailed report on Pakistani pottery134 is exceptionally well illustrated and documented, and includes analytical results from laboratory studies.

Theoretical considerations, as well as field documentation, have great merit. The way in which Arnold135 organizes the ceramic data obtained from

127 E.F. Henrickson and I. Thuesen eds., Upon This Foundation: The 'Ubaid Reconsidered (Copenhagen 1989).
131 K.D. Vitelli, Franchthi Neolithic Pottery 1: Classification and Ceramic Phases 1 and 2 (Bloomington 1993).
his own fieldwork in Mexico, Guatemala, and Peru, together with that culled from ethnographic and archaeological reports, leads to generalizations and theorizing about the massive literature on ethnographic ceramics. Arnold is also concerned with what stimulates or hinders ceramic production. The relatively few Near Eastern entries in his index suggest that there is still much left to be done with Near Eastern ceramics in this regard.

As a final note, since archaeological fieldwork is not possible at present or severely limited in many parts of the Old World, it may well be the time to reconsider from an ecological point of view the pottery that is available in museums and extensively reported upon in publications. Materials now in storage or on exhibit might be reexamined. Questions could then be posed that supplementary fieldwork might be able to answer when excavation and site surveying resume on a larger scale.

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Ceramic Petrography

IAN C. FREESTONE

The petrography of archaeological ceramics involves the description, classification, and interpretation of ceramic pastes, or fabrics, using techniques derived from those used in geology to describe rocks (petrography). The primary research tool is the petrographic, or polarizing, microscope, and the ceramics are examined as thin sections, prepared from slices or fragments of pottery that are fixed to glass slides and abraded to a standard thickness (0.03 mm). At this thickness, many of the more common minerals become translucent, and may be identified on the basis of their characteristic optical properties, such as color, refractive index, and cleavage (fracture pattern).

In ceramic petrography, attention is focused primarily upon the identification of the nonplastic inclusions that are set in the fine-grained clay matrix, as well as the determination of their textural characteristics such as abundance, shape, and size. The inclusions are typically defined as those inclusions of the paste that may be characterized effectively—in practice, those that are larger than the 0.03 mm thickness of the section. These are most commonly rock or mineral fragments, ranging up to several millimeters in diameter and occupying a large volumetric percentage of the fabric. Inclusions may occur naturally in the clay, in which case they are described as "intrinsic" or "incidental." Alternatively, they may have been added deliberately by the potter to improve the working or firing properties, in which case they are commonly described as "temper." In addition to materials derived from rocks, tempers may include a range of biological and man-made materials such as grog (crushed pottery), chaff, bone, slag, and shell.

Petrography is invaluable in the study of paste preparation techniques and can yield useful information on methods of forming and firing parameters. The interest of most archaeologists, however, is in the utility of the method in the determination of provenience. In this review, provenience studies are emphasized, together with some guidelines that are of assistance for designing a successful project or in evaluating a proposed project design.

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136 This essay has benefited from many discussions among members of the Ceramic Petrology Group. The views expressed remain my own, however. I thank Sheridan Bowman and Andrew Middleton for their comments on the draft.


139 Many authors have noted changes in the optical characteristics of minerals in fired pottery. For an account of such changes, see J.C. Echallier and S. Méry, "L’évolution minéralogique et physico-chimique des pâtes calcaires au cours de la cuisson: Expérimentation en laboratoire et application archéologique," in Méry (supra n. 136) 87–120.
PROVENIENCE STUDIES

In the broadest sense, the term “provenience” is usually understood to involve the subdivision of ceramic assemblages into production-related groups, without necessarily locating the sources themselves, although this remains the ultimate goal. Petrography may be considered useful on a number of levels. First, it is invaluable in paste classification, enabling the identification of wares produced from the same raw materials in the same technological tradition, e.g., grog-tempered ware, sandy ware, etc. The discrimination between likely production groups is more convincingly demonstrated using petrography than by macroscopic examination alone, and is best carried out on a carefully selected sample at an early stage in the processing of large bodies of excavated pottery. The close relationship between the observations in thin section and the appearance of a sherd in fracture allows petrographically defined paste groups to be used as standards against which the remaining bulk of the pottery may be sorted using low-power binocular microscopy. Outliers are readily identified in this way.

Second, petrography may be used in paste characterization. A detailed petrographic description may be used to fingerprint a paste, establish a paste group, and compare it with ceramics from a known source. Within a relatively homogeneous geological environment, however, the differences between pastes produced at different workshops may be slight and not distinguishable qualitatively. Therefore, attempts have been made to improve the precision of petrographic descriptions by estimating the volumetric proportions of the minerals present as volume percentages (modal analysis) or by measuring the grain size distributions of the inclusions (fig. 13). These measurements can be time-consuming, but offer the possibility of applying statistical techniques to establish paste groups and discriminate between sources. In this way, petrography may be used to provenience ceramics in a manner similar to trace element analysis. Nevertheless, the heterogeneous nature of the coarse fraction of the ceramic paste is a limitation, so that even quantitative petrographic approaches of this type lack the precision and sensitivity (hence the discriminating power) of modern elemental techniques such as neutron activation analysis (NAA) and inductively coupled plasma spectrometry (ICPS). NAA and ICPS routinely achieve a precision of about 2% on 20 or more elements. There are rarely more than three or four mineral species present in a ceramic paste that can be quantified with such a degree of precision. If paste groups cannot be distinguished by qualitative or semi-quantitative petrographic methods, then recourse to trace element analysis rather than quantitative petrography is the approach most likely to be successful.

Finally, the potential of petrography as a predictive provenience technique has resulted in the widespread application of the method. The rock and mineral inclusions within a paste are a reflection of the geology of the source area of the ceramic. Therefore,

Fig. 13. Pastes containing abundant inclusions of quartz sand are unlikely to be immediately diagnostic of source. In the case of this pottery from the Iron Age site of Hengistbury Head (Dorset, southern Britain), however, it has been possible to distinguish two important production groups on the basis of grain size distribution, a distinction that has been confirmed by trace element analysis. The photomicrograph, with a field of view 6 mm across, shows abundant subangular grains of quartz (pale) in a fine-grained fired clay matrix (dark).

137 Supra n. 137.
138 This type of approach is illustrated in many published applications; see Middleton and Freestone (supra n. 136) passim.
139 For a discussion of some of these approaches, see I.C. Freestone, “Extending Ceramic Petrology,” in Middleton and Freestone (supra n. 136) 399–410.
140 Petrography and elemental analysis have frequently been found to show agreement when applied to the same material. See, e.g., A.P. Middleton, M.R. Cowell, and E.W. Black, “Romano-British Relief-Patterned Flue Tiles: A Study of Provenance Using Petrography and Neutron Activation Analysis,” in Méry (supra n. 136) 49–60; G. Schneider and E. Wirz, “Chemical Approaches to Archaeological Questions: Roman Terracotta Lamps as Documents of Economic History,” in Méry (supra n. 136) 15–48, also found the chemical classification replicated in a subset of their sample subjected to thin-section analysis. Y. Manatis, R.E. Jones, I.K. Whitbread, A. Kostikas, A. Simopoulos, C. Karakalos, and C.K. Williams, “Punic Amphoras Found at Corinth, Greece: An Investigation of Their Origin and Technology,” JFA 11 (1984) 205–22, find good agreement in a range of characterization techniques.
it may be possible to predict the geology of the source area from the ceramic petrography and, from a knowledge of the regional geology, predict the location of the source. In some circumstances, only a single thin section may be needed to make such a prediction, and this characteristic distinguishes petrography from other provenience techniques that depend on statistical matching with reference groups based upon the analysis of large numbers of samples. There are many classic examples of this type of study. The studies of Peacock have been notably successful. See D.P.S. Peacock, "A Contribution to the Study of Glastonbury Ware from South-Western England," *Antf* 49 (1969) 41–61; D.P.S. Peacock and D.F. Williams, *Amphorae and the Roman Economy* (London 1986); M.G. Fulford and D.P.S. Peacock, *Excavations at Carthage: The British Mission* 1, pt. 1 (Sheffield 1984).

The term resolution is used here in a slightly different sense than that suggested by P.A. Wardle, *Bronze Age Pottery from Eastern Yorkshire* (Diss. Univ. of Bradford 1991), who uses it to indicate the geological limits, expressed in kilometers, for locating a pottery source. It is desirable to understand the constraints that act upon the petrographic method before embarking upon a research program.

**PETROGRAPHIC RESOLUTION**

The success of a project is in general determined by what may be termed the resolution of the petrographic technique—viz., the degree to which the petrographies of the ceramics under study allow discrimination between production groups or potential raw material sources. The petrographic resolution can vary greatly, depending on a number of factors that are discussed below. An awareness of these factors not only enables the evaluation of the likely success of a proposed research program, but also facilitates good project design. The geographical limits of a postulated source area also depend on a number of these factors and are closely related to the petrographic resolution.

1) *The geology of the study area.* The more variable and diverse, the more likely are production groups to have qualitatively different fabrics. Of course, the geology is likely to be more diverse on an international scale than a local one, which is reflected in the success of the technique in identifying interregional movement in some ceramics, such as Roman transport amphoras.

2) *A well-characterized data base.* A good background knowledge of the petrographies of other ceramic types from the region and period as well as of the local geology (backed up by fieldwork and sampling of potential raw materials, particularly where maps, memoirs, and reference collections are not comprehensive) can be of great value in improving the petrographic resolution so that useful conclusions may be made even in relatively unpromising situations.

3) *Ceramic technology.* In general, pastes with coarse rock and polymineralic sand tempers are more likely to provide evidence of the source geology than are very fine-grained pastes. There are, however, some outstanding examples of fine-grained pastes that are highly diagnostic of source. For example, certain fine

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145 The term resolution is used here in a slightly different sense than that suggested by P.A. Wardle, *Bronze Age Pottery from Eastern Yorkshire* (Diss. Univ. of Bradford 1991), who uses it to indicate the geological limits, expressed in kilometers, for locating a pottery source.


147 The traditional view that, in contrast to fine wares, coarse pots were not widely traded has been overturned to a large extent. Analytical studies demonstrate that cooking pots, for example, sometimes move over long distances.
wares produced in southern Italy in the Hellenistic and Roman periods are characterized by the presence of numerous very fine fragments of volcanic glass in the matrix. It is essential that the analyst take full advantage of the information offered by the petrography to understand the ceramic technology, since pottery-making traditions can mislead the analyst (for example, the potter might have mixed clays or used as temper pieces of erratic boulders that had traveled far; see fig. 15).

4) Petrological interpretation. Experience has shown that a good understanding of the modes of formation and occurrence of rocks can be very significant in interpreting the ceramic petrographies of pots. For example, the compositions of certain relatively common mineral types, such as feldspars, reflect the geological environment from which they are derived, whether plutonic, metamorphic, or volcanic. The term “ceramic petrology” is sometimes used to describe the broader theoretical framework of this approach. The implication is that the analyst possesses or has access to a level of interpretative skill beyond the purely descriptive.148

5) Reducing background “noise.” By comparing like with like and restricting the sample to ceramics that have been closely defined in terms of typology, better petrographic results can be achieved. Many of the most successful provenience studies have been based on carefully restricted ceramic types, such as “Glastonbury Ware,” “Pompeian Red Ware,” etc.

6) A sufficient sample size. Where the differences between paste groups are subtle or not immediately apparent, it is often essential that multiple examples of each group are represented in the analytical sample. The worst type of sample upon which to base a petrographic study is a selection of 40 or 50 sherds, each of which represents a different ceramic type or form. Where groups are established on the basis of statistical analysis of quantitative data, then the minimum size of a group to ensure that it is valid may well be 10 or more.

It will be recognized that the degree of resolution required for the successful outcome of a project depends upon the questions to be answered. To the archaeologist working in prehistoric Britain or France, the identification of a volcanic sand in a ceramic paste is very significant, pointing to an origin in southern Italy. To the excavator of a villa in the vicinity of Rome or Naples, such information is often of no assistance as volcanic sands are ubiquitous there. Thus, in project formulation, it is necessary to balance the resolution anticipated on the basis of geology, ceramic technology, and the available number of samples against that required to answer the questions of interest.

Even when all other controlling factors appear favorable, pottery traditions can be critical in determining the extent to which petrography is useful (fig. 16). If calcined bone or some other widely available material was used to temper a clay, then there may be no possibility of proveniencing a ware, even if production took place over the outcrop of a unique

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rock type. For this reason, a pilot study of up to 20 thin sections is always to be recommended before any major piece of work is undertaken. An informed judgment of the likely outcome can then be made, and the optimal sample can be selected.

CONCLUSIONS

With an appreciation for the factors that influence a petrographic project, a researcher should be able to make a realistic assessment of the potential of an analytical program in his/her problem area and the levels of interpretation that are possible. Projects may be structured so that, if direct provenience prediction is not possible, then useful information will be obtained at the level of paste classification or characterization. The petrographic resolution may be improved by systematic collection of reference materials, including geological data, raw material samples and comparative ceramics from the study area. Pilot studies may be carried out on selected groups of material. Finally, it should be emphasized that an experienced analyst is best fitted to advise on and carry out a project if he/she is involved in research formulation at as early a stage as possible.

Ceramic Petrology and Petrography in the Aegean

SARAH J. VAUGHAN

INTRODUCTION

Ceramic petrological and petrographic techniques, which are derived from the geological sciences, have proved to be valuable tools for both the characterization and proveniencing of ancient pottery and other ceramics (including building materials such as concrete, mortar, plaster, etc.). Petrology is broadly defined as the study of rocks according to their chemical, physical, and optical attributes, to elucidate their occurrence, mineralogy, structure, origins, history, and interrelationships. It involves considerable fieldwork in mapping and sampling rock formations in a given region, so that potential source deposits and quarries used in antiquity can be characterized. Petrography is more narrowly defined (see the preceding section by I.C. Freestone), and involves the systematic study of geological and archaeological samples by describing and interpreting their rock and mineral compositional and texture in hand specimens and, especially, in thin sections.149

HISTORICAL OVERVIEW

The original thrust of petrographic techniques, as they evolved in the 19th century, was the assemblage of sufficiently detailed information to classify rock types and their constituent minerals. One of the earliest applications of petrography to archaeological materials was undertaken by G.R. Lepsius,150 who characterized the marbles of museum artifacts and major quarries of the classical period. The problem of mineralogical variation within single quarries was not addressed in this early work, however, and the selective use of one or two of Lepsius's petrographic characteristics by later art historians led to what appeared to be overlapping source attributions. This in turn led to dissatisfaction with the technique.

The pioneering work of 19th-century scientists went largely unappreciated by archaeologists, who were working out artifact typologies based primarily on stylistic criteria. Indeed, up until the last 25 years, relatively few petrological and petrographic studies of ancient Aegean materials had been carried out.151

As for any developing discipline, some of the early work suffered from cursory stylistic and technical descriptions of the pottery, minimal petrographic detail (which is essential for future reference), and little correlative fieldwork for meaningful interpretation of the petrographic data. For example, while her preliminary petrographic data may be fine, such limitations are evident in Pittenger's summary analyses of Cycladic pottery,152 which also did not

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150 G.R. Lepsius, Griechische Marmorstudien (Berlin 1890).


include any material benchmarks for each island's domestic ceramic fabrics against which variants could have been assessed. Underfunded and poorly conceived petrographic projects, which have not been incorporated into the archaeological research design of a site from the beginning, have also resulted in undigested, largely irrelevant appendices at the end of archaeological reports.

Despite the persistent methodological and financial problems, petrographic research on ancient Aegean pottery has seen some notable recent advances in methodology,\textsuperscript{153} terminology,\textsuperscript{154} ethnographic analogy,\textsuperscript{155} experimental work in establishing agreed-upon criteria for temper identification,\textsuperscript{156} deriving technological inferences from petrographic data,\textsuperscript{157} and the archaeological and geological rationale of preliminary petrological and petrographic research.\textsuperscript{158}

PRACTICAL CONSIDERATIONS

An important distinction must be kept in mind when comparing the petrographic data of stones and clays that have been collected in the field and those of ceramic artifacts. Mineral and rock inclusions in pottery can be directly altered by the potter. For example, in refining a clay by settling or sieving out relatively heavier or larger materials, respectively, or in adding temper that may have been sorted or crushed, the petrography of the pottery fabric will appear to be inconsistent with the unmodified clay of its source.

In the Aegean, modern potters using traditional methods typically mix clays, even adding in soils, to achieve certain working and firing properties for the paste. Such mixtures are notoriously difficult to distinguish in thin sections, even when the ingredients are present in known percentages. In a recent unpublished study of clays used by traditional potters on the Cycladic island of Siphnos, I made briquettes from the recipes of some of the potters. A common mixture was a dark red clay derived from the local schist and a highly altered, pale chloritic clay from weathered schist exposures, in a ratio of 2:1. Photomicrographs of the thin section of a briquette made from this mixture show a fine micaceous fabric, with no particular clue that it represents a mixture, much less any suggestion of the relative ratios of the known components.

By analogy, mixed materials in thin sections of ancient pottery are generally difficult to identify. Contrasting mineralogical features, however, can be suggestive. For example, significantly larger and more angular rock fragments of mineralogy contrasting with that in the fabric groundmass could well be the result of crushed rock temper having been added to the clay. But the analyst must be cautious. A thin section of a briquette made from a settled sample of a granodiorite clay from Naxos also contains angular, heterogeneous rock fragments, and clays derived from some formations can exhibit marked mineralogical heterogeneity, which might be misinterpreted by an analyst as evidence of materials mixed by the potter. It is important to determine the properties of the available clays near an ancient production center, since specific clays were either suitable or unsuitable in unmixed condition for making certain items (e.g., wine jars, cooking pots) or using a specific manufacturing technique (such as wheel-throwing or hand-building). The decision to temper or not temper a clay reflects the potters' considerations of the material and technological properties of the available resources.

A petrographer must also be alert for other kinds of alterations in pottery sherds, such as the presence of secondary calcite deposited by groundwater during burial (frequently marked by concentric rings


\textsuperscript{155} P.M. Day, "Technology and Ethnography in Petrographic Studies of Ceramics," in Maniatis (supra n. 154) 139–47.


of deposition around voids), and the loss of a certain percentage and/or type of inclusion due to post-excision treatment of the pottery (especially, acid-cleaning in Greece) or to "plucking" during the abrasive preparation of the sherds as thin sections.

The petrography of archaeological pottery can provide information on a range of technological issues. For example, firing temperatures can be estimated by the relative birefringence of clay particles and the condition of primary carbonate minerals (such as calcite) in the fabric, because temperatures over 830° C contribute to the dissociation of primary carbonates and destroy clay particle birefringence. Pottery fabrics fired as high as 1000° C, however, can contain primary carbonates, whose dissociation behavior was, in fact, governed by a number of variables, including inclusion dimension, calcite crystal size, clay matrix composition, the relative vitrification (glassiness) of the ceramic surface, and the proximity of inclusions to the surface. In thin section, one can also distinguish vessel surfaces finished by applied slips from those simply wet-smoothed, and evidence of burnishing or polishing is frequently attested by the orientation of finer particles (particularly, platey clays and micas) parallel to the object's treated surface.

The size requirements of a petrographic sample, an approximately 2-cm² sherd, which is significantly more than that required for isotopic or elemental analyses (as little as 20–200 mg), can sometimes pose a problem in obtaining permission from museum and antiquity authorities. Smaller pilot projects, with careful research designs and limited sampling, are especially valuable initially. The analyst should take care that vessels of different size and function are represented for each pottery class or ware, and that the part of each vessel that is sampled is most uniformly representative of the vessel's fabric. For example, body sherds are usually adequate for mineralogical comparisons. If the parent vessels are of different dimensions, however, the petrographic profiles of the sherds may not be comparable, since the fabric of a larger vessel often contains more inclusions, providing support for the wider, taller walls, than that of a smaller vessel.

Coarse wares are particularly amenable to petrological and petrographic research, and are important in elucidating both long-distance trade (e.g., using storage jars and pithoi) and local activities (such as employing different clay bodies for cooking and storage vessels). Fine fabrics and, most recently, more utilitarian tools and products of coarser fabrics—roof tiles, drains, bricks, basins, beehives, tuyères, crucibles, spindle whorls, etc.—have been profitably studied by petrography, providing an excellent perspective on the range of ceramic raw material exploitation within a defined geographic region. The full potential of ceramic petrology and petrography will be realized, however, only when well-conceived archaeological projects are coupled with programs of field exploration and sampling of relevant clays and geological deposits.

Ancient Vitreous Materials

JULIAN HENDERSON

Vitreous materials, such as glass and glazes covering stones and crushed quartz (faience), have been produced deliberately or adventitiously for thousands of years, from at least as early as ca. 4000 B.C. Worked obsidian, a naturally formed glass, extends the human use of a vitreous material considerably further back in time. Vitreous means that a material is made of, derived from, or contains glass; according to scientific terminology, glass is described as a supercooled liquid whose structure is normally noncrystalline and lacks a long-range, ordered structure.¹⁵⁹

Included under the heading vitreous, in addition to glass, are materials that are referred to as faience, "paste," enamel, frit, and glaze. Faience consists of both glassy and crystalline components in which the crystals are almost always silica (which occurs most

ROSEDALE

Fig. 17. Plan of an excavated 17th-century A.D. glass-melting furnace of the northern type, with separate annealing furnaces, at Rosedale, Yorkshire, England. (D.W. Crossley and F.A. Aberg, *Post-Medieval Archaeology* 6 [1972] fig. 57)

abundantly as the mineral quartz). The term “paste” is often used in technologically imprecise ways. For example, on close examination, some “paste” objects are found to be made or molded from an opaque glass, which is composed of fused particles of ground glass. Enamel, on the other hand, is clearly definable as translucent or opaque glass set into a metal or glass surface—most commonly in antiquity by cloisonné or champevé techniques on metal. Frit is composed of the basic raw materials of glass production that are only partially fused. Again, the archaeological usage of the term “frit” can be quite ambiguous. Glazes are simply glasses applied to pottery or stone surfaces, and often contain high lead oxide levels. Their “fit” or adhesion to a surface is especially important and, as with vitreous enamels, the relative amount and rate of expansion and contraction of the glaze and substrate is critical for its structural integrity. A family of vitreous materials known as fuel-ash slags is produced accidentally as by-products of many high-temperature industries.

MANUFACTURE, RAW MATERIALS, AND PROPERTIES

Vitreous materials are produced using a range of raw materials. These include silica, an alkali such as soda or potassium oxide, and a calcium-rich raw material (e.g., lime), which, when fused, form a soda-lime-silica glass. Lead oxide, mineral colorants, opacifiers, clarifiers, and opalizers are used for creating and modifying the color and physical appearance of vitreous materials. Waste glass (called cullet) is often added to the “batch” of raw materials and

reduces the overall melting temperature; its use is therefore economically advantageous. Obviously, quite specific temperature regimes are necessary to melt or sinter raw materials (the latter involves heating the raw materials below their melting points until they form a solid mass), as well as to recycle glass, apply enamels and glazes effectively, anneal glass and glazes (i.e., reheat them following manufacture, in order to allow them to “relax” or stabilize), manufacture faience, and develop or retain color and opacity/ clarity in vitreous materials. Furnaces and kilns were designed quite specifically in keeping with the close control of temperatures demanded by the industrial processes. For example, one principal glass-melting furnace type (the so-called southern type) is comprised of a stoke hole, melting chamber, and lower-temperature annealing oven as separate chambers of a single construction, whereas the so-called northern type has an annealing oven that is separate from the main furnace (fig. 17).

Lower temperatures were also involved in fritting glass raw materials—that is, partially melting primary raw materials and removing any impurities—than for full fusion, and such operations were sometimes carried out in special furnaces. Experimenting with a range of manufacturing techniques and conditions reveals the complexities of ancient vitreous material technology. As one example, the effect of varying the percentage of oxygen on the color of the finished product can be studied and then related to the colors of ancient artifacts. It is very important that such investigations spring from a close consideration of the ancient materials in their proper archaeological contexts.

Excavation of sites where ancient vitreous materials were made into artifacts can potentially provide valuable evidence for raw materials, furnaces, kilns, crucibles, and fuel used, in addition to the vitreous products and by-products themselves. Such a study would normally be carried out for an entire site or region, and the organization of the vitreous material industry should be linked to other high-temperature activities for which different pyrotechnological expertise and equipment (e.g., fuels, furnace or kiln design, and the use of ceramic materials) might have been shared or influenced vitreous material technology.

161 J. Henderson, “The Scientific Analysis of Ancient Glass and Its Archaeological Interpretation,” in J. Henderson ed., Scientific Analysis in Archaeology and Its Interpretation (Oxford University Committee for Archaeology Monograph

Fig. 18. Backscattered electron micrograph of fluorite crystals, seen as black particles 1–5 μ in size, in a 16th-century A.D. Chinese opaque turquoise cloisonné enamel. Discrete clusters of different-size fluorite crystals indicate that the enamel was fused within the cloisonné in situ.

SCIENTIFIC ANALYSIS

A wide range of modern physicochemical techniques have been used to study vitreous materials.161 Even though earlier investigations provided evidence for meaningful chemical compositional groups,162 the techniques used up to about 1970 tended to be slow and time-consuming. Consequently, a data base for ancient vitreous material compositions only slowly developed. Recently, faster and more automated techniques of data collection and analysis have enabled ancient vitreous materials to be characterized more exactly over broader geographical areas and longer time spans. In some cases, the provenience of an artifact can be assigned only on the basis of its chemical composition.

The available scientific techniques provide a range of information about vitreous materials. Scanning electron microscopy (SEM) is particularly useful for photographing and identifying opacifying crystals and frits as small as 1 μ in size in glasses and glazes (fig. 18). The chemical compositions of vitreous materials can be determined using X-ray fluorescence analysis (XRF), electron-probe microanalysis (EPMA), and proton-induced X-ray emission spectrometry (PIXE). These surface techniques are minimally destructive or nondestructive. If surface layers have been weathered, however, they must be removed by

161 J. Henderson, “The Scientific Analysis of Ancient Glass and Its Archaeological Interpretation,” in J. Henderson ed., Scientific Analysis in Archaeology and Its Interpretation (Oxford University Committee for Archaeology Monograph

polishing before analysis. An additional advantage of these techniques is that one can see what is being analyzed and thereby avoid impurities and structural irregularities. Neutron activation analysis (NAA) has the drawback that a ca. 200 mg sample must be pulverized; silica, the predominant constituent of vitreous materials, is also not measured, although the concentrations of other important trace and minor elements can be precisely determined. Mass spectrometry, another destructive technique requiring very small samples, is particularly useful in sourcing any lead that is present. It is often advisable to use more than one technique, since each relies on different physical and chemical principles that result in different sensitivities.

Behind equipment paraphernalia and complexity, however, the most important consideration in any study of ancient vitreous materials is research design. To structure a clear and concise set of archaeological and technological problems to be investigated is essential. To do science for science’s sake, though important, may not always contribute to the archaeological interpretation in a meaningful way. Fully integrating archaeological and scientific aspects is essential for resolving specific technological and cultural issues, as the following case study demonstrates.

A CASE STUDY: BRONZE AGE GLASS IN EUROPE

Much ancient glassmaking before the first millennium A.D. was dominated by soda-lime-silica technology. One interesting exception, however, occurred at the turn of the millennium (ca. 1100–1000 B.C., as dated by dendrochronology), when an entirely new vitreous technology emerged in parts of Europe. The industry is characterized by an innovative use of raw materials. Relatively high potassium oxide levels of up to 13% by weight are the earliest recorded instances of such glass; in soda-lime glass, potassium oxide is typically ca. 0.5% or 2–3% depending upon the soda source. The new glass is also characterized by low calcium oxide and magnesia levels. High

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silica levels are caused by crystals dispersed through the glass, which reflect a relatively high proportion of light and make the glass appear “brilliant.” The low magnesia and high potassium oxide levels of the glass have led to it being labeled LMHK. The earliest glasses of this type are concentrated in northern Italy (at the entrepôt of Fratessina at the head of the Adriatic) and Switzerland (at a Bronze Age site on Lake Neuchâtel). This European glass is very different from the ancient soda-lime glass of the Near East and Egypt (fig. 19) and of later periods (from the Hellenistic period to early medieval times) in Europe. Since it appears at about the same time that civilization and trade in the Near East and Egypt break down, possibly this glass helped to fill an economic vacuum. Even the LMHK Late Bronze Age glass found in eighth-seventh century B.C. Ireland (e.g., at Rathgall, Lough Gur, and Freestone Hill) can now be seen to be connected, however indirectly, to developments in northern Italy. By chemically analyzing well-provenienced and well-dated glass examples, it has thus been possible to shed light on economic, technological, and cultural developments in European prehistory.

Toward the end of the first millennium A.D. in Europe, a similar shift from soda-lime glass to the high potassium “forest” glass of the high medieval period occurred. The technological change appears to have been relatively fast, and was due to economic and/or political disruptions in alkali (soda) supply, which forced glassmakers to use plant ashes that have a higher potassium oxide content. The enormous demand for stained glass windows in churches, which now had to be made from the “forest” glass, must have caused major dislocations in the organization of the industry. Scientific analyses of medieval “Limoges” enamels, a related vitreous technology of the period, show that while this industry shared in the use of high potassium glass, it also used glasses derived from probable recycled Roman tesserae and/or possibly early Islamic glass.

CONCLUSIONS

The study of ancient vitreous materials already ranges over a large area of time and space—from fourth-millennium B.C. Egyptian faience to the earliest glass of the third–second millennium B.C. Near East to European glazes and enamels of later periods. Outside of the Near East and Europe, the prehistoric high alumina soda-lime glasses of India and the high barium oxide glasses of Han China are evidence for silicate innovation.166

Analytical techniques promise both to broaden and deepen our understanding of vitreous technologies and their roles in societies. PIXE and inductively coupled plasma emission spectrometry (ICPMS) enable chemical compositions to be measured at trace levels, providing very specific provenience data. Transmission electron microscopy (TEM) enables minute inclusions, down to a thousandth of a millimeter, to be photographed and analyzed.

In general, a sufficient number of closely datable artifacts is of overriding significance in the study of ancient vitreous materials. Analytical equipment can provide high-quality data, but the interpretation of the results is, in the end, strongly dependent on research design and whether or not the archaeological materials form coherent archaeological groupings.

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Xeroradiographic Imaging

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Xeroradiography is a radiographic imaging technique similar to photocopying techniques pioneered by the Xerox Corporation. The image is produced by placing the object of interest on a charged selenium plate and irradiating it with a standard X-ray source. Differences in charge density produce an image that is then rapidly transferred onto a 24.5 × 34.5 cm paper in a special copy machine. There is no film to develop. Typical exposures are lower in energy and exposure time than film radiography, and

the results are available within 3–5 minutes of beginning the imaging process.167

As many studies have demonstrated, the images are easy to “read” and understand because edges, joints, or pores are enhanced with a halo effect.168 The researcher evaluating xeroradiographic images, however, should understand the constraints of the technique. For example, the print is a mirror image of the object, unless reversed for publication purposes. The images also superimpose edge-enhanced surface detail onto the internal structure, and the side nearest the charged selenium plate is imaged in more detail than the side away from the plate. This effect can be significant if the artifact is very thick or is a hollow vessel.

The mechanism of achieving contrast is different from that of film radiography where the image is proportional to incident X-ray intensity on the film.109 In electrostatic imaging, such as xeroradiography, charges accumulate at boundaries and around small details, and, much like a capacitor, a sufficiently large electric field will discharge across an edge. Any residual charge imbalance can discharge again and again, thereby producing an edge-enhancement. Because differing charge buildups and discharges occur, areas of varying density on a xeroradiograph cannot be compared quantitatively. The technique has a wide dynamic range in which many objects of diverse materials can be imaged in a single exposure; although densities are less well distinguished than with film radiography, discontinuities are enhanced. The wide range of densities that can be imaged and seen in a xeroradiograph are often obscured in a black-and-white print.

167 We thank Jane Norman and Thomas Chase of the Freer Gallery of Art and Arthur M. Sackler Gallery, and the staff of the Department of Radiography of the Alexandria (VA) Hospital, for their assistance in the xeroradiography of the gazelle rhyton discussed below. D. Stoneham of the Research Laboratory for Archaeology and the History of Art (University of Oxford) provided the thermoluminescent dating of the rhyton. A. Gunther, M. Goodway, and R. Henrickson offered useful comments on an earlier draft of this manuscript.


A positive xeroradiographic image will usually display the porosity and details of manufacture, while a negative image shows better the inclusions or higher-density features of an object.170 One of the limitations of xeroradiography, however, is a 20-μ spatial resolution, which is coarser than the 3-μ resolution of current X-ray film.

EXAMINATION OF A GAZELLE RHYTON

A ceramic rhyton of a gazelle head in the Arthur M. Sackler Gallery of the Smithsonian Institution (fig. 20) provides an example of the technological information that can be obtained by xeroradiography.171 Although a gift to the Smithsonian and unprovenienced, the vessel is possibly from Iran, and is dated by thermoluminescence to the first century B.C.—first century A.D.

The rhyton was clearly made in several pieces that had been jointed together. Visual examination also suggested that the beaker portion of the vessel was either wheel-thrown or hand-built with strips or coils, whereas the rhyton head was hand-modeled. Very fine circumferential ridges, about 0.3–2.0 mm apart, can be seen on the interior using an intense penlight at a glancing or low angle to the surface, and indicate the smoothing of the surface.172 In addition, circumferential grooves, about 3–4 cm apart, can be felt on the interior. Since these grooves are horizontal and do not spiral to the rim as is observed on wheel-thrown vessels, they are most likely to have been produced by hand-building. Because of weathering and pitting, no additional information could be ascertained from the exterior surface.


The xeroradiographs (fig. 21a-b) confirm that the beaker portion of the rhyton was hand-built with strips or coils. The process of throwing results in the alignment of air pockets in the clay body at an angle of about 30–45° from the throwing grooves and ridges.\textsuperscript{173} In contrast, coiling techniques produce a horizontal alignment of porosity, as is observed in figure 21a. It should be noted that, if the vessel wall were shaped after coiling, porosity alignment might also be angled off from the horizontal.

The uneven wall thickness of the carefully sculpted head supports the hypothesis of hand-modeling as its method of manufacture. Rounded fingertip-sized impressions, but no indentations made by pointed or blunt tools, are seen on the head's interior. Because some of the exterior features are undercut, the head could not have been made in a single, open-face mold. The lack of joints indicates that the head was made from a single piece of clay.

Even though molding and throwing would have been more efficient, the care and excellence in craftsmanship of the gazelle rhyton, in particular the quality of its sculpting using the labor-intensive methods of hand-building and modeling, suggest that this was a luxury item that would not have been produced in large numbers. The method is unlike that used for other Greek zoomorphic rhyta in which the head section is molded and the beaker is thrown. Microscopic examination of the Greek rhyton collection at the Ashmolean Museum shows clear marks where the two molded halves of the heads were joined together, and spiral throwing-ridges and occasional diagonal stretch marks in upper sections of the beaker portions of the vessels.

It is also surprising that the firing temperature of the gazelle rhyton was so low that the body is quite porous and permeable to liquids. Cracks that appeared during forming and drying are present at the top of the handle, the beaker joint of the extra reinforcement clay strip extending from the throat to the base of the beaker (fig. 21a), and below the handle in the wall of the beaker. Four grooves had been created with a rounded tool below and parallel to the handle after the clay body was stiff and somewhat dry. Three of these grooves deformed the clay body sufficiently to have produced cracks in the grooves from which any liquid contents might have escaped.

Does the gazelle rhyton represent an ancient example in which technical understanding did not match the artisan's expressive sculptural capabilities? Examination using xeroradiography combined with other analytical techniques not only has allowed identification of the methods and sequence of manufacture, but also has led to further questions about the intended function and quality of craftsmanship employed in the vessel.

The xeroradiographic analysis of the gazelle rhyton illustrates the effectiveness of this nondestructive technique in discovering ancient manufacturing methods. The technique can also be applied to many other materials—textiles, paper, wood, metals, corrosion products, etc.—and types of artifacts.

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Amber (figs. 22–23) is the name originally attached to a fossil tree resin that occurs naturally over a large part of northern Europe. It is thought to have originated in a forested area of southern Scandinavia, but only secondary, tertiary, and higher-order deposits are known, and among these, the Jutland peninsula and the shores of the eastern Baltic Sea are by far the richest. But due to later geological events—the formation of the Tethys Sea, the Ice Ages, and the river systems that were formed when the glaciers melted—it was carried west to the coast of England, south to parts of the Netherlands, the North German plain, and southeast throughout all of Poland and well into European Russia. Because of the wide distribution of amber in archaeological contexts throughout the Old World, attempts to determine its provenience go back over more than a century.

In the early 19th century, the somewhat misleadingly named “Baltic amber” was held to be the only source of amber artifacts, and when these were found in excavations outside the natural range of distribution, they were ipso facto assumed to be imports from the north. In the course of the 19th century, mineralogists discovered, described, and named as many as 100 fossil resins occurring throughout Europe as well as other continents. In 1872, the Italian mineralogist Capellini first suggested that some of these non-Baltic deposits, including those he himself had found near Bologna, might well have served as raw material for amber artifacts in prehistoric times, and that a Baltic origin should no longer be assumed. The suggestion was not well received by most archaeologists and led to a quite heated discussion during the International Congress of Prehistoric Anthropology and Archaeology in Stockholm in 1874.

But the question had been raised, and the attempt to answer it by scientific means constitutes an important and instructive chapter in the early history of archaeometry. The German apothecary Otto Helm set out to identify Baltic amber by chemical analysis. The method he used was the quantitative determination of a characteristic component of Baltic amber, succinic acid, which can be liberated from the resin...
by hydrolysis or pyrolysis in amounts ranging from 3 to 8%. Over a period of 25 years, Helm sought to show that Baltic amber was the only source of archaeological amber artifacts found in the Old World, including most famously the amber beads Schliemann had found in Grave Circle A at Mycenae.176 Helm was not quite the detached, objective scientist: his explicit goal was to prove Capellini wrong. When it became evident that amber-like fossil resins native to Italy, Romania, France, and Portugal contained as much or more succinic acid as Baltic amber,177 he high-handedly dismissed that evidence and claimed that he could recognize these resins as non-Baltic by sight. Apart from its central methodological flaw, this early provenience analysis of amber had other disadvantages. As much as a gram of an archaeological amber find had to be destroyed for a single analysis, and the natural reluctance of archaeologists to sacrifice what would often be an entire singular find limited the application of the succinic acid method to a few dozen cases. Lastly, the question of provenience was often cast too narrowly: finds from an excavation were compared to Baltic amber, on the one hand, and to a single variety of non-Baltic amber, such as Sicilian amber, on the other. If the finds were “more like” one than the other reference source, they were assigned to it in blatant violation of the fallacy of the excluded middle.

The failure of this early instance of provenience analysis by physicochemical means had two predictable results: it lowered the confidence of archaeologists in the usefulness of the natural sciences in the service of archaeology, and it discouraged further work toward solving the amber problem. No attempts to determine the provenience of amber were made for more than half a century after Helm’s death. When the search for a reliable method was resumed, the arsenal of analytical chemistry had been enlarged by a range of powerful instrumental methods. One of these, infrared spectroscopy, has provided the solution to a very old question. When infrared light passes through a material, those wavelengths are absorbed that correspond to the amount of energy required to support the vibrations of atoms within molecules. The emerging infrared light lacks those wavelengths and thus furnishes a pattern in which they are diminished or missing. The resulting spectrum gives information about the chemical structure of the material, but it can also be used, purely empirically, as a “fingerprint” characteristic of this, and only this, material.

In 1964, we could show that Baltic amber had a unique infrared absorption spectrum.178 That spectrum, incidentally, proved that the age-old notion that Baltic amber derives from pine trees, as claimed by Pliny the Elder, is wrong. The spectra clearly place the botanical origin not in the genus Pinus but in the closely related genus Araucaria.179 For the purposes of archaeological provenience analysis, however, the uniqueness of the “fingerprint” is enough.

Learning from the shortcomings of Helm’s work, we proceeded with methodological rigor. The infrared spectra of more than 2,000 samples of fossil resins, collected from the mineralogical collections of natural history museums in Europe and the United States, were determined. No European fossil resin matched the infrared spectrum of Baltic amber, which is characterized by a single absorption in the wave number range between 1100 and 1300 cm\(^{-1}\) that is preceded by a broad shoulder (fig. 23). Infrared spectroscopy thus offers a reliable way of identifying Baltic amber with absolute certainty. Like other instrumental methods, the infrared test requires only a very small sample, typically between 1 and 2 mg, and can be performed in about 20 minutes. That has made it possible, over the course of the last 30 years, to analyze more than 5,000 archaeological amber finds from excavations throughout the Old World, with the support of many private and public foundations who have made the project possible, most notably the Division of Anthropology of the National Science Foundation. The program has been conducted under the aegis of the Union internationale des sciences préhistoriques et protohistoriques since 1978, when the U.I.S.P.P. established a “Committee on the Study of Amber” in recognition of the potential of these analyses to elucidate the amber trade and the amber routes in prehistoric Europe.

Because of space limitations, a detailed account of our results cannot be provided here; a summary

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up to 1986 of more than 100 publications is available.\textsuperscript{180} It should be noted, however, that the overwhelming majority of the archaeological amber finds of south-central and southern Europe are indeed exports of Baltic amber from the north, including all of Schliemann’s finds from Bronze Age Greece. The few exceptions are instructive: a find of amber in the Vayenas tholos at Pylos, for example, is of Sicilian, not of Baltic, amber, as is a find from the Aeneolithic necropolis of Laterza in southern Italy.\textsuperscript{181} A presumed find of amber from Tell Asmar (ancient Eshnunna), dated to 2500–2400 B.C., has been shown to be not amber, but East African copal.\textsuperscript{182} Continued research on amber promises to shed additional light on its cultural and economic importance in antiquity.

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\section*{Skeletal Remains}

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The study of human remains from archaeological contexts is one of the many research areas comprising physical anthropology. In contrast to archaeological research that deals with the material culture resulting from human activities, skeletal analyses focus directly on the people responsible for such activities. The methods used in skeletal analyses are based on those employed for diagnostic purposes in forensic anthropology, medicine, epidemiology, and anthropological studies of living populations. They are directed toward determining population origins and kinship, nutrition, disease status, and longevity of past populations. From a broader perspective, they provide the basic data for studying the nature and rate of human evolution.

A skeletal investigation begins by determining the manner in which the individual(s) was interred, as evidenced by the position of the bones (whether an intact or disturbed burial). This is followed by the determination of age and gender, which are used to estimate life expectancy for the population studied (palaeodemography). Physical characteristics of individuals are usually defined by measurement of the size and shape of the skull and long bones (morphometry), as well as the presence of discrete traits. Resemblances between individuals and populations are then used to evaluate kinship and population affinities. More sophisticated methods now coming into use include analysis of mitochondrial and nuclear DNA extracted directly from the skeletal remains, which provide direct information on the genome and pathogens present. Evaluation of nutrition and disease status, as well as evidence of trauma (palaeopathology), provides additional information on the life history of individuals and an estimate of the quality of life for the population under study. Marked differences in incidence of disease between subgroups may result from differences in occupation and access to available resources. This comprises an important element of mortuary studies that investigate the correlation of social status to burial type.

The techniques used in the above analyses range from the simple to the sophisticated. Age, gender, gross pathology, and phenotype can be determined from visual assessment, supplemented by measurements made with calipers and tapes.\textsuperscript{183} More sophisticated studies using radiographs, computerized tomography (c–t) scans, and optical and scanning electron microscopy improve the degree of accuracy achieved, especially for determination of age and pathology, while biochemical analyses of trace elements and isotopes can provide additional information on diet.\textsuperscript{184}

As in all archaeological studies, many factors affect the reliability of the available samples, including excavation priorities or constraints, burial practices of the population under study, and soil conditions causing poor preservation (especially of fragile in-

\textsuperscript{183} W.M. Bass, \textit{Human Osteology} (Columbia 1987) is a standard manual for bone identification and measurement.
fant bones). To these must be added the “blurring” factor that is due to the fact that skeletal assemblages do not usually represent one point in time, but rather the accumulated deaths of several generations. Migration, immigration, and/or differences in fecundity over time may thus contribute to fluctuations in the age/sex profiles represented.185

THE NATUFIANS: A CASE STUDY FROM THE NEAR EAST

Skeletal remains from the Epipalaeolithic or Natufian period illustrate the potential and limitations of skeletal analyses in resolving specific issues, especially when dealing with small, biased samples. Dated between ca. 12,500 and 10,500 B.P., Natufian sites show a marked increase in settlement size, permanent habitation, and architecture as compared with the preceding Kebaran period. These developments are coupled with an increase in artifacts and features that are generally attributed to cereal collection and utilization, such as pestles, querns, sickle blades, and storage pits. In the succeeding Neolithic period, similar tools and facilities are definitely being used to process and store plant domesticates.

The Natufian period has been subdivided into three phases on the basis of tool types, and most research on this culture has been directed toward understanding the “triggers” that were responsible for the transition from hunting and gathering to plant and animal domestication and the establishment of permanent settlements throughout the Near East.186 Skeletal remains have been found at most Natufian sites, and research has focused on population affinities, disease, and diet.187

SAMPLE SIZE AND REPRESENTATIVENESS

Natufian skeletal remains, which have been recovered from the sites of Shubah, Kebara, El Wad, Eynan, Nahal Oren, Erq el Ahmar, and Hayonim in Israel and the West Bank, are the primary focus here. Numerous sites in Jordan (e.g., Beidha) and in Syria (e.g., Abu Hureyra on the Euphrates), however, have also yielded Natufian material.

Sample sizes for Natufian sites in Israel and the West Bank range from seven individuals at Erq el Ahmar to more than 100 at Eynan. At most sites, both primary (intact) and secondarily disturbed burials were found. Preservation of bones ranged from moderate to poor, and the frequency of infants varied from site to site. Because of poor preservation, age or gender could not be reliably defined for more than half the adults excavated, while detailed morphometric analyses could be carried out on even fewer specimens. The teeth and mandibles were best preserved.

The extent to which the Natufian age distribution is biased by differential burial practices can be roughly estimated by comparing life-tables calculated for living populations with those for Natufians. As might be expected, infant deaths in a modern society are inversely related to affluence, being most frequent in the first months of life and declining later in childhood. None of the Natufian assemblages has been studied, however, fits this model. Diagenesis (differential preservation) cannot account for this discrepancy, since the relative number of infant remains recovered from sites with good bone preservation is not any greater than that for sites with poor preservation. The most economical explanation, which has also been established for other periods, would appear to be that most Natufian infants were not buried in the same location as older children and adults. The age distribution is then obviously skewed, limiting the validity of palaeodemographic analyses. A further confounding factor is the small sample size. The discovery of only several hundred individuals for a ca. 2,000-year time span implies that there are many gaps in the skeletal record, which is in accordance with the archaeological finding of periodic abandonment of sites.

While detailed palaeodemographic analyses of Natufian populations are clearly inappropriate, an alternative approach that provides some information on longevity has been to assess the ratio of younger to older adults. In the Natufian period, as in most hunter-gatherer groups studied, very few adults sur-


187 Recent summaries and comprehensive bibliographies of skeletal analyses appear in Bar-Yosef and Valla (supra n. 66) by A. Belfer-Cohen, L.A. Schepartz, and B. Arensburg (“New Biological Data for the Natufian Popu-

vived beyond age 50. By contrast, ancient agricultural societies in Israel and the West Bank had between 10 and 20% survival rates to this age.\textsuperscript{188}

MORPHOMETRY AND FUNCTIONAL ANATOMY

All who have studied the Natufians from these sites in Israel and the West Bank agree on the overall physical similarities of the populations. Individuals are characterized by short to medium stature, large, somewhat dolichocranic (long) skulls, and short, broad faces. The teeth show a high incidence of lingual tubercles on upper incisors and large Carabelli's cusps on upper first molars. The Natufians differ markedly from contemporary populations in North Africa and the Nile Valley, which are extremely robust, with very much larger skulls and teeth, and well adapted to hunting and eating large game (of. figs. 24–25).\textsuperscript{189}

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\textsuperscript{188} Smith et al. and Smith (supra n. 187).

At Hayonim, at least seven adults (29% of the sample population) have a congenital absence of a third molar, while its overall frequency in Natufians is of the order of 10%. This condition is inherited, so that the exceptionally high frequency at Hayonim indicates close kinship among at least some of those buried there. In a preliminary study, Ferembach reported that the Natufians from Eynan appeared to be taller and have larger heads than individuals from other sites, suggesting that these differences might be related to nutrition. This hypothesis, however, has not been supported by the findings on the relative incidence of disease at Hayonim and elsewhere, nor is the number of intact specimens on which detailed morphometric studies have been carried out sufficient to determine intra- and intersite variation. Highlighting the limited sample sizes available for comparative studies is the fact that stature estimates for the Lower Natufian phase at Eynan were based on only one complete male femur and three incomplete femurs.

Small sample sizes similarly limit intersite and interperiod analyses of cranio-facial parameters. Fortunately, mandibles are better preserved than other skeletal elements, and the number available for analysis is sufficient for basic statistical inferences. The data show that a significant reduction in mandibular robusticity occurred during the Natufian period, thus corroborating the evidence for changing diets and reduced selective pressures on jaws based on patterns of dental disease.

In a recent article, Renfrew stated that skeletal analyses are of limited value for studying population origins, since skeletal parameters may be modified by environmental stress. Certainly, environmental stress during childhood may depress growth, but other skeletal and dental parameters are less affected. Indeed, in the classical study by Boas, usually quoted in support of plasticity of cranial measurements, the differences found in head length between immigrants to the United States and their offspring were small. Later studies have found that most parameters of the cranio-facial complex show a high degree of hereditability and so are reliable for studies of population distance. At the same time, the possible influence of stressed conditions on growth can be gauged by reference to the presence of developmental defects such as dental hypoplasia and growth arrest lines.

A supplementary approach to population studies has been the use of dental traits, which have been found to be extremely reliable in studies of the population affiliations of modern and ancient societies. Renfrew’s criticisms regarding the effect of environmental stress on skeletal morphology can then be countered by careful evaluation of the severity of developmental defects in the samples compared, as well as by the use of parameters that show a high degree of inheritability such as dental traits. For the Natufians, such studies have emphasized the similarities of Natufian populations from all sites and phases.

PALAEOPATHOLOGIES WITH CHANGING DIET

Environmental stress in the Natufians has been assessed in terms of developmental defects and other pathologies. Fortunately for the physical anthropologist, the timing and severity of events, which are sufficiently stressful to depress growth, result in permanent scars in the teeth and bones that can be readily identified in adults. The latter include hypoplastic defects of teeth (fig. 26) and hypercalcified growth arrest lines (Harris lines) in long bones. Simi-

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191 Soliveres-Massei (supra n. 187).
192 Smith et al. (supra n. 187).
196 The rationale and methods used in dental anthropology are reported in a series of classic articles in *Dental Anthropology*, edited by D.R. Brothwell (New York 1963). Note especially the article by the late A.A. Dahlberg, “Analysis of the American Indian Dentition,” pp. 149–78.
larly, loss of cortical bone (periostitis), resulting from chronic malnutrition and/or disease in the weeks preceding death, can also be diagnosed from the bones (fig. 27). The frequency of hypoplastic defects in Natufian teeth is approximately 50%, compared with approximately 33% in Middle Palaeolithic Homo sapiens and 90% in later agricultural populations of Israel and the West Bank. The relative frequency of growth arrest lines in long bones shows a similar patterning that demonstrates the intermediate status of the Natufians. Other pathological signs, such as reduction in bone mass (osteopenia) and inflammatory or degenerative lesions of the bones, also occur in lower frequencies in the Natufians than in later agricultural populations.¹⁹⁷

The results obtained from the study of pathologies and developmental defects thus concur in aligning the Natufians with hunter-gatherers, who show little pathology, rather than with agriculturalists. Some researchers, however, have argued that few signs of developmental lesions or other pathologies will be found if individuals succumb rapidly to disease rather than surviving long enough for the body to respond.¹⁹⁸ Thus, they hypothesize that a low frequency of growth insults may equally characterize populations with high or low stress levels. Certainly, a catastrophe or severe epidemic may cause sudden death of large numbers of the population over a short period of time. Unless the population is decimated, however, some equilibrium is eventually reached, and survival for even two or three days is sufficient for a visible response to infection or severe malnutrition to occur in the bones or developing teeth. For most Natufian sites, the samples extend over several generations, so that we are not dealing with a single episode. The frequency of developmental defects and other skeletal pathologies in samples from the different sites and periods is stable, indicating that the level of environmental stress affecting the bony tissues was fairly constant. In contrast, the severity of dental disease increased over time, pointing to a marked dietary change within the Natufian period.

Hunter-gatherers typically eat foods that require prolonged mastication and are largely self-cleansing. Teeth of early Homo sapiens, like those of contemporary hunters and gatherers, are characterized by little caries or periodontal disease, while attrition rates vary according to the abrasiveness of the diet. Most agriculturalists, on the other hand, eat softer foods, including large quantities of cooked carbohydrates that stick to the teeth. This predisposes agriculturalists to dental caries and periodontal disease, while attrition rates vary not only with the abrasiveness of the food but also with methods of food preparation. For example, flour ground using simple milling stones produces considerable grit that contributes to rapid tooth wear. For this reason, early agriculturalists show severe attrition, in addition to higher rates of caries and periodontal disease than hunters and gatherers.

Dental disease patterns in Natufian populations indicate increased consumption of cooked carbohydrates over time. The dental disease patterns of the Natufians more nearly resemble those of early agriculturalists than those of hunter-gatherers in rates of attrition, caries, and periodontal disease. Moreover, when specimens are separated out by phase, the severity of dental disease can be seen to increase over time, suggesting a gradual increase in

¹⁹⁷ Smith et al. (supra n. 187).

¹⁹⁸ Wood et al. (supra n. 185).
cereal consumption. Studies based on strontium/calcium (Sr/Ca) ratios of bones provide independent support for the hypothesis of increased cereal consumption in the Natufian period.\(^{199}\) Recently, acorns have been proposed as the main source of the increased carbohydrate consumption in the Natufian period,\(^{200}\) despite their absence from the plant remains. This hypothesis still remains to be tested by dental microwear analysis using scanning electron microscopy. Since acorn flour lacks the abrasive phytates present in the husks and stalks of cereals, it should result in a smoother, more polished surface of the abraded teeth than that produced by cereal consumption.

**CONCLUSIONS**

Research on the skeletal remains of the Natufians is ongoing. As this brief review has shown, skeletal analyses offer unique perspectives on past societies and individuals, and can provide specific answers to questions that cannot be addressed by other means. The latest innovation is nuclear and mitochondrial DNA analysis of ancient skeletal remains and mummified tissues, which promises to be a very powerful technique with wide application. While the cost of such analyses presently prohibits their use on a routine basis, they should enable the physical anthropologist to test hypotheses derived from morphometric and palaeopathologic analyses by relating a known pathology to a DNA mutation or to the presence of a specific pathogen as identified by its DNA. Many questions involving the origins, relationships, and descendants of prehistoric and historical populations, as well as their behavior and standard of living, should also eventually be answerable.

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**Immuonochemistry Applied to Archaeology**

**A.M. CHILD AND A.M. POLLARD**

**THE IMMUNE RESPONSE**

Immunology is the study of the reaction between the immune system of a living organism (the host animal) and a foreign substance (i.e., an infectious agent or substance that the organism does not recognize as "self"). Most living creatures possess an innate immune system, which does not require prior contact with a foreign substance (i.e., an infectious agent) in order to be effective. Acquired immunity—the ability to build up resistance to infection by an immune response—is a characteristic of vertebrates including humans.

The immune response includes a recognition system in which the host animal creates "designer molecules" called antibodies that are capable of recognizing and reacting with the invading substance (the antigen).\(^{201}\) Immunochemistry is the application of this antibody-antigen reaction in contexts outside the host creature (referred to as *in vitro*), to detect and quantify specific compounds, such as the proteins in blood. Immunochemistry normally triumphs over conventional organic analysis because its detection limits are much lower.

The recognition process itself works on the basis of molecular geometry (in much the same way as the docking of a space shuttle!). The foreign substance (or antigen—the molecule that generates the antibody) enters the host via the bloodstream or by transport across a mucous membrane (e.g., the cells lining the lungs or gut). It then encounters particular cells called B-lymphocytes. Each B-lymphocyte is capable of producing only one type of antibody that will have a particularly shaped "docking mechanism." The antigen selects the most suitable B-lymphocyte cells, and triggers them not only to produce antibodies, but also to reproduce themselves, thus enabling the host to respond more quickly to

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\(^{200}\) D.L. Olszewski, "Subsistence Ecology in the Mediter-

similar invaders in the future (fig. 28). Different parts of the foreign invader may trigger different B-lymphocytes to produce a range of antibodies, all of which will react with the original antigen. This is the molecular basis of the resistance to disease.

**DETECTION METHODS**

For immunochemical work, the molecule to be identified or quantified (e.g., the human bone protein osteocalcin) is injected into the bloodstream of a host animal such as a rabbit and becomes the antigen. This stimulates the rabbit’s immune system to produce antibodies to human osteocalcin (described as rabbit anti-human osteocalcin). These antibodies can be collected and purified, and are then used to bind with human osteocalcin wherever it may be encountered (for instance, in mixed protein extracted from archaeological bone).

In order to be certain that this binding has taken place, it is important to be able to demonstrate the existence of the antibody-antigen complex thus formed. This can be done by a variety of methods, but in archaeological immunochemistry, two main techniques have been used: radiolabeling, known as RIA (radioimmunoassay, using a low activity radioactive compound attached to the antibody), or enzyme labeling. The latter method (ELISA—Enzyme-Linked Immunosorbant Assay) is now becoming more popular because it does not require the use of radioactive material. It has the disadvantage, however, that a further step is needed, usually the addition of another chemical that will change color when it comes in contact with the enzyme. The amount of antigen detected can then be quantified because the depth of color change is proportional to the amount of antibody-antigen complex produced. One problem posed by archaeological material is that extracted solutions are often colored by humic compounds from the soil, which may mask the color change.

Both these detection systems can be used in conjunction with gel separation techniques, in which the molecules extracted are separated according to size and electric charge (electrophoresis), followed by transfer onto a suitable supporting membrane (blotting) prior to detection. This gives increased

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specificity, since the molecular weight range of the antigen can also be measured (dot-blotting or Western blot).

ARCHAEOLOGICAL APPLICATIONS

The principal use of immunochemistry in archaeology has been to demonstrate the presence of a particular biological compound in material from an archaeological context. A typical example would be the detection of apohaemoglobin (a blood protein) in archaeological bone. To date, much of this work has largely been directed toward discovering how long biomolecules can survive in an immunologically recognizable form. So far, the direct archaeological benefits of this work have yet to be seen, but hold some promise for the detection of diseases that leave no lesions in bony tissue.

In general, the applications of immunochemistry to palaeobiology and archaeology fall into the following three broad categories:

1) The demonstration of protein survival in "dinosaurs" and other fossil species. More specifically, the degree of affinity between modern antibodies and extracted fossil antigens has allowed a phylogenetic study of certain fossil and modern animals, such as mammoth, mastodon, and modern elephants or seals and terrestrial carnivores. Archaeologically more relevant are the studies of Neolithic and Bronze Age equids, and the preliminary work on Neanderthal, Homo erectus, Australopithecus robustus, and Cro-Magnon man. The assumption is that the affinity or degree of binding between an antibody raised against a particular protein from the modern species and an ancient antigen (the comparable protein extracted from the ancient sample) is a measure of the genetic similarity between the two species. Arguably, a better measure of this may now be provided by DNA homologies.

2) The detection of proteins in archaeological human bone and/or mummified tissue. As noted above, this research at present is largely driven by curiosity about the length of time that biomolecules can survive in archaeological human tissue from a variety of contexts. Proteins in human bone that have been studied include apohaemoglobin (which, together with iron, is responsible for oxygen transport in the bloodstream) and albumin (the most abundant dissolved protein in serum).

Complications arise with the immunochemical detection of degraded protein (see below), but potentially this approach could be used for the diagnosis of a range of diseases that are not currently visible in the archaeological record.

3) A third area of application is much more controversial—the use of immunochemical tests to identify blood residue proteins both on stone tools and as a pigment in rock art. The subject was first investigated in 1983, when T. Loy identified the species of origin of blood residues on stone tool surfaces from recrystallized haemoglobin, after confirming the presence of blood using test-strips. The latter are used as a very presumptive screening method for the detection of albumin and apohaemoglobin in fresh urine samples. Fresh samples are required, since, after one day, there is contamination by the products of bacterial metabolism that can give false positives. Myoglobin and chlorophyll, along with other porphyrin-ring containing substances, also give false positives. Because of the caution with which dried blood residues are treated by forensic scientists and because it was unclear whether Loy's samples were uncontaminated, his results were greeted rather skeptically. Further work by Loy and others has now proved beyond a reasonable doubt that recognizable proteins can indeed survive for long periods, although a number of investigators still express concern about the techniques used in some of these blood residue studies. The oldest reported blood residue dates to 90,000 years ago, from Tabun Cave in Israel.

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THE PROBLEM OF DEGRADED PROTEIN

Although antibody-antigen recognition is based on a three-dimensional geometrical "matching," it actually involves only a small region of the antigen. In other words, even in a relatively large molecule such as apohaemoglobin, recognition involves only a very small fraction of the total structure, which is known as the epitope (fig. 29). The latter may be either a specific short sequence of the amino acid chain that makes up the protein, or it may be a number of nonsequential parts of the chain that just happen to lie together in space because of the three-dimensional nature of the molecule. An antigen may have several epitopes, which is why one antigen may induce many different antibodies.

Given that these recognition sites are only a small part of the total structure, it follows that incomplete (i.e., degraded) proteins may still be recognized by an antibody raised against the complete molecule, provided that the particular epitope is intact. Conversely, and more likely, it also follows that a partially degraded molecule may have lost the particular sequence or shape that the antibody recognizes, and therefore go undetected. This is a problem peculiar to archaeological and palaeobiological proteins, and gives rise to a number of possibilities that must be considered. If antibodies are raised against intact protein, what are the chances of missing slightly degraded proteins? Alternatively, antibodies raised against degraded proteins are likely to have a high affinity for proteins other than those against which they were raised (i.e., they give false positives). These problems, when coupled with those of contamination, which is a characteristic of any biological study of archaeological material, make the immunochemical study of prehistoric human bone a challenging field.

MUMMIFIED TISSUE AS A CASE STUDY

Although most archaeological human remains are skeletonized, there is a whole class of mummified tissue that is characterized by the survival of a significant amount of soft tissue, which is of great interest to the palaeobiologist and palaeoserologist. Mummies—both natural and artificial—have now been extensively studied, and are probably the most fruitful area for the application of immunochemical techniques. It is here that immunochemical detection of protein, in addition to providing information about the survival of particular proteins, can also be expected to give evidence of infectious diseases. Antibodies to disease are themselves proteins (called immunoglobulins), which, if produced by the host in vivo may survive in mummified tissue, and therefore be detectable by immunochemical methods.

The amino acids that link together to form proteins can also be studied, either individually in providing a potential dating technique (known as amino acid racemization) or collectively for confirming the identity of proteins by matching their amino acid profile with modern standards. Another class of biomolecules, the lipids (fats), are potential...
sources of information about tissue integrity, diet, lifestyle, and evidence of disease.

Palaeosorology, in particular the study of ancient blood groups, is reported to work best when soft tissue is preserved. Since blood groups, as defined by the ABO antigens, can be determined from cells extracted from bone, hair, skin, or muscle, as well as blood cells, there have naturally been a number of studies in which blood grouping has been attempted on mummies. Standard tests for free ABO antigens have yielded poor results, but tests adapted for tissues devoid of blood are claimed to have given adequate results. These data have been used to study relationships between living and prehistoric populations in the Aleutian Islands, southwestern United States, Peru, and Chile. More recently, however, it has been realized that blood grouping on material extracted from soil is extremely dubious due to the ubiquity of interfering material, and it is not now recommended. Again, it would appear that if population genetics are required, the best approach is now to use DNA homologies. Potentially, therefore, it would seem that useful palaeoanthropological information can be obtained from the palaeobiology of mummified tissue, although most authors stress that this must be used in conjunction with other information.

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Palaeogenetics: DNA for the Archaeologist

INGOLF THUESEN

In 1981, Chinese scientists reported the extraction of nucleic acids, the genetic material of all living cells, from a body found in the Changsa Han tomb. Despite the considerable implications of the discovery, the result was hardly recognized at the time. Four years would pass before scientists in the Western hemisphere presented similar results from this new field of science, which now is materializing in an interdisciplinary space between archaeology, molecular biology, genetics, biological anthropology, palaeozoology, palaeobotany, and palaeontology. For reasons mentioned below, the discipline is here called palaeogenetics, but other names have been applied to it, such as genetic archaeology, biomolecular archaeology, or simply molecular archaeology. The discovery of the method and its impact on archaeological science have been compared to that of radiocarbon dating, although the potential of reconstructing aspects of ancient biological life is more far-reaching than dating such remains. Thus far, most palaeogenetic research has been concentrated on the development of analytical methods. Considerable effort has also gone into finding the oldest genetic material. A weevil trapped in amber, which is dated to 120–135 million years B.P., has been reported, and plant remains in amber have also produced DNA. Even if a very conservative estimate is assumed for the preservation of ancient DNA (5000–10,000 years), these discoveries demonstrate that it can survive under special circumstances for much longer times.

GENERAL BACKGROUND

Organic life takes shape due to a coded record in DNA molecules (Deoxyribo-Nucleic Acid), which are located in the chromosomes of the cell nucleus. The four “building blocks” of DNA molecules are nu-
cleotides that are labeled A, T, C, and G according to their base contents (A = adenine, T = thymine, C = cytosine, and G = guanine). The nucleotides are joined in pairs (A-T and C-G) to form a long double helix, which through the interaction with RNA (Ribo-Nucleic Acid) determines and regulates the synthesizing of proteins in particular enzymes. A particular sequence of nucleotides, a gene, determines a specific protein. DNA molecules, which store the biological information, are transmitted through reproduction among individuals. Thus, all the inherited characteristics of the individual (the genotype) can be described by its DNA. Defects or changes in the genes occur (e.g., by ionizing radiation), leading to mutations and inherited diseases such as cystic fibrosis and hemophilia. The evolution of a domesticated plant or animal species is due to human exploitation and selection of individuals or races that have optimal genetic characteristics.

At the termination of life, enzymatic activity normally initiates destruction of DNA and RNA. Under one set of extraordinary conditions, however, caused either by nature itself or by human intent, some of the nucleic acid in cells or tissue may survive by the process of mummification.

ARCHAEOLOGICAL APPLICATIONS AND PROCEDURES

An early attempt to extract and characterize ancient DNA was made on mummified tissue from an extinct zebra species, the quagga. The successful extraction of DNA from an Egyptian mummy soon followed. The results showed that it was possible to extract small segments of the genome. An obstacle in these pioneering efforts was to prove the authenticity of the DNA extracted from the specimen. Mummies in museums have often been handled by a number of individuals, and just a single cell from a conservator or scientist may contaminate the sample. This problem is greatly magnified if the amplification method known as PCR (Polymerase Chain Reaction) is used. A single sequence of DNA, whether targeted or a result of contamination, will be multiplied to several million copies by this technique. On the other hand, the strength of the method in generating ancient DNA is apparent. In theory, one surviving ancient molecule or segment is sufficient for characterizing some biological aspect of a plant, animal, or human individual (e.g., part of a Y-chromosomal DNA-segment can establish that a human individual is male).

Radiocarbon dating of ancient DNA assumes that contamination factors have been excluded. For museum specimens, contamination from handling can be ignored when non-human animal or plant species are being tested, since specific non-human DNA sequences are targeted. For human samples, contamination must be avoided or removed (e.g., by sampling from body regions that have never been exposed or handled by humans, or by cleaning the exposed surfaces of the samples).

Although the discovery of ancient DNA from mummy tissue in museum collections was groundbreaking, its archaeological applications are restricted. Only a finite number of mummies are available for analyses. Therefore, attempts were made to extract DNA from ancient bone and teeth. In 1989 and 1990, two research groups independently reported successful extraction of human DNA from bones. Because of its very broad applicability to human and animal bone remains, this discovery has important implications for future archaeological research.

Since the discipline of palaeogenetics is barely 10 years old, its archaeological accomplishments have been limited. There are a few instances of sex determination and ethnic characterization of human archaeological material. Biological topics, such as taxonomy and general evolutionary theory, have generally received the most attention. Egyptian mummies have already been mentioned. Broader-based, more systematic research programs are now in progress. The prehistoric and historical populations of central Italy and Spain are being studied using...
palaeogenetic methods.\textsuperscript{227} A multidisciplinary project has been initiated for the Guanche mummies of the Canary Islands.\textsuperscript{228} Successful extractions of DNA from carbonized plant remains have been reported for ancient Jordan (Tell es-Sa‘idieh).\textsuperscript{229} Our palaeogenetic research group has been engaged in pilot studies since 1986 to adapt palaeogenetic methods to archaeological issues, both in analyzing museum specimens and in developing appropriate field methods.\textsuperscript{230}

The scientific procedure begins with the formulation of an archaeological problem that can conceivably be answered on the basis of genetic information. The individual is sampled from a well-preserved part. For example, for a human skeleton, a piece of a femur or a tooth is excellent. Any contamination must be avoided. The DNA in the sample is then extracted according to protocols, which may differ depending on the type of tissue, skin, bone, etc.\textsuperscript{231} If the extracted DNA is damaged, it can be repaired by other procedures to obtain adequate ancient DNA, i.e., DNA that can be routinely handled by molecular biological procedures. Sometimes the extracted DNA contains substances that inhibit the PCR amplification; this problem can be solved by further purification procedures.

The next step in the analysis is genetic characterization of the extracted DNA, which requires knowledge of the particular sequences that characterize sex, biological kinship and ethnicity, and species variation or defects (such as inherited diseases). For determination of human sex, the X- and Y-chromosomes are obvious targets. For species variation, particular highly variable regions of the genome are relevant. In that regard, particular attention has been directed to so-called mitochondrial DNA (mtDNA). These DNA molecules are located in organelles (mitochondria) outside the cell nucleus, and are inherited only maternally.

The targeted DNA sequence from the sample is amplified by PCR. The nucleotides of the PCR product are sequenced and compared to reference DNA sequences in order to establish the species and other biological characteristics. With these results, the archaeological problem has been resolved or must be reassessed for further research.

\textbf{A CASE STUDY FROM ANCIENT SYRIA}

In 1990 and 1991, a Danish archaeological expedition excavated remains of a settlement and cemetery at Tell Mashnaqa in the middle Khabur River

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{sampling.jpg}
\caption{Fig. 30. Sampling of human remains for DNA analysis in the field in eastern Syria. A tooth, after being removed from a cranium, is placed in a tube with a DNA-extraction buffer.}
\end{figure}

\textsuperscript{227} R. Mariani-Costantini and colleagues at the Institute of Pathology, Università Gabriele D’Annunzio, Chieti, Italy; and A. Perez-Pérez and colleagues at the Secc. Antropologia, Universidad de Barcelona, Spain.

\textsuperscript{228} A.C. Auferheide (Department of Pathology, University of Minnesota, Duluth), C. Rodríguez Martín (Museo arqueológico de Tenerife, Santa Cruz, Canary Islands), and colleagues. DNA analyses have also been carried out by P. Rogan (University Hospital, Hershey, Penn.), and W. Salo (University of Minnesota, Duluth).


\textsuperscript{230} I coordinate a palaeogenetic research group at the University of Copenhagen and the National Museum in Denmark. Many of the ideas and the case study presented here are based on the work of this group, whose members include Henrik Nielsen (Department of Biochemistry), Søren Nørby (Department of Forensic Genetics), Jens Peder Hart Hansen (Laboratory for Biological Anthropology), all at the University of Copenhagen, and Bent Aaby, who is in the Science Unit of the National Museum.

\textsuperscript{231} See B. Herrmann and S. Hummel eds., Ancient DNA (New York 1993).
region, Syria. The finds have been radiocarbon dated by accelerator mass spectrometry (AMS) to ca. 5000 B.C. Palaeogenetic methods were employed to develop field methods and to obtain cultural-historical information. How long would DNA in fragile 7,000-year-old human bones be preserved in a hot and mostly dry environment? If preserved, palaeogenetic information on sex and ethnicity might be obtained.

In 1990, the samples of bones, which were brought back to the laboratory in Copenhagen, gave negative results for DNA, and the observed chemical reactions indicated that destructive enzymatic activities might have been triggered by exposure of the bones to air and light. Therefore, a procedure was developed in the next field season to reduce the risk of post-exposure degradation and modern contamination. Burials were carefully located before bone material was exposed. A team of scientists (including molecular biologists and physical and dental anthropologists) excavated the human remains. The position of the body and large bones were identified before the skeleton was completely exposed. A few centimeters of bone were removed and placed in tubes with DNA-extraction buffers as soon as the skeleton was uncovered. Gloves were worn to avoid contamination. Teeth were especially important, since it is believed that DNA in the interior, sealed environment of the tooth might be better preserved. After recording and photographing, a tooth would be pulled out from the jaw and placed in a tube with a DNA-extraction buffer (fig. 30). After a few hours, DNA-extraction was initiated in the camp headquarters.

This routine produced a large series of samples from the burials. Although the laboratory analyses are still in progress, the preliminary results indicate that specific palaeogenetic routines can be carried out in the field, even under the difficult and trying conditions of the east Syrian desert.

FUTURE PERSPECTIVES

The application of palaeogenetics to archaeological remains depends upon the close collaboration of archaeologists and geneticists. Such research promises to contribute significantly to the reconstruction of past human life and environmental adaptation. Determination of human sex, biological ethnicity, and kinship are realistic objectives given the rapidly growing knowledge of the human genome. For other animal and plant species, ancient DNA analysis should contribute significantly to traditional morphological identification. Since DNA from microorganisms will also eventually be isolated and identified, new perspectives on inherited and infectious diseases, the fermentation of ancient foods and beverages, etc., should emerge.

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Archaeological Conservation

CATHERINE SEASE

Every civilization has had people repairing and conserving objects of cultural importance. It is not uncommon, but always fascinating, to excavate artifacts that were repaired in antiquity. The conservation of archaeological material as we know it has slowly developed into a discipline over the past 200 years. In the 16th, 17th, and 18th centuries, much cleaning, repairing, and restoring of antiquities was done empirically by craftsmen or archaeologists and was not based on scientific principles. Heavy-handed restorations led to the alteration and sometimes destruction of a considerable amount of excavated material. By the early 19th century, reaction by archaeologists to these restorations precipitated a change resulting in a preference for antiquities in their original condition. At this time, publications also began to appear that dealt with the treatment of antiquities, as well as the analysis of the materials of which they were made.

In 1888, the Royal Museums of Berlin established their Chemical Laboratory, and Friedrich Rathgen, its first director, became the first scientist hired to...
work in a museum laboratory. He recognized the need for a systematic approach to conservation and a scientific understanding of how and why artifacts deteriorate. Over his 39-year career, Rathgen was actively involved in developing and applying physical and chemical methods to the preservation of archaeological materials, and he thus played an important role in the development of archaeological conservation as a science and profession. As similar laboratories were established at other museums, the number of scientists working on the conservation of artifacts grew.

At the same time, the literature pertaining to archaeological conservation grew. Rathgen's handbook, *Die Konservierung von Altertumsfunden* (Berlin) appeared in 1898; an English translation appeared in 1905 entitled *The Preservation of Antiquities: A Handbook for Curators* (Cambridge). This was followed in 1934 by the publication of Harold Plenderleith’s *The Preservation of Antiquities*, which in its revised form (London 1971) has until recently been a standard reference for English-speaking conservators.

Most early conservation treatment took place in laboratories, and field conservation consisted predominantly of rudimentary techniques to remove excavated material safely from the ground and to a laboratory where it could be studied. In 1888, Flinders Petrie published a short article in the *Archaeological Journal* (vol. 65, pp. 85–89) in which he described treatment methods he employed in the field on freshly excavated material. Today, three manuals and numerous publications provide the archaeologist with basic field conservation techniques.

In the early years, no formal training for conservators existed. Conservators received their training through an apprenticeship system working in museum laboratories. In 1957, the Institute of Archaeology, University of London, established the first university course in archaeological conservation.

Archaeological conservators today are highly trained specialists with a broad knowledge of all materials found on excavations. Ancillary disciplines, including archaeology, materials science, chemistry, ancient technology, and art history, are important parts of the conservator’s training. Conservators need to understand the different materials from which artifacts are made and their chemical and physical structures. By understanding how these materials deteriorate and under what conditions, conservators are able to treat artifacts to prevent further deteri-

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oration from taking place. Excellent manual skills and a sensitivity for objects and materials are also prerequisites for a conservator.

In the field, a conservator is typically responsible for cleaning all artifacts, stabilizing metals and fugitive paints, piecing together broken objects, and lifting delicate objects out of the ground (figs. 31–32). In some instances, treatment can be considered merely first-aid measures for safely excavating objects and shipping them to a conservation facility where they can be examined. A series of lifting techniques has been developed over the years for this purpose. More and more frequently, however, due to laws governing the removal of material from the country of origin, the only conservation treatment that artifacts receive will be that done in the field. This places greater pressure on the conservator to treat artifacts more fully in the field, so that the maximum information can be retrieved from each object (see fig. 33), research carried out, and publication drawings and photographs made before the artifacts disappear into museum storerooms.

Documentation is an important part of any conservation treatment. Conservators maintain written and photographic records detailing the condition of an object before and after treatment, the various steps in its treatment, the materials used, and any observations that might be of interest to the archaeologist, conservator, and other scientists who may subsequently work on and study the object. For example, textiles and other organic materials are frequently preserved only in the corrosion products of associated metal artifacts (fig. 33). A trained eye and careful cleaning techniques enable a conservator to bring to light evidence that could easily be destroyed by inexperienced hands.

Conservators can also help in planning and implementing the storage of artifacts, of particular importance for multiseason excavations that provide on-site storage for years before artifacts go to the local or national museum. By assuring optimum storage conditions, particularly for metal artifacts, the long-term preservation of the excavated material is greatly increased. Conservators can also help pack objects safely to ensure their safe transport whether to the local museum or back to a laboratory or research facility in another country. Taking time and care over the packing of artifacts can mean the difference between their survival or destruction.

In addition to their knowledge of conservation, conservators bring additional expertise to an excavation. Experience working on known materials frequently enables the conservator to identify the ma-
terials from which objects are made. Sometimes this information can be of importance to the archaeologist when exotic materials unusual to the site are found. For example, at a site on Crete, material that was first labeled as fine ware ceramics was eventually identified by the author as fragments of ostrich eggshell.

A knowledge of ancient manufacturing processes frequently helps a conservator make observations about objects that other members of the team cannot. In cleaning an object, the conservator is the first person in perhaps thousands of years to examine it carefully, noting details of manufacture and use that add to the information the object reveals.

A conservator may be called upon to make casts or impressions of objects to aid in their study. For example, cylinder seals or coins cannot usually be taken out of a country for study. Rollings of the seals or plaster casts of the coins, however, often offer a more cost-effective means of studying this material. Numismatists also often prefer to publish photographs of coin casts, as they frequently show more detail than photographs of the coins themselves.