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RECONSTRUCTING AND INTERPRETING THE TECHNOLOGIES OF ANCIENT CERAMICS.

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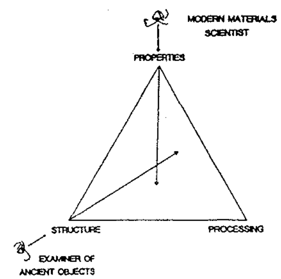
The application of modern methods and strategies of materials science has allowed study of the technology of ancient ceramics to enter a new era. Ceramics include refractories, plasters and cements, some pigments, glasses, pottery, porcelain, bricks, tiles and enamels. Some of the questions necessary to understand and interpret ancient ceramics are given below.

Questions to Reconstruct Ceramic Technology:
What is the physical basis of appearance; i.e., why does the object look the way it does?
Of what raw materials is it made? What are their constraints and their variability?
What are the methods and sequences of manufacture?
What range of technical parameters is discovered within the object, group of ceramics, industry or site level by level?
What level of technological complexity is found by determining the nature and physical chemistry of the envelope of constraining processing parameters. What is the degree of intentionality or behavior practiced in the technology?

Questions to Interpret Ceramic Technology:
What is the context of the technology, both in which it exists and from which it developed?
What are the cultural constraints and how do they interact with the technological constraints?
How are development, production and distribution organized, and what are the rate limiting steps-- social or technological?
When does a structural change in technology become a cognitive or behavioral change?

POINT OF VIEW: STRUCTURE-PROPERTY-PROCESSING RELATIONSHIP

To understand and interpret the technology of ancient ceramics, it is necessary to adopt a modern materials science point of view, i.e. to establish structure-property-processing relationships, to start on a macroscopic scale and proceed to a microscopic scale (1). A modern materials scientist attempts to develop particular properties in a material or device by producing a special structure through innovative methods of processing. An examiner of ancient objects eyes this three-way relationship from another corner, i.e., all that remains to be studied is the structure; the properties and processes must be reconstructed by analyzing and interpreting that structure. This is similar to an anthropological or archaeological formulation of research methodology, if form, function and value are substituted for structure, processing and properties, respectively.



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BLACK BOXES TO RESOLVE "NUTS AND BOLTS" QUESTIONS

Recent advances in instrumentation allow both extensive reconstruction of processing and the measurement of properties using samples smaller than a cubic millimeter, so long as they are representative and the possibility of weathering, corrosion or other treatment can be eliminated. Rare archaeological artifacts, art treasures, and manufacturing elements-- objects in the process of being made or the attendant processing facilities, furnaces, etc.-- can be microsampled and analyzed with a dense information yield. However, the context of those objects sampled must be understood. Thus, optical microscopy and nondestructive evaluation on a large population of similar objects is essential to problem formulation prior to selecting and taking microsamples. The samples then can be chosen to display a range of properties, stages of manufacture, heat treatment or some other variable, such that minimal samples yield maximal results.

Such methods as scanning electron microscopy, transmission electron microscopy, scanning transmission electron microscopy, electron beam microprobe, energy loss spectroscopy and differential thermal analysis have allowed determination of microstructure and microcomposition, phases present, temperatures of processing and reconstruction of the processes of nucleation and growth, decomposition, melting and sintering. Knowledge of such details has allowed reconstruction of the physical chemistry of processing as well as determination of the raw materials and, in some cases, the impurities and heterogeneities in those raw materials. Non-destructive testing methods, such as radiography, xeroradiography, tomography and acoustic profiling, have demonstrated that alignment and morphology of porosity are essential to understanding forming technology. Finally, measurements of properties, such as optical properties, color, hardness, tensile strength, permeability, surface roughness, or ranges of particle sizes have served as clues to understanding technical decisions made long ago. Following are some of the most useful tests employed on ancient ceramics.

Techniques of Data Collection:

Scale of Test	Physical Tests	Chemical Tests
Macro-structure, Bulk and Trace Analysis	Film Radiography Xeroradiography C.A.T. Scan Photostimulable Phosphors	Atomic Absorption Emission Spectroscopy X-Ray Fluorescence Neutron Activation Pb Isotope on lead glazes and glasses
Micro-structure, Phase Analysis	Optical Microscopy Quantitative Stereology SEM, TEM, STEM Auger	Chemical Microscopy X-Ray or E' Diffraction EDS, WDS, E' Energy Loss Chromatography-Mass Spec F.T.I.R. of binders
Heat Treatment	DTA, TGA, Dilatometry, Refiring, Melting	Combined with XRD and SEM with EDS or Mass Spec
Standards, Replicas,	Same tests as original	Same tests as original

ANALYTICAL TOOLS FOR DATA EVALUATION

Carrying out measurements, however, is not enough to allow either reconstruction or interpretation of the technology of ancient ceramics. There are at least four types of data evaluation used to turn data into results: statistics, phase diagrams, thermodynamics and kinetics. Only the first one is widely used to understand ancient ceramics. Phase diagrams are used or constructed to determine the whether reactions will occur at equilibrium. Thermodynamic reconstruction is used to tell which reactions are energetically favorable. Kinetics gives an indication of the rate limiting steps, whether such reactions can occur in the real, time-dependent world, and what the constraints are to achieve a particular composition and/or structure.

INTELLECTUAL TECHNIQUES OF ANALYSIS

Once the results of macro- and microstructures are known and composition and phase analysis complete, several techniques of organizing results can aid interpretation (2): deconstruction, structuralism, contextualism and processual determinism.

Deconstruction, a term borrowed from literary criticism, is an internalist point of view-- an object or group of objects is conceptually taken apart in miniscule detail, such that every part, defect and join is evident, and thus some of the reasons for appearance are understood and some can be translated into sequences of behavior. Structuralism involves establishing the patterns of a ceramic technology through time and space, and really implies that one is in command of the deconstructed details. Structuralism is a comparative method establishing the degree to which sequence and variation of practice is patterned. Contextualism, whether historical, archaeological or natural (ecological), is an externalist viewpoint for determining significance in which the meaning of a technology in socio-economic, politico-military or religio-philosophical terms far outweighs knowledge of details and patterns. Due to space limitations, context-based and -derived arguments are ignored in this article. Processual determinism involves an appreciation of the conservativism of technology as a body of skills in which the process of development and details of the practice of a technology constrain the possibilities of future development.

TECHNOLOGICAL DEVELOPMENTS

Because of the nature of archaeological data, we can never be sure that the first of anything has been discovered, and probability militates against it. Instead, enough of something must be found in sealed contexts to allow its identification with a particular time and place. So we really cannot use the record of ancient ceramics to understand the conditions for invention in ancient technology, but we can examine the problems of development and transfer of technology. When we think of ancient ceramics and try to put them in a context of other materials, a reconstruction of technological developments reads like the following:

25,000 B.C. Fired ceramic figurines, Eastern Europe

14,500 B.C.	Clay-based pigments, Western Europe
13,000 B.C.	Plasters as adhesive for hafting, Levant
12,000 B.C.	Heat treatment of flint to improve flaking properties
9000 B.C.	Wrought native copper, Near East (3)
8000-6400	Plaster sculptures, vessels, architectural elements; Agrarian revolution, Near East
7000	Earthenware pottery and refractories, Syro-Palestine
5000-3000	Copper melting, smelting experiments, Near East
4000	Faience, frit, glazed quartz and steatite imitating lapis and turquoise Egypt, Near East
3400	Wheel-formed small vessels, Near East
3000-2500	Lost wax casting of bronzes, Near East
2500 B.C.	Granulation gold and silver alloy, Near East
2000	Piece-mold casting, stoneware, China
1500	Manmade glasses, glazed earthenware, Iran-Iraq
700 B.C.	Vitreous earthenware for transport amphoras or impermeable containers, Mediterranean
600 B.C.	Cast iron, China
200 B.C.	Barium-lead glasses, China
50 B.C.-50 A.D.	Glass blowing, Mediterranean
200-300 A.D.	Vitreous enamels and lead glass, Mediterranean
900-1300	Dense, translucent porcelain, China
1000 A.D.	Glazes imitating jade, China
1100 A.D.	Luster glazes, Near East
1400 A.D.	Salt-glazed stoneware, Germany
1550/1615	Modern research lab (4), China/Europe
1750 A.D.	Industrial revolution, Europe and U.S.

MATERIALS SCIENCE DEVELOPMENTS

When we use the strategy and methods of modern materials science, the result of such study is that many of the ceramics which we think of as modern inventions were actually tacitly used to make ancient ceramic objects. For instance, as will be described briefly in the next section, rheology was controlled to apply pigments to the cave walls at Lascaux about 14,500 B.C.; fiber-reinforced composites were used to manufacture Neolithic pottery in West Asia at 7000 B.C.; liquid phase sintering of finely ground materials was used to produce Egyptian blue pigments about 4000 B.C. Control of oxidation state was used to produce red, brown, grey and black iron colors on pottery at about 5500 B.C. as well as blue and green copper coloration at 4000 B.C. Liquid-liquid phase separation was the mechanism of formation of translucent, blue-colored northern Chinese Jun glazes of the eleventh century. Crystal growth was promoted by intentional coarse milling and poor mixing of glaze raw materials to produce the translucent blue-green of southern Chinese glazes from Longquan; whereas, crazing and local absorbtion by black particles was used to produce the effect of Korean Koryo celadon. Glazes were deposited from the vapor phase in German salt-glazed stoneware. Lusterware, common is Islamic potteries of the 12th century A.D., involved diffusion of silver and copper ions into the glaze from a thin film deposited from the vapor within a fine powder layer. Interference films of tin oxide which exhibit superplastic behavior to form particular silky or velvety textures are responsible for the iridescent appearance of Tiffany glass. An approximate chronology of these developments is:

25,000 B.C.	Use of thermal shock in heat treatment of figurines; the processing becomes part of use
14,500 B.C.	Rheology of pigment flow controlled at Lascaux
12,000 B.C.	Solid state grain boundary alteration of flint
8000 B.C.	Lime and gypsum plaster pyrotechnology
7000 B.C.	Fiber-reinforced composite earthenware
5500 B.C.	Redox of iron to control red to black colors
4000 B.C.	Liquid phase sintering of manmade pigments; Powder processing and synthetic gems; Soda-lime-silicate technology
50 B.C.- 50 A.D.	Optical glass industry for lenses and windows; control of temperature-viscosity relationships
200-300 A.D.	Low temperature glasses, glazes and enamels
900-1200	Lowering of iron impurities in ceramic bodies and glazes to produce white porcelain
1000-1200	Liquid-liquid phase separation and controlled nucleation and crystallization to produce translucency in Chinese glazes; In Korea black particles as local light absorbers in glazes; Thin films of silver and copper deposited from the vapor phase and diffused into glasses to produce metallic lusters; Control of glass pH to determine copper green or blue
1881 A.D.	Superplasticity of CVD tin oxide to produce iridescent textures on surfaces of glasses

Many more mechanisms and processes corresponding to "modern" technology will be added to this list, as they are recognized, analyzed and interpreted.

EXAMPLES OF ANCIENT INNOVATIVE TECHNOLOGICAL BEHAVIOR

Some examples of the results of ancient innovative technological behavior which I have studied are given below. They involve the introduction and growth of a new technology or the production of great objects. Early ceramics were used for purposes other than their property of firing to rocklike hardness. Essentially we can now view ceramics as the development of a soft stone technology, having examples at 25,000 B.C. of paleolithic female and animal figurines from Dolni Vestoniçe, Czechslovakia, and at 14,500 B.C. in the clay-based pigments found in the murals at Lascaux in France.

At Dolni Vestonice were found more than 6,000 fragments of figurines radiocarbon dated to 25,000 B.C. along with three kilns and a settlement site in a complex of about 10 such sites (5). One analysis from before 1940 described the figurines as made of mammoth bone, mammoth fat and ash, and they were interpreted to have been intentionally broken and put into a fire, perhaps as part of a hunting ritual (5). However, most of the fractures are high energy, branching fractures probably from thermal shock, and the raw material, based on comparison of composition, microstructure and phase analysis, consists of loess soil from the site. These figurines probably were not made as durable, portable goods, but the additive process of making of the figurines and their heat treatment was the pattern of their use. Enough water was mixed with the sandy clay body to decrease the porosity of the loess and to render it plastic, then bits were added together for the bodies with legs, ears and other details formed separately (5). There are fingerprints and inscribed details on surfaces, but no pigments. They were fired in reducing conditions to 500-700 ^{o}C, and rarely 800 ^{o}C. The figurines still have ash adhering to them. Some were fired wet in a kiln, such that they were thermal shocked with considerable sound and explosion. Dolni Vestonice has the only known instance of a corpus of fired clay ceramics for 18,000 years.

Lascaux is a cave with black linear images of bulls and smaller, solid images of horses varying in color from orangish-red to reddish-brown. The pigments were drawn on the damp limestone cave wall and built up in thicknesses of up to one half millimeter; a different technology was used for the red and black pigments (6). A fine, submicron particle size manganese dioxide was chosen for the black from a range of particle sizes locally available. Most local manganese dioxide had a range coarse particle sizes up to 100 microns and was found to be unsuitable during testing. Processing of the red pigments involved selection of a range of fine particle red to yellow raw materials, grinding to eliminate coarse quartz gangue, mixing of different colors on a rock support prior to their application, mixing on the surface of the chalkstick, and even kneading of the wetted chalkstick as part of the process of application. Some of the chalksticks were fabricated, and subsequently kneaded to mix colorants and control flow of pigment onto the wall by controlling water content and rheology. Most hematite has a platy submicron morphology, and when applied wetted or onto a damp wall, it gives a dark brown color because the platelets align parallel to the wall surface. Mixing of the reds was necessary to insure the range of color. Thus, at Lascaux, we find a complex and diverse technology in the Upper Paleolithic period.

The earliest ceramic technology involving consistent firing of large quantities of raw material to temperatures above cooking temperatures was that of lime and gypsum plasters (7). Large quantities of lime plaster, requiring temperatures of about 800-850 C. and gypsum plaster, requiring 250 C for decomposition, were used for pendants and beads, walls coatings, floors, life-sized sculptures, bowls, storage vessels and many other functions starting about 8000 B.C. Lime plaster is much more difficult to work than gypsum plaster because of the longer time required to set, lower plasticity and caustic feel. However, lime plaster has lower solubility and is more durable than gypsum plaster. To coat walls and floors, it can be smeared in place, but to make objects, especially large ones it must be worked in small amounts such as bits, handfuls or slabs, and built up in layers just tall enough to prevent slumping. Surfaces of vessels and objects were finished with thin skim coats, similar to architectural elements. Choice of plaster depended on raw materials availability and choice; for instance, most vessels are made of lime plaster. Both limestone and gypsum rock and sediments were used as precursors. However, in the Near East, sources of calcareous and clayey earths are mixed and difficult to differentiate without empirical testing. When clay resources were differentiated and successfully processed in the inverse sequence to plasters (that is, adding water then firing as opposed to firing, adding water and forming), this same forming technology of section-built slab construction was transferred to production of the earliest pottery. Fired clay objects have the advantages over plaster of being noncaustic and more easily formed and more dense after firing. In addition, pottery can and was fired to a range of porosities and permeabilities which would allow liquid storage as well as water cooling.

The earliest pottery was made in the Near East about 7000 B.C. of a fiber-reinforced composite (8). Short lengths of straw and chaff were added to the fine, calcareous montmorillonite clays in order to add strength during construction, to decrease shrinkage during drying and probably to help lighten the weight of large vessels and trays. Porosity characterization is the key to determining forming methods; porosity from organic fiber burnout is aligned parallel to joins, and porosity from joining outlines construction elements. Xeroradiography to determine internal structure and optical microscopy of surfaces and edge fractures were used to established that some 40,000 sherds from 16 sites from Egypt to Pakistan were made using the same technology, sequential slab construction, for a period of at least 4000 years. In other words, although the beginnings of this pottery tradition offer a complex interaction of the properties of raw materials and historical constraints of traditional practices, the transmission of this technology was widespread and effective, and the technology remained extremely conservative. Even when new methods were introduced, such as use of a potter's wheel at 3400 B.C., only a small portion of the ceramics were made with the new technology, and those consisted of small cups. Three examples of this same method are used today in the Near East. In addition, the Near Eastern technology is completely different from the coiling and paddle and anvil construction practiced in Neolithic northern China (10). However, in both instances pottery is found as a necessary part of the gradual and complex process of stops-and-starts in which peoples practicing hunting and gathering were able to settle into a sedentary village agriculture way of life with attendant domestication of plants and animals and development of crafts and architecture.

In addition to pottery, ceramics consisting primarily of clay-bonded sand served as refractories for ovens and kilns for the testing of materials, prior to the development of smelted metals technology. Solid-state reactions were investigated in the iron oxide system by varying the oxidation state to form red and black, fugitive or nondurable pigments on pottery. By mixing hematite with clay, the slip-pigment mixture will sinter, and the color will be permanent-- a technology developed in the Neolithic period (11). To form a more durable pigment on pottery, fluxes such as potassium (probably in the form of ash) were added to the slip beginning about 5500 B.C. at several sites. To form black and red polychrome decoration using the same iron pigment, instead of manganese and hematite, respectively, the sintering behavior of clay must be controlled as well as the amount of flux additive. Such high-tech control reached an apogee during the first millennium B.C. with Greek black-figure-on-red-ground and then the more naturalistic red-on-black pottery (12). Fine clays were selected by sedimentation and fluxes were added to form a slip suspension painted onto what would fire to the black-slipped areas. The coarser clay was used for the body which would fire red. During firing between 700-900 ^{o}C, oxidation followed by heavy reduction at peak temperature turned the entire surface black. Then reoxidation caused the poorly sintered body to turn red. However, due to the better sintered, more dense and glassy mixture of fine clay and magnitite, reoxidation could not occur in the slipped surfaces, and the color remained black. Once the differential sintering behavior was understood, the task of firing was reduced to a rate problem which depended on the thickness of the slip and the degree of sintering achieved with a somewhat variable raw material.

The first high-tech, non-clay ceramics were developed about 4000 B.C. to imitate precious stones such as lapis lazuli and turquoise. These ceramics were Egyptian faience, a ground quartz body with a soda-lime-copper-silicate glaze; and Egyptian blue, the manmade $CuCaSiO_4$ pigment; and the carving and grinding of soft steatite, followed by firing to increase hardness and sometimes addition copper for color (13). Egyptian faience cannot be made with a ferruginous clay substrate because the colors look muddy and greenish. White clays occur rarely in the Near East and were not used to form pottery. The white faience body was derived from the ground stone industry which produced bowls, beads and small objects. The innovation involved combining a powder processing technology with experimental pyrotechnology such that liquid phase sintering of quartz with a soda-lime-copper-silicate occurred. Faience can be glazed by three methods: application glazing, cementation and efflorescence (13). Replications of each of these processes were compared with ancient faience artifacts. The greatest diversity of manufacturing method was found at the beginnings of the technology in which all three methods were found and several variants, and then not again for almost 2000-2500 years until the beginnings of the glass industry about 1500 B.C. This lack of experimentation is found not only in faience technology but also in the shapes of vessels. The same style of surface decoration and vessel shape was used in Egypt for vessels in gold, alabaster, faience and wood, such that vessels in different materials resembled each other; when vessels were made of glass, the shapes were in imitation of these vessels in other materials. The faience industry which involved the multiple-stage fritting of powdered raw materials gradually evolved into the glass industry in which glasses were wound around porous fritted cores, annealed and the cores subsequently removed. In fact, the transformation of the faience into the glass industry can be seen as a search for thicker glazes and less porous bodies. Other methods of forming were also developed, such as the sintering of rod crosssections and pressing of glasses into molds. Processing temperatures remained at the lower end of the working range for glasses, such that the steps in forming do not resemble modern methods. For instance, rod were rolled out with a paddle instead of being pulled.

The Roman glass blowing industry involved processing changes, finer and higher temperature control of a more limited range of glass composition, which led to new products in glass and the first large quantity production of glass. Thus, glass

became a product of everyday life, rather than a limited luxury product seen and used by only a few people at the top of the social pyramid. In addition, Roman glass blowing technology marks the founding of the optical and window glass industries and was followed by the essential stagnation of the technology until the fuel and refractories revolution of the late nineteeth and twentieth centuries again changed the technology to allow large quantities of glass to be automatically produced (14). A Roman glassblower probably would have felt at home in an eighteenth century glass house. Prior to Roman blowing technology, small quantities of mostly opaque glasses had been produced beginning about 1500 B.C. using mostly bead-making and molding techniques. Glass-blowing developed, probably in a two-stage process, around the Mediterranean periphery with Italy and the Levant being preferred sites between 50 B.C. and 50 A.D. and spread with the Roman Empire to produce glass for impermeable storage and serving vessels, and even burial urns. The blowing process is much easier with transparent glass. Being able to see into the glass while it was being produced allowed more control of wall thickness and shape, thus walls could be thinner and more objects could be produced with a limited supply of glass. Decolorizing glass by balancing amounts of manganese and iron oxides led to considerable chemical experimentation. In addition, transparent glass imitated a status-laden luxury product, carved rock crystal. A lot of fuel needed to be collected and processed, compared to the limited amount of glass which could be made. In fact, one factor in the rapid spread of the glass blowing industry which approximated the frontiers of the Roman Empire may have been the depletion of local fuel. Thus, optimizing amounts of molten glass, an energy intensive material, was important. Some Roman drinking glasses are so thin that they can be flexed in the hand. Our fire-polished safety rims find a precursor in the folded-over rims and bases of some Roman glasses. The types of goods produced replaced the earthenware and wood of common tables, and the industry bifurcated into production of common and luxury wares. Certainly by the third century A.D., amazing control of color chemistry, annealing, cutting and expansion coefficient was attained, as for instance in the Lycurgus vessel (15). Given these conditions, it is no wonder that the optical glass industry dates to Roman times with the production of windows and lenses.

Impermeable ceramic containers for beverage and water storage are not, however, a Roman invention; they date to the Neolithic of the Near East. However, this property was not produced as the endpoint of a systematic technology, but rather as part of a range of products with differing properties. Corinthian transport amphora production provides one example of the systematic production of impermeable vessels for the transport of oil, wine, pickled fish and sauces (16). These vessels were like oil drums of the classical world, dating from the seventh to second centuries B.C. Many city states and island producers had their own characteristic style of jar; however, Corinth, Greece, was the only one to produce impermeable amphoras. A special sequence of handbuilding was developed to form the heavily tempered composite body. The amphoras were fired higher than most other contemporary clay products and the temper acted to resist slumping of the heavily fluxed calcareous illitic clay body. In other words, composition, fabrication and firing practices were tailored to produce the property of impermeability. What is surprising is that instead of finding that the ceramic technology of amphoras becomes more precisely controlled or sophisticated with time, we find just the opposite. About 400-500 B.C. the technology changed to one which produced permeable transport amphoras. Instead of degrading, we find that it was transformed from one which was difficult to practice, labor intensive, exacting and time consuming, to one which produced permeable transport vessels in about one fifth the time and without constraints on composition and firing-- the reason was that another technology was integrated, polymers. Organic coatings, such as pine resin, for lining ceramic vessels were used in Corinth, Greece, and Carthage, Tunesia. Further investigations will undoubtedly find earlier examples of organic linings used for various purposes (Neolithic bitumen-lined ceramic vessels being one example which needs to be investigated).

Chinese and Korean celadon green glazes were made in the eleventh through fifteenth centuries A.D. in imitation of the color and translucent textural qualities of jade (17). Chinese scholars number ten different types of celadons during this period. These celadons developed out of a long-lived first millennium A.D. green glazing technology called Yue, in which finely ground and well mixed raw materials were fired to about 1100 ^{o}C. to form homogeneous, transparent greyish-green glazes. Several complex technologies requiring exact processing parameters were practiced which developed out of a craft workshop organization of production. The translucency of northern Chinese Jun glazes was produced by liquid phase separation in which the temperature was held at about 1250 ^{o}C for a long time such that crystobalite formed around quartz particles in the glaze and wollastonite precipitated to increase the pathlength of light through the glaze. One southern Chinese tradition, Longquan celadon, required the coarse milling and poor mixing of raw materials, such that anorthite nucleated and grew in regions rich in alumina and potassia, and wollastonite crystal growth occurred in regions rich in calcium and silica. Korean Koryo dynasty celadon glazes had a composition similar to the high lime Yue glazes and the resultant fluidity effectively prevented nucleation and growth. Translucency is caused by small absorbing centers of black magnetite interspersed in the glaze with quartz particles. In all of these glazes, fine bubbles suspended in the glaze cause light scattering which brightens the glazes. In addition, quartz particles diffract the light and a rough white background at the back of the glazes serves to further scatter the light.

The Chinese green glazes on vitreous white porcelain were imitated in Islamic pottery centers of the twelfth century A.D. by using a high index of refraction lead glaze colored green with copper to cover a white body made of quartz, ground glass and a small amount of fine, very plastic clay (18). In the fifteenth century A.D., the pH of the glaze was altered to control the blue and green copper colors in Iznik tiles, with the striking effect that the same colorant could be made green or blue. Copper in an alkaline soda-lime-silicate was ground as an underglaze colorant and painted next to copper in a ground lead-silicate and both

were covered with a similar expansion coefficient lead-silicate glaze. Thus, what started as an imitation of Chinese celadon but made in a wholly Near Eastern idiom, using local raw materials and proven methods of processing, developed into an indigenous, brightly colored architectural tile tradition. Pottery made in the celadon, as well as the blue-and-white tradition, was exported from Chinese and Islamic centers of production to Europe and used to line treasure cabinets of the wealthy as status symbols and items of conversation. The imitations were often so good that one active pursuit of art historians during the last century was to separate these different wares and to figure out their sources. Again, such expert imitation derives from a craft workshop organization of production, without the advantage of principles of modern engineering design.

Refiring of overglaze enamels to produce brilliant colors on a semi-vitreous stoneware or quartz-frit body developed east and west, respectively, about 1000 and 1300 A.D., although many low fire, lead-based colors had been developed as glass enamels for Roman glasses in about the 3rd century A.D. (19). Not until the mid-sixteenth century in China and early seventeenth century in Europe did a research laboratory mentality, replete with industrial espionage, invade such craft-based ceramic practices as the production of overglaze enamel colors and porcelain and the kind of division of labor found in the West during the Industrial Revolution characterize ceramic production. (20).

One other aspect of modern materials science processing, chemical vapor deposition, can be found in pre-twentieth century technology. Examples of vapor phase deposition on substrates can be found in the German salt glazing of stoneware for containers, especially those for beer, which dates to the late thirteenth and fourteenth centuries A.D., in which salt was thrown into kilns at about 1150 C to produce a durable "orange peel" textured glaze. Another example is found in the application of lusters to form silver and copper metallic surfaces on Islamic lusterware of the twelfth century (21). A clay or hematite powder is mixed with the silver or copper salt and applied over the prefired, usually white glazed, ceramic. Vaporization is followed by diffusion of the copper and silver ions into the glaze. In addition, iridescent coatings on Tiffany glass are produced by vapor phase deposition of iron and tin oxides onto the surface of preformed, but still hot, glass to form a tenth micron film in which interference phenomena produce a spectral range of color (22). In fact, to produce particular translucent visual effects which change with lighting conditions, Tiffany Studios used liquid-liquid phase separation in borate-containing glasses and growth of calcium-phosphate crystals in the glass bulk, as well as super-plasticity of reheated vapor deposited coatings to produce surface textures which varied from silky to velvety depending on the amount of reheating and flow of the coating.

ANCIENT TECHNOLOGY PREFIGURES MODERN HIGH-TECH CERAMICS

We rarely read technical papers older than this decade, and often tend to think in twentieth century ideals of unilineal progress from the scientific or industrial revolutions of the 17th or 18th centuries. We tend to forget the complex and diverse technologies that are thousands of years old which are examples of problem solving by analogical reasoning. Without modern transportation and communication, the rate of transmission was much slower. Technology involves "praxis", doing, not explaining, but throughout most of man's time, it has been developed and transmitted through a craft process, not a modern design process. Thus, not only has past technology transfer been slower, but also technological development has been different. A craft process places emphasis on maintenance of a traditional body of skills, learned in childhood by watching and doing, in which technical decisions become a kind of tacit knowledge; thus, conservativism tends to maintain tradition. Why do something different or risky when the present technology works well? Change is slow and gradual with only one element of a technology changing at a time (23). Skills are transmitted by people, not objects or documents. Even when historical documents are available, case studies of technology transfer find knowledgeable and skilled people are responsible (24). A design process of development, on the other hand, involves the unbiased technical evaluation of multiple alternatives, and the re-evaluation of those options as the object or device is being developed and often before it is built. Models are evaluated as if they were objects in a imaginary or "Gedenken" experiment.

Even though many differences between craft and modern design processes are found, a creative core of art and science is present in many ancient activities. Fully human activities-- such as abstracting, inventing and using symbols, remembering patterns, analogical reasoning, anticipating, developing diverse and complex technologies-- are certainly evident from paleolithic times onward. In the record of technology left by objects, sufficient detail is present to detect patterns of materials developments. Usually there is a period of time between development of a new material, and the time when the properties of that material are fully exploited and a characteristic technology develops. The character of the technology that develops is constrained by historical and social decisions and by known ways of doing things, all of which are not necessarily the "best" ways of doing things by modern standards; thus, the characteristic technology is optimized for social and technological purposes within a particular time frame and can serve as a way of investigating technological and social activities.

In answer to the questions posed by this symposium of a review of advances and progress in our knowledge of ceramic technology and in epistemology, research strategy and analytical technique, I think answers of present superiority are inappropriate because of the complexity and diversity of ancient technology. Rather, the range of technical parameters which ceramic technology encompasses have now become much more limited, but our abilities to see, investigate and exchange information about the range of scale and structure in the universe have become greater. Exactly, this process is found when we compare the wide technical constraints on production of fiber-reinforced neolithic pottery or plaster in which considerable variability in raw material composition, drying, forming, and firing is found, with the more limited range of variability and greater degree of control required by Roman glass practice, and with the even greater control of Chinese glaze technology. However, the same

kinds of constraints and processes of evaluation used for fiber-reinforced earthenware are being applied to the current metal and ceramic matrix composites for aircraft engines, even though a more limited range of variability is tolerable in composition and processing. Now, we are able to reap the benefits of our increased capability to see and analyze by applying this capability to study the behavior of ancient ceramists and to reconstruct, interpret and better appreciate the technologies of their products.

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REFERENCES

1. Cohen, M. and M. Kranzberg, Materials Science and Engineering; It's Evolution, Practice and Prospects, Elsevier, NY, 1978.
2. S. Reber and M.R. Smith, in High-Tech Ceramics: Past and Present, Ceramics and Civilization, Vol. 3, W.D. Kingery, ed., A.Cer.S., Columbus, OH, 1987, pp. 1-18.
3. M. Goodway, "Casting", Metals Handbook, Vol. 15, ASM Int'l, Metals Park, OH, 1988.
4. According to criteria presented by T.S. Kuhn, The Structure of the Scientific Revolutions, U. Chicago Press, Chicago, IL, 1962.
5. P.B. Vandiver, O. Soffer and B. Klima, presented at Soc. of Am. Arch., May 1988; ms. submited to Archaeology.
6. P.B. Vandiver, Paleolithic Pigment Processing, M.S. Thesis, M.I.T., 1983.
7. W.H. Gourdin and W.D. Kingery, J. Field Arch. (1975)2:133-150; and W.D. Kingery, P. Vandiver and M. Prickett, J. Field Arch., in press.
8. P.B. Vandiver, Sequential Slab Construction, Ph.D. dissertation, M.I.T., 1985; P.B. Vandiver, Paleorient (Spring 1988).
9. P. Vandiver and P. Lacovara, Bull. Egyptological Seminar. (1985/6)7:53-86.
10. P. Vandiver, Archeomaterials (Spring 1988).
11. Vandiver, Sequential Slab Construction, op. cit. (1985).
12. W. Noll, N. Jb. Miner. Abh. (1976) 127/3:261-288, (1978)133/3:227-290, and Fortsch. Miner. (1979) 57/2:203-263.
13. P.B. Vandiver, in A. Kaczmarczyk and R.E.M. Hedges, Ancient Egyptian Faience, Aris and Phillips, Warminster, England, 1983.
14. N. Kreidl, D.R. Uhlmann and P.B. Vandiver, in Ceram. and Civ. (1989)5, A.Cer.S., Columbus, OH, in press.
15. D.B. Harden, K.S. Painter et al., Masterpieces of Glass, British Museum, London, 1968.
16. P.B. Vandiver and C.G. Koehler, Ceram. and Civ. (1985)2: 173-216, W.D. Kingery, ed., A.Cer.S., Columbus, Ohio.
17. W.D. Kingery and P.B. Vandiver, Ceramic Masterpieces: Art, Structure, Technology, MacMillan Free Press, NY, 1986, and Bull.A.Cer.S. (1983)62/11: 1269-79 and (1984)63: 612-616; and

Ceram. and Civ. (1984)1: 181-234, A.Cer.S., Columbus, OH; and Vandiver, L. Cort and C. Handwerker, Ceram. and Civ. (1988)4 in press.
18. Kingery and Vandiver, Ibid., 1986, and P.B. Vandiver and J. Carswell, in prep.
19. S.M. Goldstein, Pre-Roman and Early Roman Glass, Corning Museum, Corning, NY, 1979.
20. W.D. Kingery and D. Smith, Ceram. and Civ. (1984)1: 273-293; Kingery and Vandiver, Ceram. and Civ. (1985)2: 363-382; Kingery, Ceram. and Civ. (1986)3: 153-180.
21. Kingery and Vandiver, Ceramic Masterpieces, op. cit., 1986.
22. Kingery and Vandiver, Applic. of Sci. in the Exam. of Works of Art, ed. by P. England and L. Van Zelst, Museum of Fine Arts, Boston, MA, 1986.
23. P.B. Vandiver, op. cit., 1985; for alternate view see P. McGovern, Ceram. and Civ. (1986)2: 33-52.
24. D.H. Stapleton, Transfer of Technology to the United States in the Nineteenth Century, Ph.D. dissertation, U. of Delaware, 1975; D.J. Jeremy, Transatlantic Industrial Revolution, M.I.T. Press, Cambridge, MA, 1981.