Archaeological Ceramics

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13. Xeroradiography of Ancient Objects: A New Imaging Modality

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Introduction

This study deals with the application of xeroradiography to the examination and study of ancient materials. Technological and analytical studies of excavated material and material housed in museums have played an increasingly important role in the study of cultures past. With the early work of Sir Flinders Petrie at Tel Hesi in 1891, excavators began to develop chronologies of civilizations by ceramic typology. With the broad vision of excavators such as Dr. G. Ernest Wright, Dr. James L. Kelso, and Dr. William F. Albright, the study of ancient material was widened to encompass early technological analysis of processes and products. Early writers began to call for material studies. Among these scholars were Professor R. U. Sayce, whose book *Primitive Arts and Crafts* contained data from his lectures delivered at the University of Cambridge (England) in the 1930s, and G. Ernest Wright whose thesis entitled *The Pottery of Palestine from the Earliest Times to the End of the Bronze Age* was completed and published in 1937 by the American Schools of Oriental Research. Both men were prophetic about the need to broaden the study of excavated material and the need for multidisciplinary study of archaeological sites.

In 1965 Dr. Frederick R. Matson published his landmark book *Ceramics and Man* and stated his ecological approach to the study of ancient ceramics. In 1970 he instituted the phrase "archaeological present" to describe his ethnographic and ecological studies, all of which added new dimensions to the study of ancient material. Museums have vast deposits of material to be studied and conservators require more nondestructive analytical processes that would enable them to conserve and restore this great wealth of material. Xeroradiography offers such a new analytical process. This paper will be the first of a series that will explore the applicability of the xeroradiographic process to the solution of many of the technical problems encountered when one deals with a complex contemporary excavation. It is one more tool — a most important one — available to assist the excavator, the conservator, the art historian, the museum curator, the student, the anthropologist and the ethnographer in the search to unravel the mysteries of the past. It is a tool that can help in the hermeneutic interpretation vital to presenting a clear picture of man past. In the words of Professor Sayce (1933, p. 2):

> One of the principal characteristics of modern thought is a realization of the essential unity of all knowledge. Few nowadays would waste time in trying to define the exact scope and limits of the various branches of study. Scarcely any subject is

self-contained and self-sufficing. Each borrows from, and may in return throw light upon, many others.

Xeroradiography is an example of an interdisciplinary, interpretative, analytical, and technical process that can be of great value to all who labor in the vineyards of ancient cultures.

Xeroradiography has been in use for several years as a supplement to conventional film radiography. Its ability to delineate edges even in the presence of minimal density differences has significantly enhanced the medical radiologist's imaging abilities. The authors have therefore decided to investigate the potentials of this process in the study of ancient artifacts, and of ceramics in particular.

Technical Aspects of the Radiographic Process

Almost by definition any ideal method of analysis should be nondestructive in nature. Thus, it is no accident that many of the great advances in radiography have occurred in the field of medicine. Preservation is no less important when dealing with irreplaceable archaeological material. One would expect, therefore, that radiographic analysis would have assumed major importance in the archaeologist's armamentarium. That it has not done so is a result of significant deficiencies in film radiographic images. Fortunately, many of these deficiencies may now be overcome by the use of electrostatic imaging, i.e., xeroradiography. To understand just what this relatively new mode of X-ray imaging can bring to our perception of the structure of ancient artifacts, we must first consider the basic virtues and vices of the radiographic process.

Ever since the discovery of X-radiation by Roentgen in 1895, the classical method of producing X-ray images has involved the use of a silver halide photographic type of emulsion as the recording medium. X-radiation comprises a broad spectrum of electromagnetic radiation of extremely short wave length starting with the far ultraviolet and extending into the realm of gamma radiation. This radiation is incapable of producing any form of response, color or black and white, in the photoreceptors of the eye, but may be made apparent by use of the inherent sensitivity of silver halides to X-rays in proportion to the amount absorbed, or, alternatively, by the conversion of the X-radiation to the ultraviolet and visible spectrum through absorption and conversion by an appropriate fluorescent screen.

Visible light is imaged by refraction. Lenses are capable of bending the rays to produce a crisp (i.e., high contrast) image which is then recorded on photographic film. In contrast, there is no lens or other device capable of refracting X-rays. In practice, images may be produced by two means only — diffraction or absorption. Diffraction will only be produced in the examination of submicroscopic structures such as crystal planes (in keeping with the extremely short wave lengths of X-radiation) and thus is not a technique of value in producing images of macroscopic objects. It is therefore necessary to resort to the crudest of image formation methods — the shadowgraph — to utilize the absorption characteristics of materials of differing densities to produce a radiographic image. Thus, our radiographic images are in every sense of the word just shadows and it is a tribute to the ingenuity of the equipment designers that such finely detailed shadows can be secured, although in no manner can these images be compared to the refinement of a high quality refracted (i.e, photographic) image.

More than three quarters of a century have been devoted to the improvement of radiographic images. Insofar as generating sources are concerned, the early primitive gas tube (as temperamental a beast as any in recent history) gave way to the reliable tungsten filament (Coolidge) tube in the twenties only to be dramatically upgraded into the rotating anode tube of the thirties. This rotating anode tube successfully distributed the enormous heat developed by the sudden stoppage of the high speed electrons over an arc rather than to a localized spot. A smaller target could thus be used with an inversely proportional improvement in detail at energy levels which would otherwise melt the tungsten target and destroy the tube.

Thus, image generation has undergone continuous and significant refinement. Yet this is only half the story. The other half is of equal or greater importance: the medium upon which this image is recorded. Here the obstacles are as great or greater, for the X-ray shadowgraph is a most imperfect image in a new sense. The problem is simple and basic: X-rays, with all their legendary ability to penetrate matter, do so most imperfectly. To consider the photographic parallel once more, the atmosphere for all practical purposes is completely transparent to visible light. In contrast there is nothing short of a vacuum completely transparent to X-rays, so much so that soft (low voltage) X-rays escape the X-ray tube with difficulty if at all, and are significantly absorbed and scattered by air.

The world as depicted by X-ray imagery is, therefore, translucent rather than transparent in character. This problem would be manageable if the absorbed or deflected X-rays merely disappeared from the image-forming process. Unfortunately they do not. The key word is *scatter* — for these rays are dispersed in every direction adding up to an over-all haze through which, at times, the basic image may be barely discernible. The scatter is everywhere: within the X-ray tube, in the air, from any equipment upon which the X-ray beam impinges, in the object under study, in the film holder, in the fluorescent screen, if used, and in the film itself. The measures used to control scatter include limitation of field size as far as practical since a small volume of matter will scatter less than a large volume, use of filters to eliminate the softer and more easily scattered radiation, development of the Bucky diaphragm (a grid composed of lead strips tangential to the primary beam whose function is to absorb any radiation deviated more than a few degrees from the primary beam as a result of scatter), and the use of intensifying fluorescent screens to enhance contrast.

The magnitude of the problem becomes obvious when the photographic analogy is again employed. The contrast of a photographic system customarily expressed as the "gamma" (slope of the density versus exposure curve) is usually considered to be at an optimum in the 0.7 to 0.8 range. An uncommonly flat or obscure subject might call for a gamma of 1.0. Compare this to an X-ray imaging system where a gamma of 3.0 is mandatory to overcome the deleterious effect of scatter and produce an optimal image. Photographically, a gamma of 3.0 would represent a black and white line copy devoid of intermediate tones; yet this gamma is necessary to bring the scatter-degraded X-ray image to a near optimum visual range. In photographic parlance, radiographs would be considered to have a notably poor "modulation transfer function" (MTF). The MTF of a system is currently considered to be one of the more sophisticated measures of image quality, measuring, as it does, the degree of contrast attainable for a given level of resolution.

The essential feature of this analysis is that film radiography is an additive process. Film might be likened to an elephant that neither forgives nor forgets, and the resultant image represents a summation of all factors, good and bad, that have occurred in the image-forming process.

To sum up, many years of refinement have vastly improved the quality of radiographic film images; nevertheless significant gaps persist in our imaging capabilities.

Xeroradiography (Electrostatic Imaging)

It is against this analysis of the successes and failures of classical radiology that one must measure the newer modality "Xeroradiography." Xerography is electrophotography; xeroradiography is the radiographic application of electrophotography. Fortunately the image-forming characteristics of xeroradiography are in many respects diametrically opposed to those of film radiography. As will be shown, xeroradiography in no way replaces film radiography but does possess unique characteristics which supplement film radiography in just those areas where the latter is most deficient.

In electrophotography, advantage is taken of the ability of a selenium-coated plate to hold a charge of positive ions. This charge may then be depleted by exposure of the plate to visible light or to X-radiation. Partial depletion of the charge results in a demonstrable, though as yet invisible, electrostatic image. This plate is capable of attracting charged pigment particles, thus creating a visible image which may then be transferred to a permanent support. Thus far the method of image formation and preservation demonstrates no obvious fundamental differences as compared to film radiography. Nevertheless, there are two crucial differences in the mode of image formation:

1. Whereas the film absorbs incident radiation and thereby builds up a latent image, the xeroradiographic image is produced by a partial destruction of the electrostatic charge of the selenium plate. The film image is additive; all of the factors, favorable and unfavorable, are integrated into the formation of the final image. It is the authors' opinion that the crucial difference lies in the fact that xeroradiography is subtractive: the charge is dissipated and many of the factors influencing film image formation simply disappear and play no further part in image formation. Thus the diffusing effect of scatter is minimized. It is true that excessive scatter might, for instance, drop the residual charge from 150 to 125 volts at a given point. Nevertheless, the image is formed by voltage differential between one point and the next, and if the reader will permit an anthropomorphic approach, the plate could not care less whether scatter has reduced the charge to 150 or 125 volts; all it cares about is the residual difference between charges. Thus xeroradiographic images, through a wide range of densities, are almost impervious to the effect of scatter and thereby often avoid the image degrading effects so detrimental to film images.

2. The gamma of a xeroradiographic system is incredibly low — as measured by Wagner (Wagner et al. 1974), only 0.2. This low level of contrast would, in film images, be flat to the point where detail would be barely discernible. However, since the xeroradiographic image is electrostatic, build-up of lines of force on one side of an interface deplete those on the other side, producing the phenomenon known as "edge enhancement." This enhancement is controllable by adjusting the factors affecting the plate,

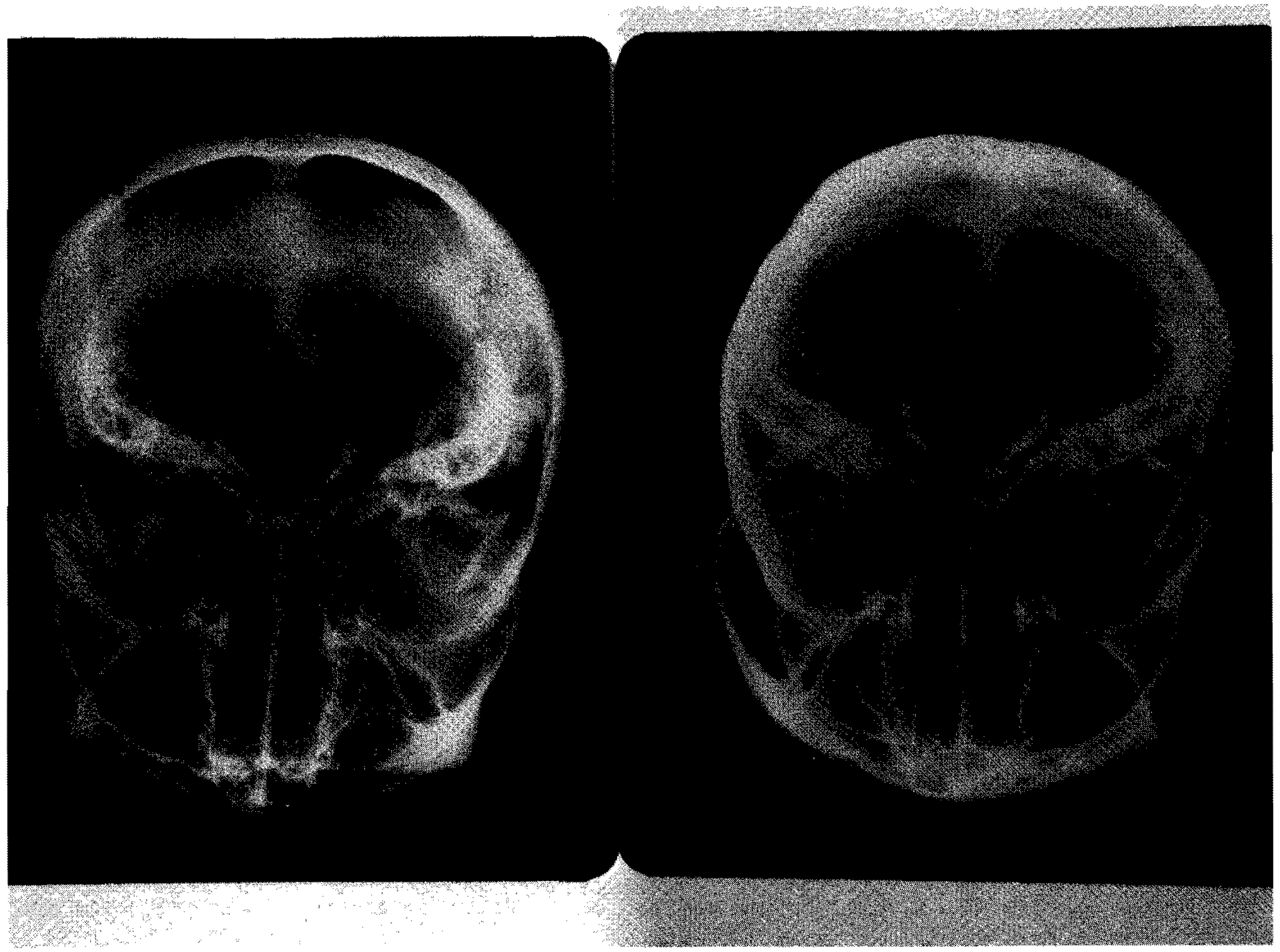


Plate 1. *a*. Film radiograph of dried skull. *b*. Film radiography with water bottle with added scatter.

thereby allowing the visualization of fine interfaces, although broad area response suffers in consequence. The result is an image of amazing tonal range (consonant with a gamma of 0.2) in which edge enhancement is utilized to render fine detail. This it does remarkably well, but with the caveat that one should not rely on the process to render comparative densities with precision. For this function, one may still rely upon the basic film radiograph.

It might be mentioned in passing that the dramatic success of the newest of X-ray modalities, the CAT scanner, is also based in part on its ability to bypass the effect of scatter in image formation. Briefly, the CAT scanner measures the density at any given point within the image plane by triangulation with computer analysis for reconstruction. Sensitive determinations of object density are possible far beyond the range of conventional radiography. However, spatial resolution capability is poor and for this reason the process offers little in the study of ancient artifacts and therefore will not be considered further in this context.

Summary

Xeroradiography represents a new imaging modality that differs from conventional film radiography in several crucial aspects. These unique characteristics, as applied to the study of ceramics, provide the investigator with the ability to demonstrate the following features to a degree not previously attainable by nondestructive methods:

1. The demonstration of crisp, accurate, scatter-free profiles of ceramic vessels of sufficient precision to replace current caliper-controlled hand sketching techniques.

2. The ability to show textures produced by aplastics or other inclusions within ceramics even when these inclusions closely resemble the basic clay

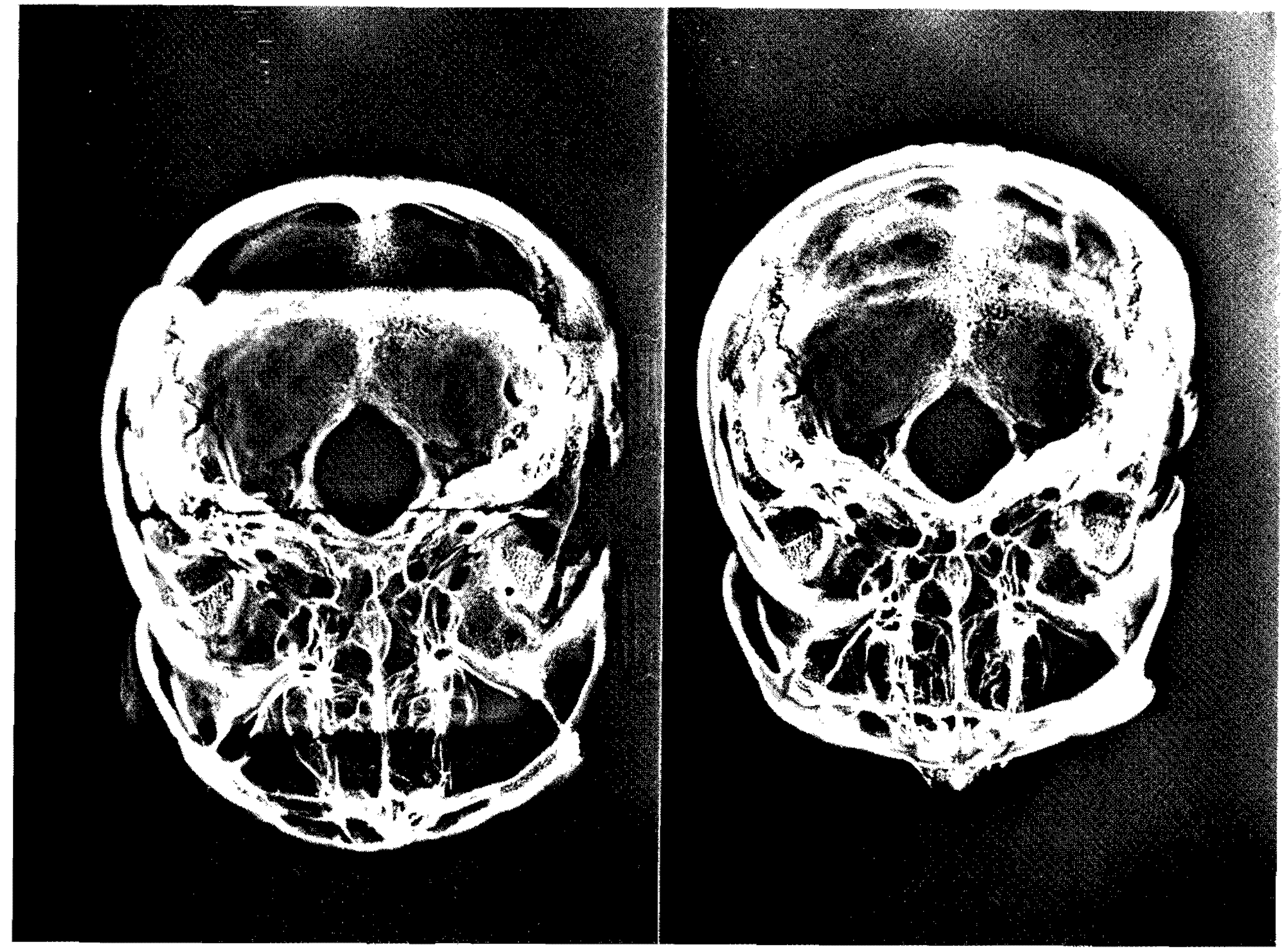


Plate 2. *a*. Xeroradiograph of dried skull. *b*. Xeroradiograph with added scatter.

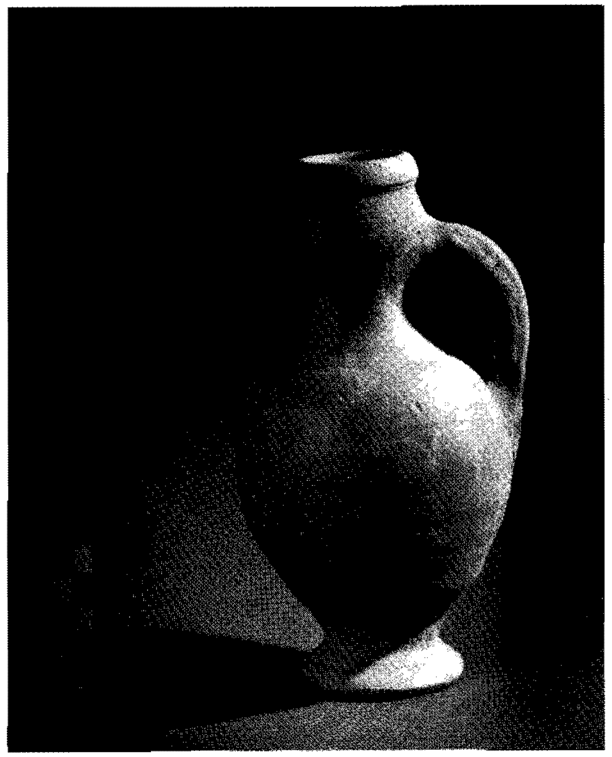
in their radiographic densities. The ability of xeroradiography to demonstrate edges to a greater degree than relative density makes this possible.

3. As a derivative of *(2)*, modes of manufacture including (but not limited to) hand- versus wheel-formed, direction of rotation of the wheel, technique of joins, repairs, later additions to ancient pottery, and so on, may now be studied with great precision.

It should be noted too that xeroradiography also finds applications in related fields through its ability to demonstrate the grain of woods, structural details in weavings even when imbedded in materials which would preclude ordinary radiographic study, the differentiation of some metals from their corrosion products, and many other applications where edge delineation may be helpful. The history and principles of the xeroradiographic process are admirably reviewed by John M. Wolfe (1972). Note should also be made of the early work of S. Heinemann (1976) in which the application of xeroradiography to the study of archaeological material is first suggested.

Analysis

Plate 1 demonstrates the degrading effect of scatter produced by the soft tissues of a living skull as contrasted to the critically sharp image of a dried skull. With xeroradiography (Plate 2), no such degrading effect is evident. Plate 3 is an example of a so-called magic pot that is quite common throughout the ancient world. The piece that we are using is a modern-made village pot that one can find in bazaars in many parts of the world, of a type usually sold to tourists. But behind the modern pot is a long history of double-chambered pots or connected pieces of pottery which were probably used in the Bronze and Iron Ages by shamans to impress people with ritual and magic phenomena that to the person in antiquity would be inexplicable. The piece of pottery at hand



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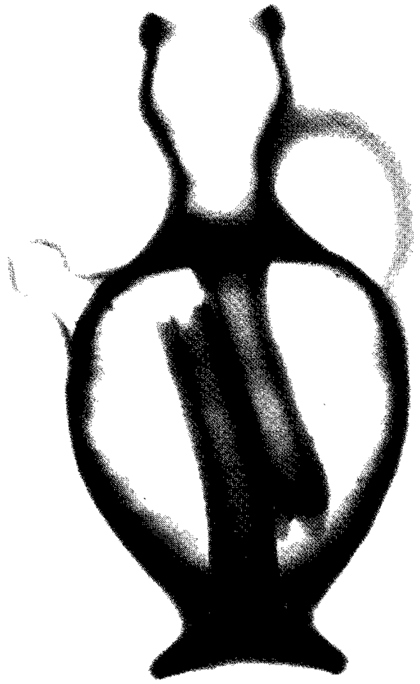

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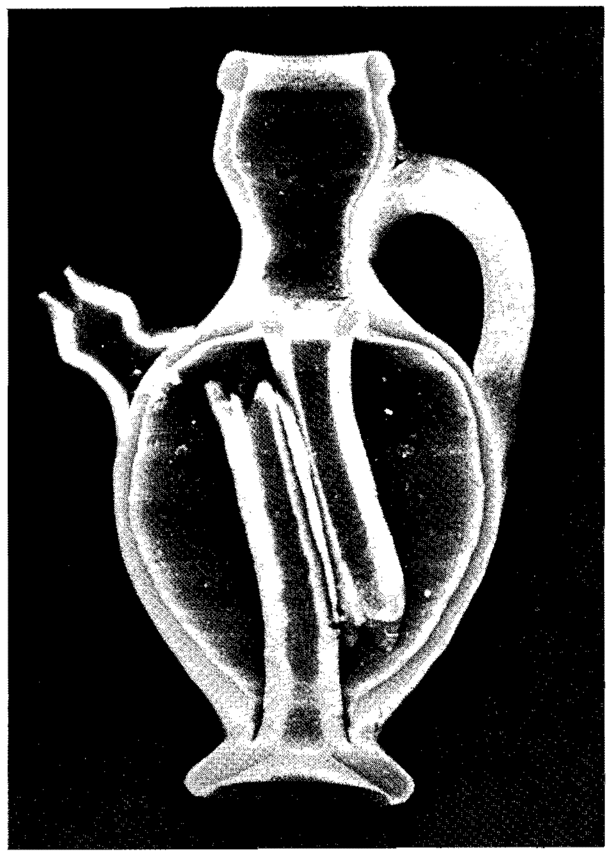

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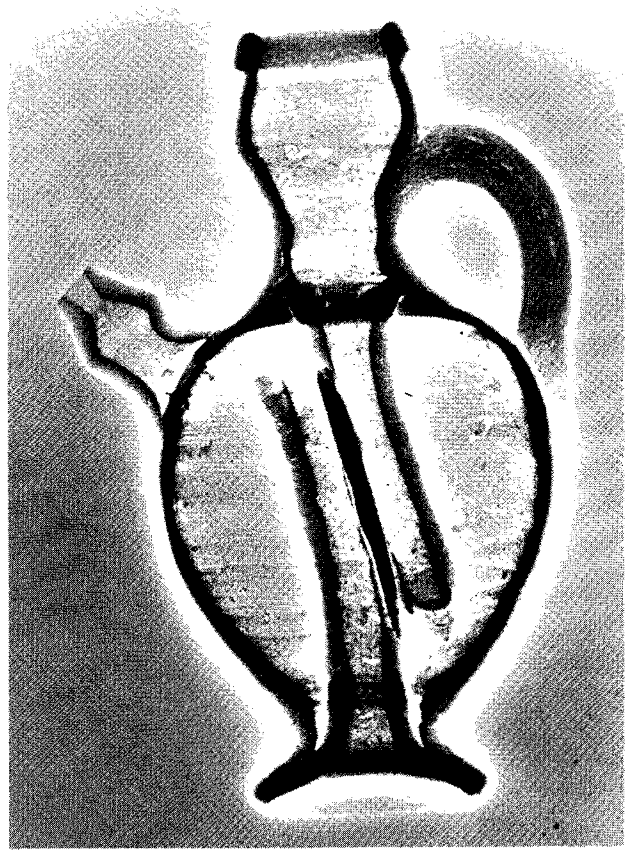

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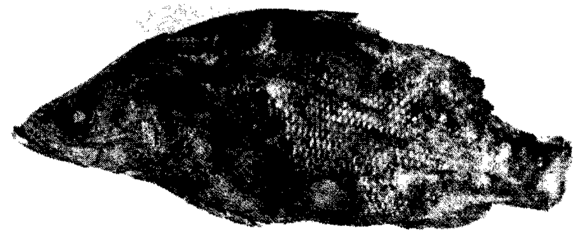

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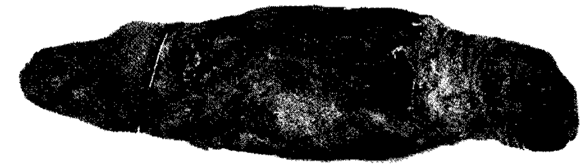

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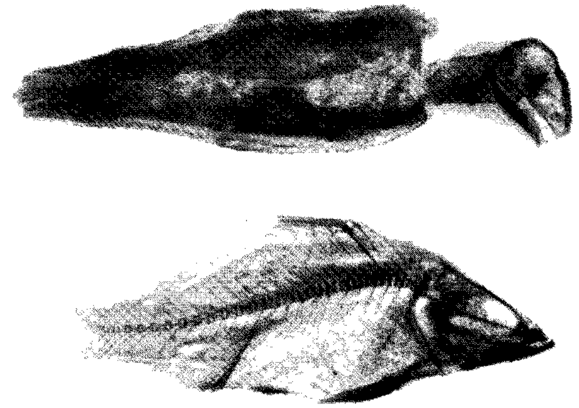

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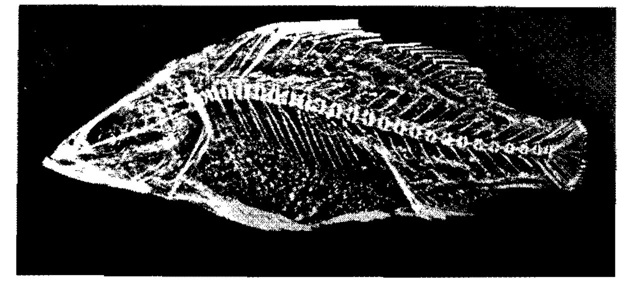

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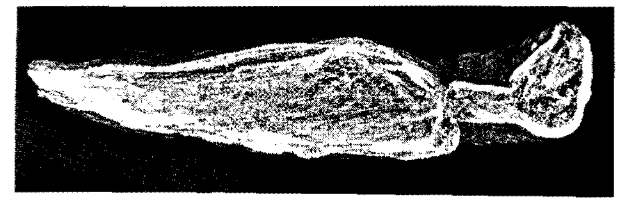

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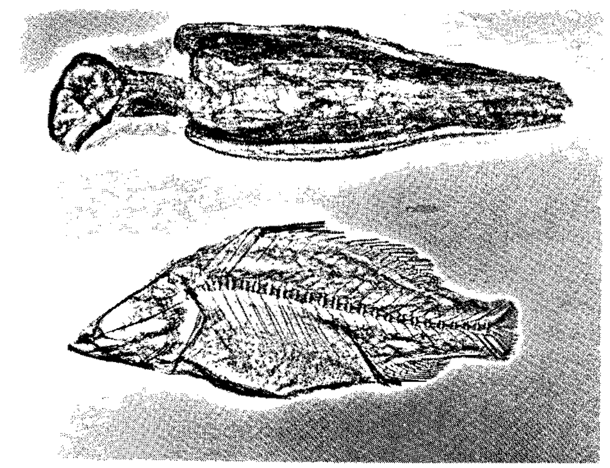

f.

◀ Plate 3. *a.* Magic pot. *b.* Film X-ray of magic pot. *c.* Xeroradiograph of magic pot (negative). *d.* Xeroradiograph of magic pot (positive).

Plate 4. *a.* Mummified fish (Egypt). *b.* Mummified bird (Egypt). *c.* Film X-ray of mummified bird and fish. *d.* Xeroradiograph of fish (negative). *e.* Xeroradiograph of bird (negative). *f.* Xeroradiograph of bird and fish (positive).

has a hole in the top into which water can be poured in the usual manner, but in addition a hole in the bottom so that the piece can be turned upside down and water poured into the bottom as well. One uses this pot by pouring water into the top, turning the piece upside down (at which point the water mysteriously does not run out), so that one can now pour some water into the hole at the bottom, turn the piece of pottery right side up — and lo and behold the water stays inside the vessel. At this point the shaman could have taken the piece of pottery by the handle and poured the water from the spout, very much to the awe of all who would be witnessing the experiment.

A modern "magic pot" was used to show how the process of xeroradiography can clearly demonstrate the workings of such a container, and show the various construction techniques used in making the vessel. One can readily see by the indication of throwing marks that the body of the vessel was thrown on a centrifugal potter's wheel. It is easy to see how two tubes were placed inside, one from the top and one from the bottom. The bottom tube also constitutes the base since the join of the base and the bottom tube is clearly visible. The neck was added as a separate piece thereby welding together the entire upper section of the vessel including the upper tube, and afterwards the rolled handle was added. In fact, one can see some air pockets at the join of the handle. Thus, without having to damage this piece by cutting or drilling, it is easy to see how the "magic pot" functions and how it was constructed.

The size, distribution, and comparative aplastic tempering material is quite visible in the xeroradiograph. If one compares the xeroradiograph to the X-ray of the same piece, the capacity of the xeroradiograph to define edges of materials of comparable densities offers a wealth of information not visible in film radiography. The edge effects characteristic of the process also produce incomparable profiles of objects and vessels, clear delineation of wall thickness, and the dynamic effect of the manufacturing processes on the material. A secondary benefit is the ability of the process to replace endless hours of drudgery by the staff artist responsible for delineating the profile.

Plate 4 is an example of using xeroradiography to study some mummified material dating to approximately 2000 B.C. from the area of Luxor in Egypt. As indicated in the illustration captions, we have an X-ray and a xeroradiograph of a mummified fish and a mummified bird. Through application of the technique of xeroradiography it is quite evident that the bird really does not contain any actual material of an ancient bird at all; as a matter of fact, there is a wooden plug in the neck and head of the bird and the

Plate 5. *a*. Colonial gunlock (corroded). *b*. Film X-ray of corroded gunlock. *c*. Xeroradiograph of corroded gunlock.

rest of the mummified bird is simply wrapped emptiness. No one knows whether a fake such as this was made in ancient times or whether this was something made more recently and sold on the antiquities market or to the tourist trade. It is quite possible that with the press of time the ancient mortician would at times produce mummified material that in fact did not contain the remains of any species which would be buried with the deceased pharaoh or member of the royal family. The fish is very intriguing because not only can you see the skeletal remains of the fish — which, by the way, show equally well in the traditional film radiograph — but in the xeroradiograph one can actually notice the fish scales and actually see parts of the fins and other details of the mummified fish not shown in the film radiograph.

Plate 5 is an example of a badly corroded colonial gunlock. The purpose was to use xeroradiography to help the conservator clean and conserve this ancient flintlock. When working with badly oxidized metal, using a variety of cleaning techniques including an air abrasive gun, one must be very careful that undue cleaning does not occur in areas where the metal has been so badly oxidized that its integrity is impaired. The film did not indicate some of the more eroded, sensitive areas. The xeroradiograph clearly indicates the details and mechanics of the flintlock and shows those areas where the metal has been so badly eroded by oxidation that an attempt to clean that particular area would simply destroy the piece.

Plate 6 is an example of the use of xeroradiography as a nondestructive method of reading ancient cuneiform clay tablets without harming the sealed fired clay envelopes. In conducting this experiment the authors were well aware of the fact that much of the information placed on tablets inside of such fired cases is cuneiform material that can in part be read on the exterior of the case. Nevertheless, it was a challenge to see if xeroradiography could be used to read tablets through the cases without having to cut into or damage the fired clay envelopes. It must be explained to those not so familiar with clay envelopes that these envelopes are covered with valuable cylinder seal impressions as well as cuneiform inscriptions which provide invaluable documentation of the individuals and time period involved. It took considerable experimentation before techniques were found that allowed us to bring out the image of the tablet inside the fired case, and as the xeroradiograph example shows, one can readily translate the tablets — a feat heretofore not possible without removing the inner tablet. We hope to carry this experiment further by using computer enhancement to make the inscription even more legible.

In conclusion, it is hoped that by using the tech-

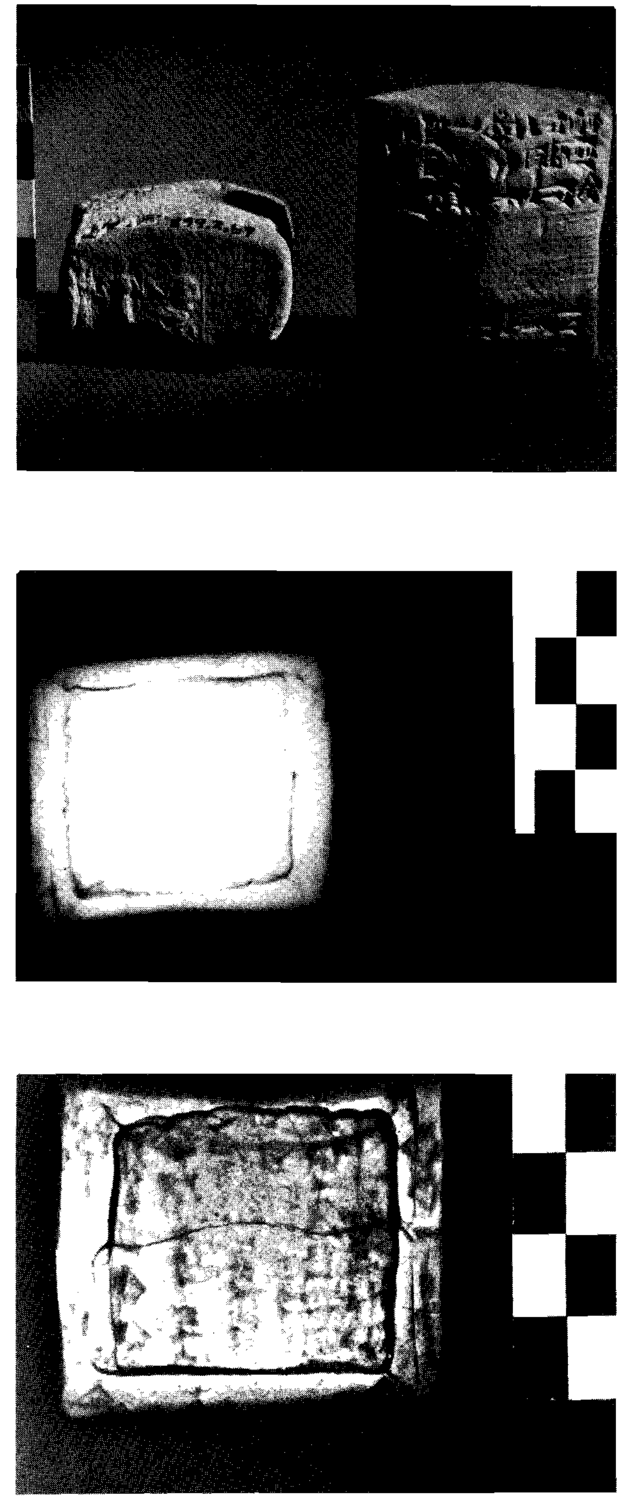

Plate 6. *a*. Cuneiform tablets in fired cases. *b*. Film X-ray of cuneiform tablet. *c*. Xeroradiograph of cuneiform tablet.

nique of xeroradiography, images and techniques can be developed that will be of great use to all those who have to work with and study the vast finds from excavated sites without having to damage the objects themselves. Our experiments will continue and we look forward to receiving problems and material from those in the field who would like to have us attempt to apply our technique as an additional tool for the excavator.

NOTE: Anyone having material that might benefit by xeroradiographic examination should feel free to contact the authors.

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14. Photoacoustic Examination of Ceramic Surface Layers

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Abstract

The periodic illumination of a solid sample results in cyclic heating and cooling which in turn produces an acoustic signal at the same frequency as the illumination rate. The strength of this signal is dependent on the light source, the absorption spectrum of the material, and the optical and thermal properties of the surface layers. The variation in the strength of the photoacoustic signal as the illumination rate is changed can provide information on the number and color of any surface layers present. The variation in acoustic signal observed as various points on the sample surface are illuminated can provide a sensitive detector of changes in surface condition or composition. This method has been applied to selected East Cretan white on dark ware sherds and the results of the examination of outer decorated surfaces as well as inner surfaces are reported.

Introduction

The photoacoustic (or optoacoustic) effect was first reported in 1881 (Bell 1881). It was noted that an audible sound was produced when a transparent cell containing carbon black was exposed to a periodic illumination. Other investigators (Tyndall 1881; Rayleigh 1881) speculated on the possible thermal mechanisms involved. Despite this early interest, the matter was not pursued and indeed disappeared from the literature for nearly a century. It reappeared in 1963 in connection with studies of the atmospheric absorption of laser beams. Since 1975 numerous investigations (Rosencwaig 1975; Rosencwaig and Gersho 1976; Monahan and Nolle 1977; Adams and Kirkbright 1977) have demonstrated that the effect, under appropriate conditions, can make a significant contribution to the analysis of solids.

Under steady illumination the temperature of an object will rise as nonradiative de-excitation processes convert part or all of the light absorbed by the solid into heat. In time the target will arrive at a temperature distribution in equilibrium with the surroundings. With a periodic interruption or "chopping" of the illumination, the average incident flux level will produce a corresponding equilibrium temperature with a superimposed fluctuating component. It is this time-varying term in the surface temperature that is responsible for the photoacoustic effect. The gas layer in contact with the target surface is heated at the periodic rate and the subsequent expansion and contraction cycles provide the boundary conditions necessary to launch an acoustic wave having the same fundamental frequency (f) as the illumination or chopping rate.

The acoustic energy level is very low and must be conserved by enclosing the test sample and a micro-