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THE ROLE OF MATERIALS RESEARCH IN CERAMICS AND ARCHAEOLOGY[1]

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■ **Abstract** Materials research has been applied successfully to the study of archaeological ceramics for the last fifty years. To learn about our history and the human condition is not just to analyze and preserve the objects but also to investigate and understand the knowledge and skills used to produce and use them. Many researchers have probed the limits and methods of such studies, always mindful that a glimpse at ancient reality lies in the details of time and place, context of finds, and experimentally produced data, usually compared with standards that were collected in an equivalent ethnographic setting or that were fabricated in a laboratory in order to elucidate the critical questions in a technology that could be understood in no other way. The basis of most studies of ancient technology has been established as microstructure; composition and firing; methods and sequence of manufacture; differentiation of use; use-wear and post-depositional processes; technological variability that can be interpreted as a pattern of stasis or innovation, which can be related to cultural continuity or change; and interpretation that can involve technology, subsistence trade, organization, and symbolic group- and self-definition.

INTRODUCTION

In his preface to the translation of Pushkin's *Eugene Onegin*, Vladimir Nabokov observed (1), "In art as in science there is no delight without the detail, and it is on the details that I have tried to fix the reader's attention. Let me repeat that unless these are thoroughly understood and remembered, all 'general ideas' (so easily acquired, so profitably resold) must necessarily remain but worn passports allowing their bearers short cuts from one area of ignorance to another." Using modern materials analysis to characterize ancient ceramics as they exemplify our cultural heritage is much the same problem. Just as an author deconstructs the

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details of a situation or character he imagines as meaningful and real enough to reassemble and record, we seek to analyze and interpret the ancient record starting with the study of "things" (in this case, ceramic things) and the context of their deposition in the archaeological record. We try to establish the details of date, place, context, materials, technology, significance, and cultural meaning—the same expectations we have of an informative newspaper article. The ceramic art object or ceramic archaeological artifact or site with ceramic architecture actually represents specific knowledge, meaning, and culture. To learn about our history and the human condition is not just to analyze and preserve the objects but also to investigate and understand the knowledge and skills used to produce and use them (2). In the quest to learn from objects, materials science has special philosophical and practical roles. The structure-property-processing-performance paradigm of materials science and engineering provides the template and the methodology, and materials research laboratories provide some of the cutting-edge tools to do the job.

RESULTS OF PAST STUDIES

Two previous articles have appeared in the *Annual Review of Materials Science* (4, 5) and one in the *Annual Review of Anthropology* (6) that have aimed to use analyses of materials, their processing and transformation into useful goods, as a way of understanding cultural phenomena. In 1986 Smith (4) stated that recent developments in materials science had allowed the visualization of material structure beyond human vision such that direct investigation of objects would lead to a critical understanding of the role of materials development in human history. His experiences with the translation of Medieval and Renaissance period European texts had shown that scholars often had misunderstood and improperly recorded the practices of craftsmen. Smith emphasized that modern researchers, in common with ancient craftsmen, learn by "doing things," and both have a special knowledge of the direct interaction with materials that reveals links among composition, properties, and processing. Such experiences, he maintained, have an aesthetic quality that arouses curiosity and allows the identification of xenomorphs or misfits, especially at boundaries where instability, interaction, and transformation occur. Isolation of such phenomena he considered as prime locations of concentrated investigation and as sources of possible discovery. However, such invention is impossible to document in the archaeological record, and only objects that represent technological development, or technological innovation and change (as when something new is brought to the market and becomes commonplace) are excavated. Smith viewed materials history as the replacement of one material or process by another for utilitarian purposes, but he believed that the subtle advances in materials technology that occurred before advances in mechanical technology resulted from the symbolic use of materials to satisfy philosophical questions and to demonstrate and control seemingly magical phenomena. His thoughts have provided many questions for those who study material culture and cultural heritage.

Smith's call for the study of archaeology from a materials point of view had been foreshadowed in 1985 by Kramer (6) who reviewed and promoted the study of modern potters in traditional settings before their wares and livelihoods were replaced by alternative materials and technologies. Kramer, like Smith, called for generation of a body of empirical data, but by using comparative ethnographic studies of traditional potters and their wares to evaluate the archaeological interpretations of ceramic evidence. The conclusions often enrich or contradict archaeological models that attempt to explain production, distribution and exchange, consumption, reuse, and discard. One purpose of ethnoarchaeology is to evaluate factors that promote or discourage preservation of clay-based products in the archaeological record, as, for instance, when a traditional village is abandoned and its degradation can be observed. Another is to is to evaluate factors that favor stylistic conservatism or innovation and change, as the meaning of change in the archaeological record is one of the critical questions. For instance, when does a change in pottery style equal a change in people? A third is to provide information on organization of ceramic production, and the shift from home-based seasonal production to workshop to full-time factory production with its attendant implication of an increase social stratification, class or caste differentiation in which artisans, craftsmen, and workers are low in status and often denied freedom to migrate, effectively being slaves. Archaeological studies of pottery produce information primarily about production, consumption, and exchange, whereas one would like to learn more about cultural organization, operation, and evolution, and especially such timely topics as gender and social identity. One area of study that is proving fruitful in this quest is in instances where historical documentation, observation of pottery communities, and archeological investigation overlap and intersect.

In 1989, in addition to traditional historical documentation, Kingery (5) used materials analysis of the products of three industries—the seventeenth century development of European porcelain at Meissen, the late nineteenth century Edison carbon microphone and electric light, and the early twentieth century Nernst zirconia-yttria lighting filament—in order to research the early development of modern materials technology and especially modern ceramics with its significant impact on the electrical and electronics communication and information industries. He placed the development of these socially desired technologies within a model of technological innovation and engineering science that is now familiar to us all in the twenty-first century. Essentially, a research laboratory conducts materials science—discovery and scientific explanation—in order to enable new materials, devices, and products that modify our lives and evolve into new socio-technical systems, such as transportation, communication, or education. Kingery was effectively using the methods prescribed by Smith and Kramer to investigate the recent historical past. In order to study modern technology, he found useful three ways of viewing, classifying, or investigating a technology. These perspectives, borrowed from studies of the history of technology, are product-centered, industry-centered, and task-focused.

The above three articles from the Annual Reviews publications represent the kinds of problems and viewpoints that were central to defining and developing the field of ceramics and archaeology in the1980s. They are focused both methodologically and heuristically. If we review articles in *Science* in the 1960s, we find a different set of questions being pursued, that is, questions that used materials analysis of archaeological artifacts or art objects specifically chosen to explore the outer bounds of the field and to provide an overview and philosophical direction. Wertime (7) attempted an industry-wide review of the development of metallurgy during the fifth to third millennia B.C. in Southwest Asia. Smith (8, 9) emphasized materials, not matter, as the basic unit of human experience, and the processing of ceramics and metals as a way of altering properties for aesthetic and utilitarian, social, and symbolic functions. Smith emphasized as fundamental the dependence of properties upon structure, and thus enunciated what has become the structure-processing-properties-performance paradigm of materials science. Wertime (10) then, even more globally, defined his field of study as pyrotechnology, the use of fire to fabricate plasters, ceramics, metals, glazes, and glasses, and he catalogued analytical methods, primarily chemical, then useful in the study of these materials. Then in 1978, Kranzberg & Smith (11) synthesized these ideas in order to make a national case for the support and funding of materials science and engineering as a separate discipline. Wertime & Wertime (12) in 1979 organized a conference to explore case studies of early pyrotechnologies and to document the evolution of the first fire-using industries. A second conference, called Archaeological Ceramics, was held a year later to focus on ancient ceramics, generously defined as non-metals, so that many technologies heretofore considered unrelated to clay-based ceramics were reported (13). The result was that the field of archaeological ceramics was enlarged to more closely approximate the field defined by the major professional organization, the American Ceramic Society, as pigments, cement, concrete and plasters, whitewares, and glasses among others. These developments cleared the way for new questions of cross-cultural comparisons of technologies, cross-craft interactions among craftsmen, and a questioning of the way we define a craft activity or specialization or industry in an ancient culture (14). The term archeomaterials was coined (15). The effect on archaeological field research has been to increase the significance of technology and materials identification and to promote the search for direct evidence of craft activities, especially workshops, furnaces, industrial debris, manufacturing elements and tools, caches of raw materials, and objects in successive processing stages in order to learn what people did, how they did it, and what they had to know to practice the technology.

METHODS, TOOLS, AND TECHNIQUES

Archaeological excavations conducted in the last century produced artifacts that were displayed in museums and organized and described by material and by technology, with stone and bone being the oldest and coming from the lowest strata, and with bronze and iron, respectively, being more recent. The presence of ceramics spanned the later stone strata and was nearly ubiquitous in higher strata up to the present, and thus was left out in the naming of periods as Old and New Stone Ages, Bronze Age, and Iron Age. In the Old Stone Age, or Paleolithic period, stone artifacts were mainly produced by percussion and flaking, where as in the New Stone Age, or Neolithic period, tools were often smoothed by grinding, but this generality has exceptions; for instance, grindstones for pigments were made and used in the Paleolithic period. With continued excavation, observations amassed a body of data that separated cultures by economic or subsistence system and social organization into the hunter-gatherer with the longest history, the farmer from the Neolithic period, and the urban-state dweller, the rural farmer, and cultural outsider or outlaw with the shortest history. The understanding of the details of this development is one of the crowning achievements of archaeology. However, the old museum-based periodization has been retained throughout the elaboration of our socio-economic, politico-military, and artistic magico-religious philosophical understanding of the significance of the ancient record.

Identification of the technologies specific to each period or economic system have led to four kinds of studies. In one case, some sought to microscopically study a technology and reproduce it, often examining the replicated artifact or processing stage using the same analytical methods as for the original artifact, Semenov's (16) investigation of stone tool surfaces in the 1920s being the first. In another case, researchers sought to produce compendia that enumerated various technologies, often retrospectively from the point of view of the modern practice and organization of a technology; one of the best and most commonly used is by Hodges (17). These compendia derive from the study of the history of western technology, and, although meant to apply to the archaeological record, often are based on such Eurocentric nineteenth century texts as Diderot's *Encyclopedia of Arts and Industries*. Thus these general guides help to establish our expectations of what will be found during an investigation but must be used with a measure of skepticism to avoid producing a retrospective technology. Some compendia are specific to particular culture areas and include technical analyses, such as the study of Egyptian materials and technologies by Lucas (18) and recent update of the text (19). In a third case, reconstructing stages in the production, use, and discard of a particular type or style of artifact through careful observation of the group of artifacts and their archaeological contexts in order to establish the nature and diversity of a technology was the methodology first set forth by Leroi-Gourhan in the 1940s (20). He called "chaîne operatoire," or the chain or sequence of operations, as the critical step of this systems approach to establishing the life history of an artifact. He then relied philosophically on the French school of structuralism for the intellectual tools to generalize to the technology and the socio-technical system into which it is embedded. In the fourth case, in order to be sure that we are seeing sharply through the changes or veil of age, a recent trend, especially for very old artifacts, has been to examine processes of deposition, degradation, corrosion, and weathering in order to separate "ecofact" from artifact, that is natural from human processing; for example to distinguish an ancient ceramic object made in a forest fire from one fired by people. The term technofact has been used to describe tools and incomplete objects in various stages of production. The significance here for methodology is that we are using or making and then testing artificial standards, the processing, structure, and properties of which are known, in order to compare with aged objects that we seek to know. Each of the four approaches outlined above has been a powerful technique in the study of pyrotechnology and archaeomaterials in general and archaeological ceramics, in particular.

Prior to the development of direct dating by radiocarbon and luminescence techniques, relative chronologies were established by the technique of serial dating. Essentially, the relative placement of diagnostic pottery shards in superimposed archaeological strata allowed comparison of relative age in different excavation squares or trenches at one site, as well as comparison of age between sites. The stylistic grouping and counting of wares by strata led to plots of abundance through time, called battleship curves, that provided a measure of material culture change from one period to another. To this refined connoisseur-ship of broken, specially shaped or decorated pottery that could only be learned through apprenticeship and practice came other strategies to aid in the determination of date. One approach, exemplified in the work of Caley (21, 22), was to analyze the chemical composition of metals, especially coins, and glasses in order to correlate changes in composition with a time period. Another approach was to attempt to make connections between one archaeological site and another of similar date by the recognition of imported trade goods and their chemical and technical identification to particular source areas or a general provenance. Shepard (23) and others tested ceramics with unusual decorations or anomalous fabrics that were probably intrusive into an archaeological site by using the geological methods of petrographic analysis to identify minerals and mineral assemblages, to quantify their relative amounts, and to relate them to possible source regions with similar suites of minerals and particular types of associated geologies. Often it was only possible to relate pottery shard imports to regions where that particular type was more abundant. Thus many studies have sought to establish the nature of the exchange by mapping abundances of artifacts at central and peripheral areas. Dating has now become a specialized craft (24), and the early chemical and structural studies have developed into more specialized techniques that have been successful in establishing aspects of regional economy, exchange systems, long-distance trade, and the source or provenience of artifacts (25).

The analytical methods to deconstruct and interpret ancient ceramic technology and to determine raw material sources and the provenance of ceramics are well established. Until we generate new questions, the tools and techniques remain static. McGovern (26) reviewed the status of scientific studies in archaeology, as well as some of the contemporary methods, for the study of archaeological materials. Much of the accumulated methodology is available in handbooks; three that are comprehensive and classics are by Shepard (23), Rye (27), and Rice (28). Although Shepard uses the type-style classification of pottery in her own studies, she states more technology can be learned from the misfits—over- or under-fired shards, misshapen ones with fabrication errors entrained, or ones with evidence of use or reuse. She presents photographs of various pottery surfaces and calls for careful microscopic examination of surface textures. Rye uses radiography to image the inner structure of ceramics and compare it with surface traces in order to elucidate methods of manufacture and the sequence of manufacturing steps. Rice provides a thorough review of previous studies and approaches to ceramic problems, but her encyclopedic text often does not provide sufficient specific technical data to permit the researcher to solve problems, such as how to calculate a coefficient of thermal expansion or determine a ceramic firing temperature, but she provides references.

Many other texts use a case study approach, as do conference and journal articles. Kingery & Vandiver (29, 29a) determine composition, microstructure, and firing temperature to interpret the appearance and production of several individual ceramic objects significant in the history of ceramic technology. A landmark ceramic exhibition at the British Museum is detailed in a catalog *Pottery in the Making*, edited by Freestone & Gaimster (30), that contains significant review articles on ceramics in various culture areas and periods from a technological and materials analysis perspective. This exhibition parallels an earlier one, entitled Masterpieces of Glass, that remains an authoritative source on the fabrication of ancient glass objects (31). Two ethnographies with significant technical content are the classics by Wulff (32) and Rye & Evans (33). Wulff places pottery within the larger context of various cultural uses of clays in Iran, and Rye & Evans investigate the glazed pottery of Pakistan. Many case studies are contained in conference proceedings. Especially significant and relevant are those that expanded the ecological and environmental context of ceramic production and use and that have been edited by Matson (34) and van der Leeuw (35). Regular conferences with case studies in archaeological ceramics are the Archaeological Chemistry conferences of the American Chemical Society, the Archaeometry conferences sponsored by the Laboratory for Archaeometry and the History of Art at Oxford, Ceramics and Civilization sponsored by the American Ceramic Society, Materials Issues in Art and Archaeology sponsored by the Materials Research Society, the International Symposium on Ancient Ceramics sponsored by the Shanghai Institute for Ceramics, as well as parts of conferences of the Archaeological Institute of America, the Society of American Archaeology, the Society of Archaeological Sciences, and others. For conservation the prime conferences are those sponsored by the International Institute of Conservation, the American Institute of Conservation, and the International Conservation Committee for Museums.

The most recent developments in ceramic analysis have been studies to identify organic residues concentrated from various parts of cooking and storage jar walls in order to reconstruct subsistence patterns. McGovern et al (36) have reconstructed a history of beer and wine, and Evershed (37) has determined the contents of medieval British stews. Organic chemistry, particularly biogeochemistry, combined with inorganic materials analysis, is promising to contribute to better understanding through environmental reconstruction of sites. Two particularly noteworthy topics are the analyses of ancient soils for the traces of activities trapped within, as well as a detailed depositional history that provides additional context, and the survey and reconstruction of the ancient landscape to interrelate human and natural processes. For instance, does environmental degradation begin with sedentary Neolithic populations? What is the carrying capacity of various ecological niches for various activities and population densities? Such studies should generate new knowledge about the mixed use of site catchement areas and areas of interaction on the peripheries of settlements. In the first case, microexcavation of blocks lifted from the site and transported to the laboratory provides the samples to be studied and tested. In the second case, techniques of remote sensing, geological coring, and prospecting are used.

Others (38, 39) have discussed ways to better remove cultural materials from the field and to conserve them through a process of assessment, documentation, stabilization, and, if necessary, intervention to preserve original material, appearance, and sometimes use, through reversible treatments. Evaluation and improvement of treatments may well become a significant endeavor for materials analysts because many objects are composite structures, such as low-fired alkaline or lead-glazed ceramics, or high-fired, high-calcium-glazed ceramics in which the body and glaze do not fit well (40). They are recognized by glazes that are crazed or flaking or by a porous body that retains salts. Current conservation treatments favor the preservation of either the body, by removing salts and delaminating the glaze by delayed crazing and slow crack growth, or the glaze, by not immersing the ceramic in water. In addition, many ceramics are a mixture of crystals and glass or an inhomogeneous glass that weathers preferentially at the least stable part of the microstructure and composition. Many low-fired earthenwares consist of clay barely dehydroxylated and held together with only a small amount of glass at the sintered contact joints. Many of these wares are difficult to conserve and lift in the field, and many do not make it to the laboratory, including entire ware types. Microstructural changes in porous materials are often small but cumulative, difficult to document, and could benefit from characterization and analysis of materials and degradation processes (41).

The process of archaeological excavation is innately destructive and descriptive and can only be conducted once. In recognition of the limitations of this methodology, the task of archaeology has been enlarged in the last few years to include not only preservation of artifacts and the reporting of the results of excavation and analyses, but also public education and outreach, site planning, and oftentimes site preservation, and even onsite museum planning and training. In addition, as archaeological sites become more scarce and precious, the need to prevent looting and theft of cultural heritage and the illicit plundering of sites, as well as their unnecessary development, requires vigorous cultural resource management. The task of ceramic technical studies will expand from reconstructing and explaining the nature of the objects and their context, along with an understanding of the knowledge, skills, and decisions used in production, use, exchange, and discard, to one of defining and preserving material culture as a significant way learning about past meaning and values. One change for ceramic studies is that many analyses will need to be non-destructive, and many museum laboratories already are developing such strategies and equipment, especially in France and Japan. The specific significance of research projects and tests will need to be made more explicit in terms of, not only scholarly value, but also public value. Sampling strategies will be articulated more carefully so as to be both representative and hierarchical, that is, proceeding from non-invasive methods for large numbers of artifacts to more destructive sampling of fewer numbers of artifacts for more cost- and time-intensive tests. Materials analysts and archaeologists are each becoming more interdisciplinary and entering one another's spheres of expertise. Interdisciplinary graduate programs in both fields are readily available at many universities. Finally, tasks following excavation may expand to the preservation of a technology through its onsite or factory replication, as well as to interpretive public outreach through local ceramic workshops.

TYPES OF PROBLEMS IN ARCHAEOLOGICAL CERAMICS

Trace element analysis is the primary means by which studies of trade, provenance, and sourcing are conducted, not only for ceramics, but for obsidian and other materials as well. Neff (25) and Bishop & Lange (42) have reviewed the current status and development of the field. Petrographic analysis, bulk chemical analysis, and microstructural studies often complement and refine the conclusions. Onsite resource survey for clay and other raw material sources is essential to transforming a study of provenance into one of sourcing. Anticipation of the geological variability is also crucial to success. Problem definition is the most significant aspect of any archaeological materials research. Once an initial study is carried out that "gets the picture right," other sources of information and studies can be brought to bear to amplify and enlarge our interpretation of the ancient world. For instance, Sayre's (43) classic study that established compositional categories of ancient glasses has been buttressed, not only by other compositional studies, but also by the study of texts and replicate processing experiments by Oppenheim (44).

Technological studies primarily have sought to establish pattern by structure. That structure can be macrostructure or microstructure. Smith (45) in his book, *History of Metallography*, detailed the success of microscopy in understanding the composition, processing, and properties of both modern and traditional metals. Lang & Middleton (46) show how macrostructure can be imaged using traditional X-radiography and xeroradiography to detect fabrication methods and sequences, defects in production, and conservation treatments that help authenticate museum objects, but also lead to an understanding of production technology. Microstructural imaging by scanning electron microscopy has found a special function in archaeological ceramic studies, which is determination of firing temperature. Kingery & Frierman (47) and Maniatis & Tite (48) have pioneered its use by refiring fragments of a ceramic to known increments of temperature and then comparing the degree of sintering of these standards to the unknown fragment that has not been refired. The firing temperature is established just below the point at which the microstructure is observed to change, especially by having the walls of pores smooth, sintered joints increased in size, and small pores round. This method is often supplemented by refiring tests that observe changes in refired color and linear firing shrinkage with increasing temperature, as well as changes in phase assemblage, as determined by X-ray diffraction or differential thermal analysis.

One of the reasons that studies of metals, both modern and ancient, progressed more rapidly in the twentieth century than studies of ceramics (and the development of new ceramic materials) is simply because clay particles are so much smaller than the grain size in most metals processed by traditional means that probes of much finer magnification are required to see the submicron and micron particle sizes. In 1992, Kingery (49), in a study of the history of sintering, alluded to the fact, as did Smith (50), that materials interactions can be viewed at interfaces with a variety of high magnification probes. This ability to study interfaces, postulate reactions, and understand fracture surfaces has been critical in the study of both clay and non-clay-based ceramics.

The study of ancient ceramics has expanded from pottery studies to numerous related materials; for instance, the Paleolithic period processing and use of pigments and ceramics (51, 52) and the Neolithic period plasters (53, 54)—studies that help us understand the place and use of materials technologies in various cultures. Also studied have been the technologies, such as faience (55), glass, and metals (56), that developed for urban elites as correlates of the hierarchical distribution of power and prestige, the accumulation of wealth, and the growth of bureaucracy. The special place of slags as a bridge between glass and metal processing also has received treatment (57). Many of the early luminaries of the field hoped for a unified history of technology in the days when the history of technology was envisioned as a progression of the newest, biggest, and best of enlightenment developments, often primarily mechanical. What has resulted is a diverse and rich picture of ancient technology that can support a complex range of interpretations from reconstruction of craft, or cross-craft interactions, cross-cultural comparisons of economy, technology, and organization, as well as regional economy and patterns of long-distance exchange and socio-technical systems.

The yield of information from a study depends on the sampling strategy, and different types of problems can be solved by different sets of samples; for instance, the intensively analyzed single sample that can prove the presence of a technology in a given time and place and can lead to an understanding of the practice of a technology, but cannot demonstrate the absence or range of a technology or technological practice. Selected from a single site or site locus, a group of samples can be chosen to demonstrate the range of technological variables—color and texture, oxidation and reduction, low- and high-firing temperature range. Technical analysis can show the range of technological variables necessary to produce a particular visual effect or a particular property, such as strength or toughness, impermeability, or translucency. From a group of sites or a single site through a depth of time, we can survey the range of variables that indicate conservatism or change in the practice of a technology. Comparison with geological or replicated standards can prove illuminating, as can a variety of other sampling strategies. For instance, at one site in the absence of pottery or pottery profiles, the small sherds stratigraphically excavated are being analyzed to develop a technological typology.

It is my opinion that without a physical basis in data generated by analysis of artifacts and objects, the reconstruction of history becomes clouded as it moves away from direct interpretation of artifacts to the interpretation of what others have written. Smith was impressed by the dichotomy between those who wrote about technology and those who practiced various crafts in Europe during the Medieval and Renaissance periods. However, that same dichotomy exists today when some write about technology and its meaning without identifying the materials or processes or "getting the technology right." Oftentimes the basis is dealing with only the written historical references that are peripheral to the technologies. Many contemporary references elucidate the technology and provide a resource to initiate problem formulation (58–68).

CONCLUSION

It is hoped that this review has convinced the reader that we can reach back through time (without a machine for time travel) to develop a critical understanding of how ancient people used craft and technology to solve problems of survival and organization and to make symbols or representations of what was important in their world, especially for its maintenance, longevity, and beautification. This process should be known not just as the study of material culture and cultural heritage, but also as an important field of materials research.

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