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

Toward the end of the first millennium A.D. in Europe, a similar shift from soda-lime glass to the high potassium "forest" glass of the high medieval period occurred.[165] The technological change appears to have been relatively fast, and was due to economic and/or political disruptions in alkali (soda) supply, which forced glassmakers to use plant ashes that have a higher potassium oxide content. The enormous demand for stained glass windows in churches, which now had to be made from the "forest" glass, must have caused major dislocations in the organization of the industry. Scientific analyses of medieval "Limoges" enamels, a related vitreous technology of the period, show that while this industry shared in the use of high potassium glass, it also used glasses derived from probable recycled Roman tesserae and/or possibly early Islamic glass.

CONCLUSIONS

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

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

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

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Xeroradiographic Imaging

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

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[165] M. Dekowna, *Szklo W Europie wczesnosredniowiecznej* (Warsaw 1980); J. Henderson and I. Holand, "The Glass from Borg, an Early Medieval Chieftain's Farm in Northern Norway," *Medieval Archaeology* 36 (1992) 29–58.

[166] See esp. J. Bhardwaj ed., *The Archaeometry of Indian Glass* (New Delhi 1990); and R.H. Brill and J.H. Martin eds., *Scientific Research in Early Chinese Glass* (Corning, N.Y. 1991).

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

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

The mechanism of achieving contrast is different from that of film radiography where the image is proportional to incident X-ray intensity on the film.[169] In electrostatic imaging, such as xeroradiography, charges accumulate at boundaries and around small details, and, much like a capacitor, a sufficiently large electric field will discharge across an edge. Any residual charge imbalance can discharge again and again, thereby producing an edge-enhancement. Because differing charge buildups and discharges occur, areas of varying density on a xeroradiograph cannot be compared quantitatively. The technique has a wide dynamic range in which many objects of diverse materials can be imaged in a single exposure; although densities are less well distinguished than with film radiography, discontinuities are enhanced. The wide range of densities that can be imaged and seen in a xeroradiograph are often obscured in a black-and-white print.

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

EXAMINATION OF A GAZELLE RHYTON

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

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

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

For discussion of the technique, see T.L. Thourson, "Xeroradiography," *Journal of the Society of Photo and Optical Instrumentation and Engineering* 56 (1975) 225–35.

[168] A.P. Middleton, J. Lang, and R. Davis, "The Application of Xeroradiography to the Study of Museum Objects," *Journal of Photographic Science* 40 (1992) 34–41; W.D. Glanzman and S.J. Fleming, "Xeroradiography: A Key to the Nature of Technological Change in Ancient Ceramic Production," *Nuclear Instruments and Methods in Physics Research* A242 (1986) 588–95; S. Heinemann, "Xeroradiography: A New Archaeological Tool," *AmerAnt* 41 (1975) 106–11.

[169] J.N. Wolfe, "Xeroradiography: Image Content and Comparison with Film Roentgenograms," *American Journal of Roentgenology* 17 (1973) 690–95.

[170] P.B. Vandiver, W.A. Ellingson, T.K. Robinson, J.L. Lobick, and F.H. Sequin, "New Applications of X-Radiographic Imaging Technologies for Archaeological Ceramics," *Archeomaterials* 5 (1991) 185–207.

[171] The rhyton, inv. no. S1987.31, has been published in *Asian Art in the Arthur M. Sackler Gallery: The Inaugural Gift* (Washington, D.C. 1987) 24 no. 16, and 43; T.S. Kawami, *Ancient Iranian Ceramics from the Arthur M. Sackler Collections* (Washington, D.C. 1992) 222 no. 141; and A. Gunter, "The Art of Eating and Drinking in Ancient Iran," *Asian Art* 1:2 (1988) 39.

[172] P.B. Vandiver, "Sequential Slab Construction: A Conservative Southwest Asiatic Ceramic Tradition, ca. 7000–3000 B.C.," *Paléorient* 13 (1987) 9–35; R.C. Henrickson, "Wheelmade or Wheel-Finished? Interpretation of 'Wheelmarks' on Pottery," in P.B. Vandiver, J. Druzik, and G.S. Wheeler eds., *Materials Issues in Art and Archaeology* 2 (Pittsburgh 1991) 523–41.

Fig. 20. Ceramic gazelle rhyton, possibly from Iran, ca. first century B.C.–first century A.D. (Arthur J. Sackler Gallery, Smithsonian Institution S1987.31). Made of a soft (Mohs 2.5), tan clay body, the vessel balances on its handle, and has a spout hole below the mouth.

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

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

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

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

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[173] P.B. Vandiver, "The Implications of Variation in Ceramic Technology," *Archeomaterials* 2 (1988) 139–74.

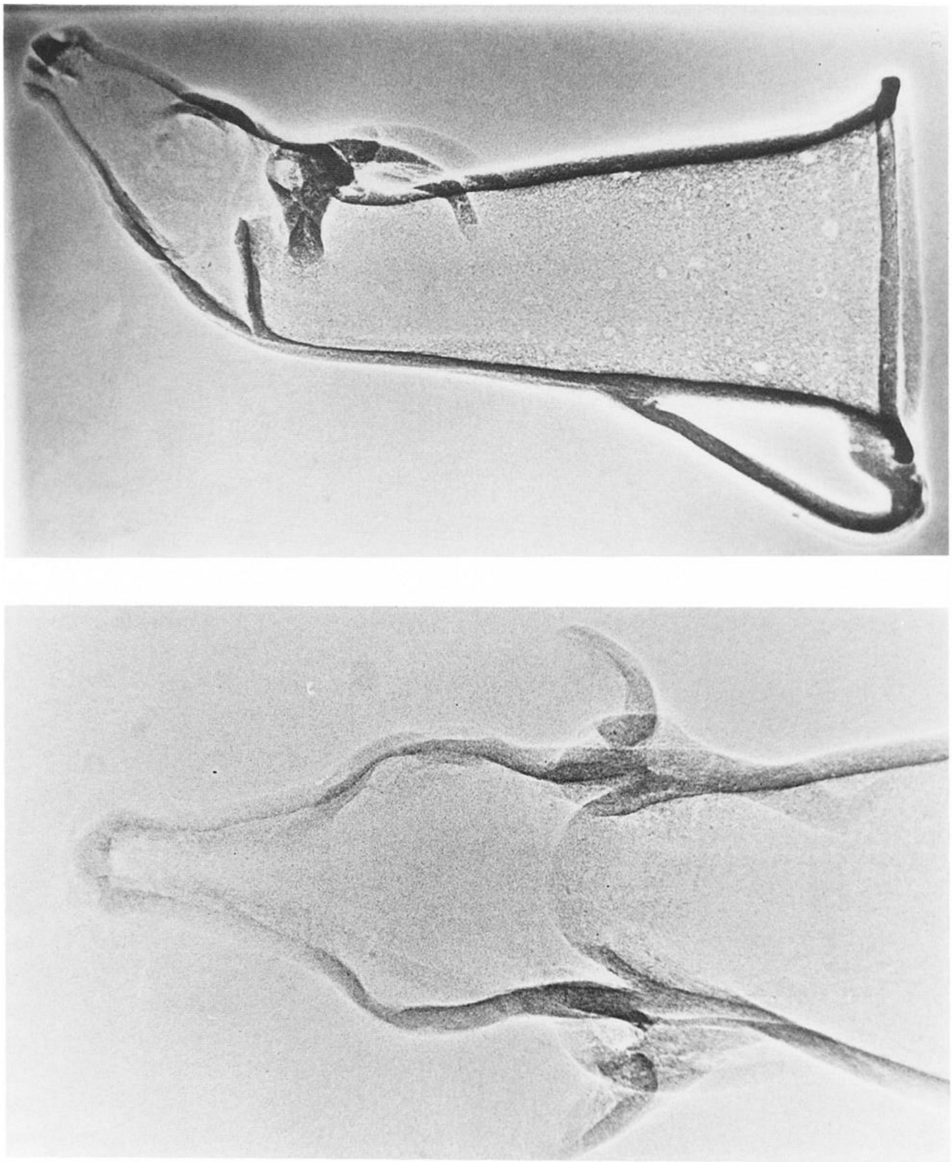

Fig. 21. a) Xeroradiograph of the left side of the gazelle rhyton (fig. 20), showing the spout hole beneath the mouth, a second hole through the mouth that was later covered over with clay, the uneven wall thickness of the carefully hand-modeled head, the extra clay strip added between the throat of the head and the base of the beaker, and the passage between the beaker and the head. The attached beaker is uniformly shaped, with an attached strip of clay for the handle. b) Xeroradiograph of the top of the rhyton, showing the attachment of the head to the beaker, and the partial rounding of the beaker base where a passage opens between the latter and the head.

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

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

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