Materials Issues in Art and Archaeology

1988

A ROLE FOR CERAMIC MATERIALS SCIENCE IN ART, HISTORY AND ARCHAEOLOGY

W. DAVID KINGERY
Regents Fellow, Smithsonian Institution, Washington, DC 20560 (Current address: Dept. of Materials Science and Engineering and Dept. of Anthropology, University of Arizona, Tucson, AZ 85721)

One's first contact with materials occurs as infants with the swaddling cloths that warm and comfort us, but also restrain us. As life goes on material objects always surround us. They structure the way we look at the world and how we arrange our thoughts; they serve a wide range of utilitarian, aesthetic, social and symbolic functions; methods of designing, manufacturing and using materials are at the core of our technology and much of our culture. Materials technology, making and using objects, is thus in a unique position relative to history and culture. While interpretations sought by study of these objects are judgmental and humanistic, they must rest on as secure a foundation of solid materials knowledge as is possible. The central paradigm of materials technology is that the selection and processing of materials gives rise to a particular structure which is the source of useful properties (Fig. 1). This is exactly the process used by the artist who aims at aesthetic properties, and the craftsman and technologist who aim at particular properties.

There are a number of different levels of structure associated with an object, each of which contains information that can be crucial for its interpretation (Fig. 2). These form a hierarchy which is ultimately based on nuclear and subnuclear particles that are the subject of high energy physics; then on the internal structure of atoms; the structure of crystals and glasses formed when atoms combine together; then when crystals and glasses are combined in an object we have what is referred to as microstructure, which has dimensions of microns and can only be seen with a microscope; and then with macrostructure in the range of millimeters; finally, the whole object and, importantly, its provenience [1,2]. Different methods of analysis are applicable to these different levels of structure, but it cannot be overemphasized that each of these levels of this hierarchy, and at each level of structure associations and context, concepts familiar to historians and archaeologists, are critical parameters that cannot be overlooked.

In the history of object examination, the upper and lower ends of the structural hierarchy have been the focus of most attention. However, it is our belief that the paradigm of modern materials science and engineering relating materials selection and processing to obtain structures that give

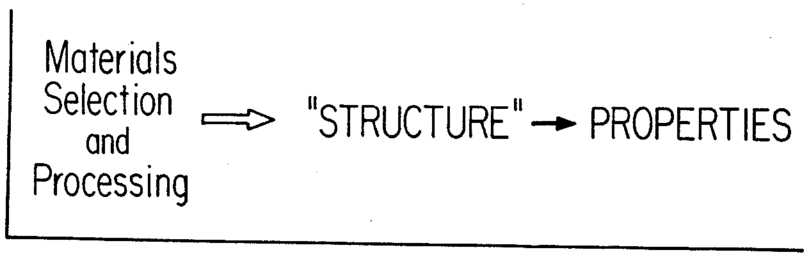

Fig. 1 A basic axiom of materials science and engineering is that materials selection and processing give rise to structure which determines properties and applications.

Mat. Res. Soc. Symp. Proc. Vol. 123. ©1988 Materials Research Society

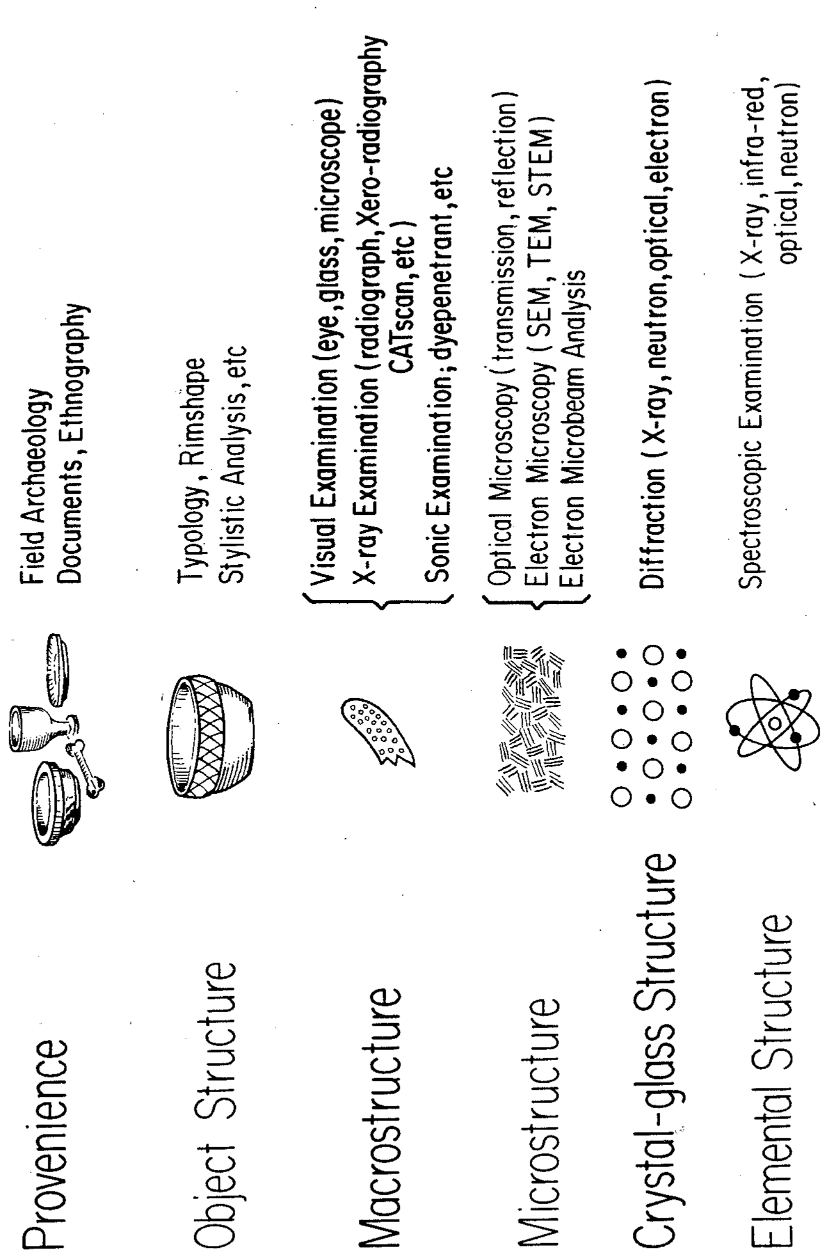

Fig. 2 A ceramic object has several different levels of structure. Different methods of analysis are informative about different levels of structure.

rise to desired aesthetic, utilitarian, social and symbolic properties and functions is isomorphous with the often intuitive techniques used in their creation. Thus, it provides a better starting point for object examination than the skills of the physicist or the field archaeologist. Being at the center of the hierarchical structure also allows more effective reaching out toward both extremes. In addition, the paradigm shown in Fig. 1 can be visualized, comprehended and applied by humanists without special extensive science training.

All history--art, technological, archaeological, political--is interactive with technology. As Fernand Braudel put it, "Technology is explained by history, and in turn, explains history; but the correlation is in neither case fully satisfactory" [3]. In object interpretation, its most intimate connections are with the design technology, manufacturing technology and use technology within which it was conceived, made and used (Fig. 3). There are feedback loops between these different technological aspects and each changes with time. This system of technology is immersed in, interacts with, affects and is affected by larger cultural ambience; its complexity and the much greater complexity of the surrounding social, political, symbolic, and cultural sets of systems suggest that any reductionist "scientific" approach will face difficulties. While we recognize this greater problem, and endorse its study, that is not our objective here. We want to focus on the narrower, but necessary, question of object interpretation which clearly provides a role for applying modern methods of materials science to better understand and interpret the traces of our unfolding history. To do this we shall focus on one case history.

PLASTER IN THE PRE-POTTERY NEOLITHIC NEAR EAST [4,5]

Obtaining the basic data necessary to study the history, development and implications of early plasters confound chemical and mineralogical techniques because the chemical composition and x-ray diffraction patterns of the starting rocks and the final products are identical. Plasters are materials that, when mixed with water to form a paste, react and set to form a rock-like product. The definitive identification of the plaster products as a plaster can be accomplished by characterizing the microstructure. For example, the gypsum rock heated to 200° or so forms a powder that reacted with water forms a rock-like material have a lath-like structure entirely different from the original rock. In archaeological samples there is some slight solubility of gypsum such that metamorphosis can occur to make the lath-like crystals more blocky. Lime plaster is made by calcining limestone rock at a much higher temperature, 800°-900°C, for some little time in order to allow the heat to penetrate through the rock, which occurs quite slowly. After cooling, the powder is mixed with water to form slaked lime which is shaped and then slowly reacts with the atmosphere to again form calcium carbonate. A microstructure typically consists of spherical particles in the submicron range quite different from the rock.

Plaster is used in tonnage amounts for architectural purposes, but to a much smaller extent for vessels and other objects. The archaeological record may be somewhat misleading since sherds of plaster with their decoration, if any, worn off look very much like lumps of limestone, are much more fragile than ceramics, and do not have the sort of stylistic information that has made them especially searched out. Even the descriptions of plaster are vague; it is described as "concrete" or a "white layer." Occasionally there are reports which describe the same material as lime plaster on one page and as plaster of Paris (i.e., gypsum plaster) on another. In any event, we have obtained a number of samples from various sites and identified them unequivocably as to the binding material in order to develop a solid data base which can be used for a critique and interpretations--what might be called middle-range research.

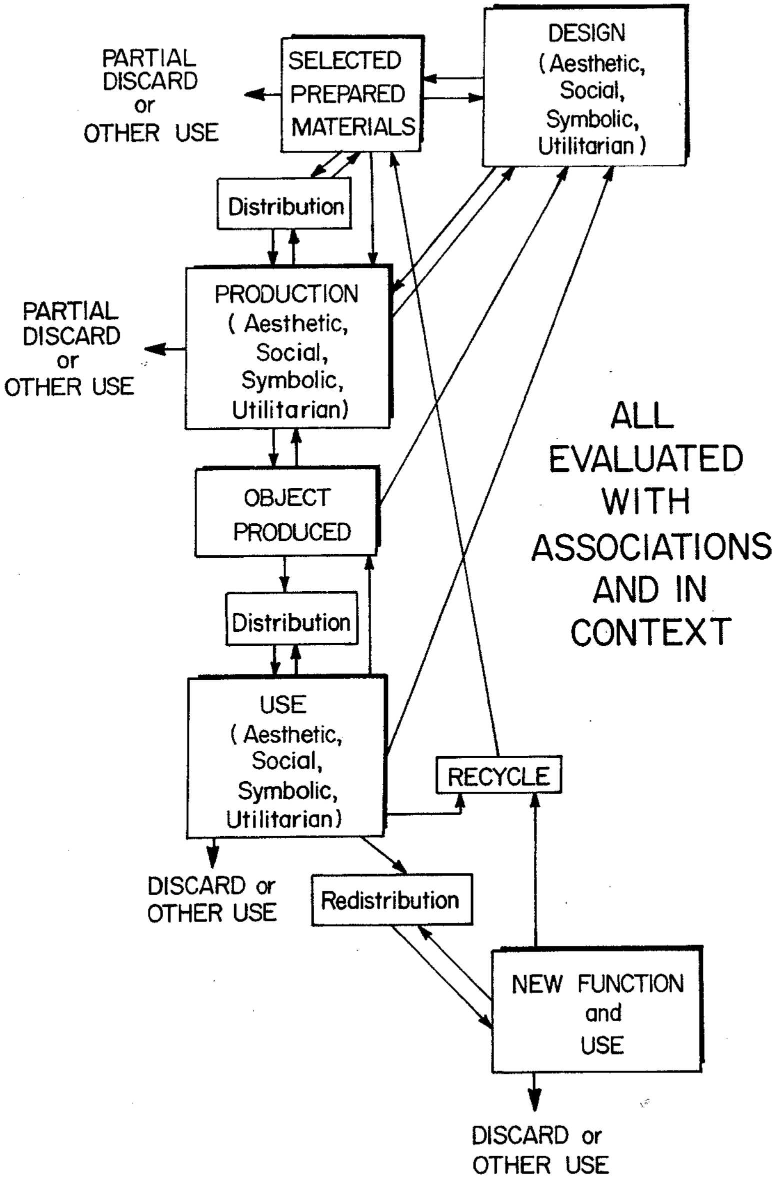

Fig. 3 Objects are central to a system of materials technology that involves design technology, materials selection and preparation, manufacturing technology, distribution and use technology; all are connected with various feedback loops.

I am quite sure that there are many other applications still to find, but the first use of lime plaster known to me occurred at an epipaleolithic site, in the southern Levant, Lagama North VIII, dated about 12,000 B.C., where it can be seen as a remnant of adhesive hafting of microliths to what we presume was a wooden tool. Sometime later, about 10,000 B.C. in a hearth at Hayonin Cave, a Natufian site, there are remnants of a lime-burning hearth. From another reputed lime-burning hearth found at Ganj Dareh we found no indication of burnt lime. The earliest architectural application also occurred at a Natufian site dated about 9000 B.C., Ain Mallaha.

It was in the Pre-Pottery Neolithic B, during the seventh millennium B.C., that plaster came into wide use as an architectural material. We have identified a number of sites in the Levant, western Syria and Anatolia in which lime plaster was employed. There is another set of sites in Iraq and further to the east where gypsum plaster was the material of choice. Along with architectural use, plasters were used to form container materials, both of gypsum at sites such as Abu Hureyra and of lime plaster at sites such as Tell Ramad, Byblos and so forth. It seems clear that along with hunting, herding, agriculture, working of stone, obsidian, flint, chert, wood and bone, weaving mats and baskets, plaster production was a significant activity in the Pre-Pottery Neolithic. Two things are special about plaster production. First, before its advent materials such as wood, bone, flint and stone were shaped by cutting, flaking and polishing; heat treatment was used to affect the property of these materials in such shaping methods. With plaster there was a revolutionary pyrochemical industry introduced in which rocks were chemically altered by fire such that the resulting powder could be made into a paste shaped in the same way as natural clay, but would set hard. It was a material that could be used in tonnage amounts for large expanses such as flooring and also for complex shapes such as sculpture. This was a whole new concept of material manipulation.

Second, the production of appreciable amounts of lime plaster is a multi-step process requiring selection of limestone free from impurities such as clay that would lead to dead burning, the rock must be heated for periods from several hours to several days depending on the amount fired at a "bright" temperature of 800°-900°C, which is equal or greater than that required for pottery and must be maintained for a longer time. The time and temperature of firing require that firewood in the amount of 2-3 times the weight of the rocks be collected and used. After firing, the material must be slaked with water and allowed to age. A suitable aggregate or temper must be added and it must then be applied and shaped as a paste. Skilled working of the surface in smoothing, often burnishing with a smooth pebble or its equivalent at the proper time to obtain local high pressures, is needed to obtain the best hardness and waste resistance. Skilled mixing of the plaster with tempering additives was necessary to optimize the process and it was clearly known that the addition of platey particles such as ochres and manganese materials, when burnished, would enhance both the appearance and properties. Clearly, the preparation and use of plaster was energy-intensive, it was labor-intensive, and it was a skilled craft.

We consider these data first with regard to geographical distribution, techno-complex areas and the diffusion process. As shown in Figure 4, if we distinguish between the lime plaster and gypsum plaster distribution, as we must on the basis of their different technologies, we see reasonably clear techno-complex areas. Lime plaster was the material of choice in the Levant and Anatolia; gypsum was the material of choice in Iraq and further to the east. It is interesting to note that the area of lime plaster use is roughly equivalent to the distribution of later dark, burnished ceramic ware which appeared in Anatolia, western Syria and the northern Levant, i.e., Amuk A, which is largely absent in Iraq. It is difficult to explain these areas in terms of raw materials, although less abundant fuel in the low lands may well have been an important factor. Lime and gypsum are widely distributed

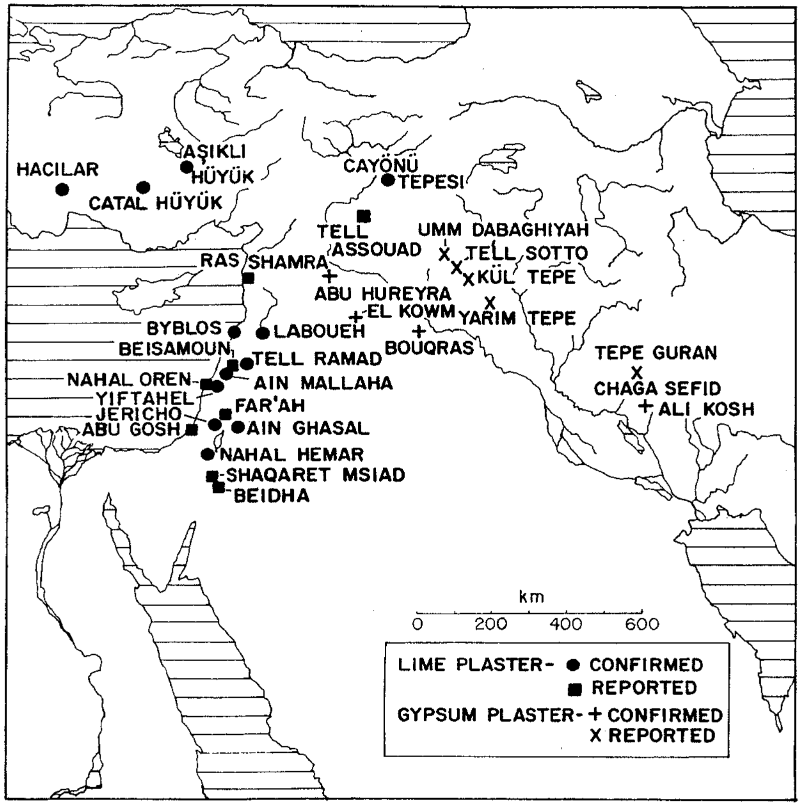

Fig. 4 Geographical distribution of lime plaster and gypsum plaster in the Pre-pottery Neolithic.

through the region and, at sites where there is a preponderance of one type of plaster, either gypsum or lime, indicating a conservative tradition, there are both limestone bowls and alabaster bowls. In contrast with the distribution of the plaster type, plaster vessel and container production is concentrated in a much smaller and different area of Syria and the Levant whilst not encountered in either Anatolia or Iraq. If these geographic techno-complex regions of interaction and commonality were ones of different ceramic types, there would certainly be a strong temptation to identify them as different cultural areas.

Having found that the plaster production is energy-intensive, labor-intensive and a skilled craft employed in the seventh millennium over quite distinctive techno-complex areas with differences between different regions, we may ask how that came to be. The process of technology diffusion is not part of the archaeological record, but there is a good deal of historical data that has recently attracted the interest of scholars and is highly pertinent for interpreting the archaeological record. With regard to technology diffusion in literate societies, much evidence shows that the mechanism of transferring skills involves extensive communication between individuals and the physical relocation of skilled individuals. There are many studies of technology transfer to the United States from Europe to illustrate this (e.g., Jeremy [6]). The result is confirmed by detailed analysis of the American firearms industry [7]. Well-known examples in ceramic history are the late sixteenth century movement of Korean potters to Japan as a result of the so-called Teabowl Wars of 1592-1598 [8] and the diffusion of porcelain technology throughout Europe from Meissen [9].

The basis for this seems to be embedded in Polanyi's analysis of the importance of tacit knowledge in carrying out skilled activities [10]. He says, "The premises of a skill cannot be discovered locally prior to its performance, nor even understood if explicitly stated." Polanyi uses the simple skill of riding a bicycle as an example. A reviewer of one of the drafts of this study asked, "But what about those third millennium recipes for beer production, glass making and metal manufacturing?" While they may be useful data for temple or palace records, administrative quality control and general interest, these descriptions of technical operations like those of Pliny and Vitruvius in Roman times, Theopholus in medieval times, and Biringuchio, Agricola and Picolpasso during the late Renaissance never served to direct the activities of craftsmen. We conclude that in the Pre-Pottery Neolithic there was an interchange in communication over wide regions fostered not only by migrant traders and prospectors, but also by the movement and relocation of skilled craftsmen from place to place.

A second consideration is the social implications of in-site and site-to-site variations. Ten years ago we calculated the amount of limestone required for the terazzo floor of one room at Cayonu Tepesi to be 4,000 pounds and for the rooms of a house in Jericho more than 1,000 pounds each, and commented that these quantities required some organized effort. The trench at Jericho did not excavate any complete house. But recently Garfinkel has excavated a complete structure at Yiftahel which has a plaster floor 17 meters long by 7-1/2 meters wide, 3-6 centimeters thick, with a total floor weight of about 7 tons [11]. Another structure has a weight estimated at 1.6 tons. Garfinkel has contrasted these with floors at Ain Ghazal where thicknesses have ranged from no plaster at all on 12 floors, 2-3 centimeters on 11 floors, 4-10 centimeters on 32 floors, and 12-14 centimeters on 7 floors. He also quotes Kenyon's observation at Jericho that some floors are unplastered, some are "good" or "excellent" plaster, and some are "unusually thick." Garfinkel proposes a social approach towards interpreting these structures, questioning the possibility of a ranked society, labor employment or labor specialization, and concludes that plaster should be more quantitatively described in future excavations [12]. We agree.

There do not seem to be quantitative data, but there are quite clear indicators as to architectural use of plaster. At Beidha, many houses with plaster floors are 30 square meters or so. There is one 63-square meter burnished plaster floor. Some floors are unplastered. At Munhata there is an area of plaster floors over 200 square meters and at Tell Ramad both houses and alleys have plaster floors. At Çatal Hüyük, plaster floors were occasionally used, but always occur in connection with shrines. At pre-ceramic Hacilar small rooms had mud plaster floors, while the larger ones had red burnished lime plaster. At Asikli Hüyük the small rooms had mud plaster floors and the larger ones plaster. In contrast, in small villages such as Jarmo, floors were of mud covered with reed mats, as is done today. That is, there are both in-site and site-to-site variations in the use of plaster which distinguish small villages from larger towns.

The production of several tons of calcined limestone is not a trivial accomplishment. Since at least two or three times as much wood as limestone is required, as much as 10 tons of fuel would have been required for one house floor. To obtain the bright temperature 800°-900°C required, an efficient fuel such as wood and at least a crude furnace is required. To maintain the bright temperature for the 2-4 days required, a long period of constant attention is necessary. After slaking the lime, mixing with aggregate and installation, the final step of burnishing and polishing such a large area requires substantial effort. Garfinkel emphasized that for the only study available of floor thicknesses at Ain Ghazal a wide variety was found, indicating a differentiation of access to this resource. On the other hand, commentators have suggested that village farming sites in the Pre-Pottery Neolithic are probably all egalitarian tribal communities.

We have confirmed that lime plaster had a very early history and was widely used as a production technology by the Pre-Pottery Neolithic B. There are many plaster-floored towns, while contemporaneous sites show but little use of plaster. Within plaster-using sites the material was employed preferentially for some structures with different levels of sophistication and application thickness making it clear that this was an unequally distributed labor-intensive, energy-intensive product. The towns with extensive plaster are also ones with larger concentrations of rare and exotic trade items. Areas devoted to specialized manufacturing activity, extensive development of cultic and shrine areas, carefully crafted sculptures which we shall come to, and a level of technical sophistication that reinforces the skilled production and non-egalitarian distribution of architectural and other plaster. The coeval existence of egalitarian tribal villages and towns with craft specialization, stratified social status and economic differentiation during the Pre-Pottery Neolithic seems very likely.

Another aspect of plaster development is concerned with the nature of invention, innovation and technology. Our finding that epipaleolithic and Natufian applications long before the seventh millenium are in line with what is now a generally accepted view that the invention of a new technology occurs long before its widespread application. Invention is essentially an individual achievement that recurs from time to time but only rarely becomes part of the archaeological record. Innovation brings an invention into technological practice and has mostly been treated by economic theorists as involving both perceived utility and entrepreneurial action. Once adopted, a proven, safe and reliable technology invariably becomes conservative and subsequent modifying innovations are gradual and incremental. This is rational and has been true of technology down to the present day.

The emergence of plaster manufacturing was fairly rapid when it occurred and became widely distributed. In this sense it is also characteristic of successful new technological methods of production and fits the model of swarming behavior of innovators, of a self-catalyzed chemical process in which initial adoption of a new style or technology accelerates the rate of subsequent adoption, a positive feedback process with a multiplier effect. The labor-intensive, energy-intensive use of tonnage quantities of plaster having a perceived utility sufficient for this multiplier auto-catalytic effect to take hold and lead to a successful establishment as a manufacturing

process is difficult to imagine outside of towns with available surplus labor and social stratification to direct its employment. Recent studies by Moore have pushed back the earlier stages of the Agricultural Revolution to the epipaleolithic such that during the sixth millennium agriculture and stock-breeding had become the main sources of subsistence. Along with other data regarding trade and crafts, the presence of surplus food and labor in the larger, sedentary towns at some periods of the year during the seventh millennium and the development of social stratification seems very likely. As we have discussed, the skilled craft of plaster manufacture and use on a tonnage scale is only credible with a conjecture that the emergence of towns was accompanied by such change in social structure and is virtually incredible without that hypothesis.

Once plaster manufacturing technology emerged, it was, like other technologies, subject to a constant series of innovative modifications and improvements, each of which was small in itself but of substantial cumulative importance. One of these was the idea of adding a mineral-tempering aggregate to produce a concrete of greater strength at lesser cost. This led to the use of aggregate materials of aesthetic as well as functional utility. This is seen in the terazzo floor at Cayonu Tepesi and in a different context in the use of crystalline calcite grains in the jewelry beads which have been found in the Nahal Hemar Cave above the Dead Sea [13,14]. Clear calcite grains give a sparkle to the beads that is quite remarkable. After forming, these beads were rolled in green emerald-like mineral particles of dioptase, $CuSiO_3 \cdot H_2O$, to form a sparkling green surface. A subsequent innovation was the use of fiber reinforcement seen in sculptural fragments from Nahal Hemar. These wood fibers form a structure equivalent in every respect to modern-day fiber-reinforced plastics and either the forerunner or follower of fiber-reinforced pisé and mud brick manufacture.

With regard to sculptural technology which required several innovations, one was the use of a tied bundle of reeds in an armature for the overlying sculpture as a way of providing rigidity to the initial plaster or marly clay plaster which was used as the underlying material. The underlying material in these sculptures was made of a marly clay which did not require the expensive plaster manufacture, but if it had not had the proper surface would have been subject to moisture erosion and have had low hardness and poor polish. As a result, in the near-surface layer nearly pure slaked lime was added to the mixture to increase the dry strength and speed the drying process, much as it was used in protoelamite Anshan about 3,000 B.C. [15], and as it is used today for stucco construction.

Cumulatively, the innovations which developed and special techniques are consistent with all we know about the modifications in a conservative technology. They led to optimized construction materials and applications for sculpture which are essentially identical to modern practice. This series of developments provides strong support for the view of a complex technology practiced within a socially stratified society having craft specialization.

Small samples of melted metals have been found in neolithic contexts and are most often associated with pottery production. We think it much more likely that they were formed in the much more intense and prolonged heat associated with lime plaster production. All the early fused metal finds are in the area of lime plaster manufacture shown in Figure 4. This "invention" of metal smelting occurred more than two thousand years before the "innovation" of the chalcolithic era.

Finally, many authors have commented on the fact that when ceramic vessels began to be made in the Near East they appeared with such a high level of quality that the technology must have been imported. However, we have seen that all the inventive and innovative requirements for ceramic manufacture were already present within the preceding widespread plaster technology. Firing procedures for lime plaster were more stringent than for pottery, requiring longer heating at about the same temperature. The use of mineral and vegetal additive was practiced, there was slip-coating with ochre red and manganese black paints, the use of burnishing leather-hard material to form a hard, smooth, more impermeable surface was well known. As a result, the widespread appearance of pottery vessels must be considered, like that of plaster manufacture, an autocatalytic phenomenon for which the rate-limiting factor was social choice, not technology, In assessing the emergence of ceramics, we remember that the earliest ceramic vessels (the oft-repeated invention) are found in aceramic levels at many different and widely separated sites and that early pottery had neither strength nor impermeability superior to materials being displaced. We think the most likely reasons for the widespread use of ceramics were social changes engendered by the transformation to agriculture and stóckbreeding as the only sources of subsistence which would have led to a decreased role for all modes of gathering, together with the growth of towns to a point where previously used competing materials such as suitable wood, basketry materials, and soft, easily carved stone were less and less available in the immediate vicinity of a town with appreciable population. Pottery became seen as a more cost-effective alternative in this new society.

REFERENCES

1. W. D. Kingery, Plausible Inferences from Ceramic Artifacts, J. Field Arch., 8, 457 (1981).
2. W. D. Kingery, Microstructure Analysis As Part of a Holistic Interpretation of Ceramic Art and Archaeological Artifacts, Archaeomaterials 1 (2), 91-99 (1987).
3. Fernand Braudel, The Structure of Everyday Life, Harper and Rowe, New York, p. 334 (1981).
4. W. H. Gourdin and W. D. Kingery, The Beginning of Pyrotechnology: Neolithic and Egyptian Lime Plaster, J. Field Arch. 2, 133-150 (1975).
5. W. D. Kingery, P. B. Vandiver and M. Prickett, J. Field Arch., in press (1988).
6. David J. Jeremy, Transatlantic Industrial Revolution, M.I.T. Press, Cambridge, MA (1981).
7. M. Roe Smith, Harpers Ferry Armory and the New Technology: The Challenge of Change, Ithaca, NY, Cornell University Press (1977).
8. Louise A. Cort, Korean Influences in Japanese Ceramics: The Impact of the Teabowl Wars of 1592-1598, pp. 331-362 in W. D. Kingery (ed.), Ceramics and Civilization II: Technology and Style, American Ceramic Society, Columbus, OH (1986).
9. W. D. Kingery, The Development of European Porcelain, pp. 153-180 in W. D. Kingery (ed.), Ceramics and Civilization III: High-Technology Ceramics - Past, Present and Future, American Ceramic Society, Westerville, OH (1987).
10. M. Polanyi, Personal Knowledge, University of Chicago Press, Chicago (1958); M. Polanyi, The Creative Imagination, Chem. and Eng. News 44, 85-93 (1966).
11. Y. Garfinkel, A Neolithic Village from the Seventh Millennium B.C. in Lower Galilee, Israel, J. Field Arch. 14, 199-212 (1987).
12. Y. Garfinkel, Burnt Lime Products and the Social Implications in the Pre-Pottery B Villages of the Near East, Paleorient 31(1), 69-75 (1987).
13. O. Bar-Yosef, A Cave in the Desert. Nahal Hemar, Cat. No. 285, The Israel Museum, Jerusalem (1985).
14. W. D. Kingery, Nahal Hemar Plaster Beads, work in progress (1986).
15. M. J. Blackman, The Manufacture and Use of Burned Lime Plaster at Proto-Elamite Anshan (Iran), pp. 107-115 in T. A. Wertheim and S. F. Wertime (eds), Early Pyrotechnology, Smithsonian Institution Press, Washington, DC (1982).

B. Technology of Ancient Metals