

FINAL REPORT:

**DEVELOPMENT OF HIGH-RESOLUTION, DIGITAL, COLOR AND
INFRARED
PHOTOGRAPHIC METHODS FOR PRESERVING IMAGERY ON
HOPEWELLIAN COPPER ARTIFACTS**

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ABSTRACT

Prehistoric Hopewellian peoples of Ohio (ca. 150 B.C. - A.D. 400) produced fine geometric and representational art that played central roles in their social organization and religious practices. A 37 week, complete visual survey of nearly all major eastern United States collections of Ohio Hopewellian artifacts revealed that many of the 304 extant copper breastplates, celts, and headplates have on them the remains of artistic compositions previously undetected. The images resemble other Hopewellian and earlier Adena art in other media in their content and style, and include representations of leaders (humans, animal impersonators) in ceremonial dress and animals of the natural world. Previous physical and chemical studies of the art works, as well as taphonomic observations, suggested that the artistic compositions were certainly made by collage of various organic and inorganic materials and possibly by painting with at least ten minerals pigments.

This project successfully achieved its three goals: (1) to identify more exactly the nature of the materials used to create the imagery on copper; (2) to identify the artistic processes used to create the imagery; and (3) to develop a systematic, integrated set of digital photographic techniques for effectively recovering, enhancing, and displaying the art works on Hopewellian copper artifacts, as one approach to preserving the images and guiding their conservation. A team of eleven researchers, with specialties in archaeology, remote sensory systems, digital image photography and enhancement, applied metallurgy, mineralogy, petrology, paleoethnobotany, and prehistoric textile analysis carried out the project work.

Ultrahigh resolution (3360 x 2253 pixel) color digital photographs of 219 sides of copper breastplates, celts, and headplates, and near-infrared and midrange-infrared digital images of 263 sides of these kinds of copper artifacts, were captured with three different sensor systems. The sensor systems included a Leaf Lumina color digital camera, a Cohu 4810 near-infrared camera with sensing ranges of 0.7 to 1.0 microns, and a Hamamatsu C1000-03 midrange infrared camera with sensing ranges of 1.0 to 1.8 microns.

The mineralogy of all inorganic materials on 44 sides of copper artifacts were inventoried and found to include cuprite, malachite, azurite, chrysocolla, turquoise, hematite, and hydroxyapatite (bone), some of these materials in multiple morphological variants. Soil, mica, mother-of-pearl, calcite or aragonite, a powdered bone and calcite pigment, a powdered talc/serpentine pigment, and ash were also identified. Many surface characteristics of the powdered bone and calcite pigment showed that it had been painted on at least one artifact. Most examples of the copper-based minerals were found to have the surface characteristics, diversity, and contextual association with organics typical of copper patinas, like those produced by contemporary copper artists and jewelry makers. A major finding of this project was that the artistic compositions found on Hopewellian breastplates, celts, and headplates were made commonly by chemically inducing patinas on these artifacts.

The organic surface materials on both sides of 77 copper artifacts were inventoried and found to include textiles composed of Group I plant fibers (herbaceous plants like Indian hemp and milkweed), leather and hide, feathers, fur, bark, carbonized wood, uncarbonized seeds, bast, monocot stems, cut-up plant stems, a plant-fiber plaster of a kind, and unknown organics. Organics were observed much more commonly on the copper artifacts than previously thought. Their presence can be attributed in part to their use in making art works on the copper through their arrangements as collages and their role in creating copper patinas, specifically as a means for holding corrosive acids or acid-salt mixtures on the copper surfaces in prescribed areas of the artistic compositions. The occurrence of some kinds of organic materials on the artifacts, in a limited number of cases, can possibly be attributed to their having been placed on the copper artifacts during decommissioning rituals, probably to the artifacts having been wrapped in textiles prior to burial, and possibly to the artifacts having been placed next to clothing comprised of hide, fur, and/or feather.

Textiles of four different weaves, including oblique interlacing, spaced 2-strand twining, alternate pair twining, and spaced alternate pair twining, as well as cordage were found on about half (68 of 132) of the surveyed sides of copper artifacts. Their occurrence on the copper artifacts can be explained by the same five processes cited above for organic materials in general.

Quantitative modeling of corrosion processes using Pourbaix thermodynamic quantitative models confirmed that the great variety of copper corrosion minerals on the artifacts cannot be attributed to natural processes of corrosion of copper in the ground, but can be explained by patination and/or painting with corrosion pigments. The mineralogical studies showed that painting was very infrequently done, leaving patination as the primary explanation.

Experimental replication of the Hopewellian art works on copper using contemporary copper patination methods, along with salts and acids easily available to Native Americans of the Eastern Woodlands, confirmed that all of the observed kinds of corrosion products and their patterning as images on the Hopewellian objects can be explained by artistic patination. Given what is known about the distribution and kinds of organic materials on the artifacts, most of the patinas were probably produced intentionally and directly, while some may have resulted unintentionally from the decoration of the artifacts with cutouts made of textiles, hide, and other moisture-holding organics, and with intentionally shaped arrangements of fine plant materials.

Microscopic examination of the broken edges of 20 of 49 broken copper breastplates showed that nearly all the breaks were well-covered with cuprite and malachite, and that the breaks are ancient and were made prior to burial. This finding supports the idea that, upon being decommissioned, some breastplates, like many other kinds of artifacts in other media, were broken into pieces resembling animal and human forms of the kinds found in the artistic compositions created on them and in other formal Hopewellian art.

Two methods for capturing digital images were innovated during the project. Curved objects were photographed multiple times from different, overlapping, controlled vantages and joined together in Adobe Photoshop to create continuous, minimally distorted, flat layouts of them. Photographic lighting oriented at prescribed angles allowed an optimal documentation of the surface relief of objects as well as their colors.

Methods of digital image enhancement and the five captured spectra were evaluated for their capabilities in discriminating among different kinds of surface materials and in discerning art works made of those materials. Improvements in the photographic definition of the artworks were made by two kinds of contrast enhancements, both of which were found productive and applied to all of the color images captured: a total histogram stretch, in which the histogram of all three bands of the RGB image were stretched at once, and an individual color band histogram stretch, in which the histogram of each band was stretched separately. Histogram equalization was seldom found helpful in resolving the art works. The contrast and clarity of all near-infrared and midrange-infrared digital images were improved with a sharpening filter in Adobe Photoshop followed by a histogram stretch—the experimentally determined, optimal order of operations. Other image enhancement methods that were explored and found fruitful were seven different kinds of calculations among stretched bands of different color ($R \times B$, $R \times B$ -inverse, R -inverse $\times B$, R -inverse $\times B$ -inverse, $B \times G$, B -inverse $\times G$ -inverse, and $B - G$), formed in Adobe Photoshop, and the creation of hybrid infrared and color images, formed in the GIS program, IDRISI. The latter required modifying the resolution, resizing, and registering of the color, near-infrared, and midrange-infrared bands so as to coordinate with each other.

Qualitative evaluations of the above image enhancement procedures showed which specific band calculations are more commonly effective and which less in revealing the art works on the copper artifacts, although all seven band calculations were helpful in some material context, considering the entire corpus of artifacts. In addition, the Red and NIR bands and combinations of these with other colors generally seemed to provide the art works their greatest visibility. Different hybrid combinations of color, near-infrared, and midrange-infrared bands and color band calculations were found necessary to maximally reveal the different art works made of different materials, and sometimes the different features comprised of different materials within an art work, as might be expected. Specific material and image conditions were also found to determine the effectiveness of using supervised versus unsupervised clustering methods of image enhancement, cluster analytic versus palette boundary redefinition methods of image enhancement, and palette blending versus a palette with crisp boundaries among colors to enhance images. Principle components methods of redefining spectral dimensions of an image were not found useful in enhancing the visibility of the art works compared to using color or infrared bands or band calculations selected for their directly observable, individual effectiveness in enhancing features of an art work. The use of cool, neutral colors rather than primary or secondary colors to display images was found helpful in displaying art works.

A canonical discriminant function analysis of the five color, near-infrared, and midrange-infrared spectral bands of 52 kinds of materials found on Hopewellian copper artifacts indicated the green and midrange infrared bands to encompass most of the variability in image brightness that discriminated among the kinds of materials and to be essential to digitally enhancing and defining art works. The red and near-infrared bands were also found important in these regards, as found in the qualitative evaluations of enhancement procedures.

Together, the qualitative and quantitative studies provide clear guidelines for enhancing digital color and infrared photographs of Hopewell copper artifacts so that art works on them can be maximally discerned.

CHAPTER 1

INTRODUCTION, PROJECT GOAL, AND PREVIOUS STUDIES

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Introduction to the Project and Its Goals

Prehistoric Hopewellian peoples of the eastern United States (ca. 150 B.C. - A.D. 400) are well known for their artworks of copper, which were buried with their dead or in caches within earthen mounds. A systematic, in-depth survey of 320 copper ceremonial plaques, headdresses, and celts from southern Ohio and Indiana indicates that many appear to bear artistic design elements and compositions similar in style to those of known Hopewellian and earlier Adena art in other media from the eastern United States. At the time of the grant application, the apparent artworks were thought to have been made entirely by painting with mineral pigments and by collage with other materials that are unnatural to copper. Chemical and physical materials testing and microscopy suggested these artistic processes. During the course of the grant research, an additional artistic process was documented: the purposeful creation of copper corrosion products patinas. Materials analysis, corrosion modeling, microscopic examination of the copper objects revealed this process, and experimental replication of artistic works verified it.

While it is clear that certain copper objects bear artistic imagery, many are harder to decipher by the naked eye, alone. The purposes of the proposed research have been three: (1) to identify the nature of the materials used to create the copper-based imagery, (2) to identify the artistic processes used to create the imagery, and (3) to develop a systematic, integrated set of digital photographic techniques for effectively recovering, enhancing, and displaying images on Hopewellian (and other) copper artifacts, as one approach to preserving the images and guiding subsequent efforts to conserve them. Initial testing had shown that certain photographic methods were effective, but the range of materials and preservation conditions for which this is true, and the tailoring of specific techniques to given material types, remain to be systematically investigated. In the course of the proposed methodological work, potential images on the items were preserved photographically.

The Archaeological Context

The Ohio Hopewell were semi-mobile, apparently swidden horticulturalists and hunter-gatherers (Wymer 1996, 1997) who lived in the major river valleys of southern Ohio between ca. 150 B.C. and A.D. 400. Ohio Hopewellian peoples lived in small homesteads and camps of one or a few households each, which were dispersed over the valleys. Multiple households were probably organized into communities which centered on earthwork-burial mound sites that held their dead (Brose and Greber 1979; Brown 1981, 1982; Carr and Maslowski 1995; Dancey 1991; Dancey and Pacheco 1997; Greber 1979; Greber and Ruhl 1989; Konigsberg 1993; Pacheco 1988; Prufer et al 1965).

Ohio Hopewellian communities appear to have been integrated and regulated in several fashions: (1) ritually by periodic mortuary and other ceremonies, and perhaps feasts, within the earthworks (Seeman 1979; Smith 1992); (2) socioeconomically by local utilitarian exchange (Carr and Komorowski 1995); (3) politically by shaman-like leaders and clan or lineage heads who sometimes impersonated animals (e.g., the deer-"rabbit" impersonator from Mound 25, Hopewell site, Moorehead 1922:128; the Wray figurine bear impersonator from Newark; the decorated stone head from Edwin Harness, Greber 1983:33; see also the earlier raptor-human faces on Adena tablets, Otto 1975; Webb and Baby 1957); and (4) symbolically and ideologically by art and exotic raw materials that apparently were displayed and used by social-ceremonial leaders (e.g., Greber and Ruhl 1989), and that expressed a common, basic world view (Carr 1998, 1999; Seeman 1995).

The Ohio Hopewell are well known for their fine mortuary and ceremonial art, and their procurement of fancy raw materials from distant sources over the continent to make much of that art. Geometric and representational line engravings on animal and human bone, terra-cotta and stone sculptures, and forms created out of copper, silver, meteoritic iron, mica, shell, obsidian, etc., comprise the most common kinds of published art (e.g., Brose et al. 1985; Otto 1992; Penney 1983, 1985, 1989). Archaeological complexes with similar mortuary-ceremonial art occur across the eastern United States from the Great Lakes to the Gulf Coast, and from New York to western Missouri (Griffin 1967:181).

Problem Development and Project Goals

Over the course of 37 weeks during 1995-1997, the PI made complete visual surveys of nearly all extant major collections of Ohio Hopewell and Mann-Phase (Indiana) Hopewell artifacts housed in 12 museums, universities, and private collections in the United States (e.g., The Chicago Field Museum, The Peabody Museum of Harvard University, The Ohio Historical Center, Columbus). The survey was financially supported by the Wenner-Gren Foundation of Anthropological Research, the Chicago Field Museum, and Arizona State University. The purpose of the survey was to find unpublished examples of Hopewellian art. During this work, the PI noticed that many of the 320 extant copper plaques, headplates, and celts, as well as some earspools, pendants, and other copper items, appear to have on them the remains of artistic design elements and compositions that previously had gone undetected. Some images are clear; many are more subtle in their preservation. The items come from at least 15 major mound-earthwork complexes and smaller mound sites in diverse depositional environments.

The content, style, and techniques of production of the apparent images lend them credibility. The images systematically repeat among objects and resemble those found in Hopewellian and earlier Adena art in other media. The images are primarily of apparent animals, humans, or animal-human composites similar to those referenced above. The animal species most frequently represented are raptorial bird, bear, deer, wolf, and cat -- species that commonly served as clan totemic animals and names of clans or phratries in the historic northern Woodlands (Trigger 1978). These figures are arranged in

compositions that have bilateral or quadripartite symmetry, figure-ground reversal, and complex intertwining of shapes -- traits of Hopewellian iconography, generally.

At the time of grant application to NCPTT, the methods by which the imagery appeared to have been made include: painting with mineral pigments, and the application and arrangement of a variety of materials, including cut-out shapes of textiles, bark, ground-up plant material, small segments of plant stems, untwisted plant fibers, cordage, sand, bone, pearls, and feathers. A pigmented, gum or sap-like, possible adhesive had also been observed. In some cases, a fiber-paste layer appeared to have been built up over the copper surface, and then differentially removed to create bas-relief area-fills or to expose the underlying plate so as to create images in the negative.

In retrospect, artistic work of these various kinds on copper Hopewellian artifacts is not unexpected: copper plaques, headplates, and earspools are known to have sometimes been decorated with designs by other, better preserved, sometimes conceptually-related means, including embossing, area cut-outs, and silver and meteoric iron applique'. In addition, a logical chronological development in art on rectangular forms can be found in the shift from Early Woodland Adena stone and clay tablets that were engraved, to early Middle Woodland Hopewellian copper plaques from Mound City that were embossed or cut out, to later Middle Woodland Ohio Hopewellian copper plaques (e.g., from Hopewell, Seip) decorated by painting and material applications. Artworks of all three times share similarities in content and layout (e.g., raptorial birds placed in the four directions/corners), as well as structure (e.g., figure-ground reversal and intertwined figures).

Preliminary Materials Analyses and Development of Digital Photographic Methods

To begin to understand how images were manufactured on the copper objects, to explore their taphonomy, and to assess methods for clarifying the images, two kinds of preliminary studies were made: (1) chemical and microscopic studies of the materials that form the images, and (2) digital photographic and other methods of image enhancement. The studies were made primarily by the team researchers for this proposed project.

Preliminary materials analytical chemical and microscopic studies.

Microsamples of 11 differently colored surface materials -- 10 thought to be mineral pigments and one an organic binder or adhesive -- were removed from 63 locations on 11 copper plaques, headplates, and celts from four different Ohio Hopewell archaeological sites (depositional and taphonomic environments): Hopewell, Seip, Ater, and Fortney. The samples were taken from areas that are integral parts of likely human or animal images or their contrasting backgrounds, and that appear unnaturally homogeneous in color. The material types of the samples were determined with five complementary physico-chemical methods: (1) electron microprobe analysis using energy dispersive detection, (2) Raman microspectroscopy using 514.5 nm and 785 nm

excitation wavelengths, (3) x-ray diffraction using a Debye-Sherer camera, (4) SEM microphotography at 50 - 200X and 3000X, and (5) petrological description under a stereo-zoomscope at 6 - 31X. These methods respectively documented the samples' elemental compositions, inter-atomic bonding characteristics, crystallographic structure, crystal micromorphology, and crystal habit.

The ten minerals were found to fall into two groups: (1) noncopper compounds that do not derive from copper corrosion and that, from all evidence, appear to be applied pigments, and (2) copper corrosion products that could, on the basis of their chemistry alone, be either applied pigments or *in situ* developments. The noncopper compounds are red, yellow, white, and brown-black in color -- the same colors used in other Ohio Hopewell artwork, the colors of the soils used in contrasting distributions to build some Ohio Hopewell mounds and earthworks, and the colors found in much historic Woodland Native American art and ceremony. The compounds include: (1) hematite; (2) serpentine; (3) probably bone with a small amount of calcite, dolomite, shell, pearl, and/or some other primarily calcium carbonate material; and (4) probably an organic-rich soil. The copper-based compounds are red, aqua, blue-green, turquoise, and deep blue, and include (5) cuprite, (6) chrysocolla, (7) malachite, (8) azurite, (9) turquoise, and (10) perhaps others in minor amounts. The one possible organic binder for the pigments, or adhesive, was found to bubble under the heat of the microprobe electron beam and to be noncrystalline, as expected. It contains red and yellow colorants fully dissolved within it.

The copper-bearing compounds, which form integral parts of images like the noncopper ones, logically could indicate artistry either directly or indirectly. Two hypotheses were investigated during the course of the NCPTT research project. (1) Natural copper corrosion products could have been scraped from native copper, or mined along with native copper at its sources, to form pigments of green, blue, or red, which were then added to some vehicle/binder. Different corrosion-derived paints of different colors could then have been applied to different areas of a composition. (2) Different corrosion products of varying colors could have developed naturally *in situ* in different images or parts of images because these areas were originally treated with different fugitive substances to form images (e.g., cut-outs or arrangements of organic materials). Areas treated differently would then have posed varying corrosion environments that differed in pH, available elements, and/or water-retention, leading to the formation of different corrosion minerals of different colors in those areas (see Jakes and Sibley 1984:421 for analogous archaeological examples). In this case, the shapes of any images would have been preserved, but their original colors would not have.

A variety of observations by copper corrosion and mineralogy professionals on the research team suggested hypotheses 1 and 2, i.e., that the copper-based minerals from images were either applied as pigments or developed *in situ* naturally: (1) image areas comprised of chrysocolla, malachite, and azurite and having crisp, regular, linear or curvilinear edges unnatural to copper corrosion growth; (2) apparent "drying lines"--where malachite and azurite seem to have accumulated at the drying edges of an image; (3) colored areas probably produced by the mixing of two copper corrosion pigments, the particles of which are jumbled together and do not grow from the copper substrate; (4)

image areas having apparent copper corrosion pigments that lay on top of applied organic materials and lack development from the copper substrate; (5) celts and plaques with a uniform background color of azurite and with image-areas of turquoise--minerals that mathematical-chemical preliminary modeling showed are not stable compounds in the soil conditions (pH, temperature, water, dissolved ions) of Ohio, and that are not reported as natural, *in-situ* developed components of the Ohio geological landscape; (6) delaminating layers of possible paints of several colors; and (7) drying cracks of possible paints of several colors. The mathematical-chemical modeling was accomplished with an exploratory construction of some "phase diagrams" of the equilibrium thermodynamics of copper-aqueous systems.

By the end of the project, evidence to support hypothesis 1 had waned considerably, whereas hypothesis 2 was well supported and extended. What had not been anticipated but was observed during the NCPTT research is that the process by which images were created through corrosion was, in many cases, intentional patination by Hopewell artists rather than a byproduct of their artwork in fugitive organics, as in hypothesis 2.

The geological formations from which copper pigments might have been mined, assuming hypothesis 1, has not been determined. However, deposits of chrysocolla, malachite, azurite, turquoise and cuprite occur in the copper-bearing localities of Michigan, Tennessee, Pennsylvania, and/or Alabama (Roberts et al. 1990) -- areas exploited by Hopewellian peoples for other ceremonial raw materials and artifacts.

Preliminary Studies of Digital Photography and Image Enhancement Methods

The second kind of study made preliminary to the NCPTT-supported research aimed at assessing digital photographic and image enhancement methods for clarifying the images that appeared to have been rendered on the copper artifacts. This section necessarily begins with two literature reviews before proceeding to discuss the preliminary analyses that were made.

Literature Review of Digital Photography. Digital imaging of the kind applied in this project involves the detection of multiple, distinct bands (frequencies) of visible and/or infrared light within each of a large matrix of cells (pixels) within a viewing area. Such digital imaging has a long history in the fields of remote sensing by satellite and aerial photography (American Society of Photogrammetry 1968, 1983, 1984; Castleman 1979; Pratt 1978; Gonzalez and Wintz 1977; Lilles and Kiefer 1987). However, only in the past several years have color digital cameras with the fine resolution, compact size, and reasonable cost that is required in archaeological and museum analytical work become available. Thus, such applications have been few in these fields. Digital photography is now used in some museums (e.g., American Museum of Natural History) to make permanent, nondeteriorating records of irreplaceable objects that are subject to degradation, loss of ownership, or repatriation. Davis and Steponaitis (1996) used digital photography for this purpose and to provide concerned Native American tribes with visual records of burial goods housed at the University of North Carolina. Bearman

(1996) used a digital camera with near-infrared sensors to photograph portions of the Dead Sea scrolls in preparation for enhancing the writing on darkened, unreadable portions. One of the earliest applications of digital photography to archaeology was made underwater. An electronic still camera with direct digital output, which allowed the operator to preview images, was used to document the U.S.S. Hamilton, which sunk in Lake Ontario during the War of 1812 (Stewart 1991).

In art history, infrared (IR) photography using a digital camera with sensors of infrared waves, or infrared-sensitive film, has been used commonly to view underdrawings below a painting's surface, to view layers of painting over painting, and to pinpoint areas of aging and damage on artworks (e.g., De Boer 1970; Desneux 1958; Dunkerton et al 1987; McKim-Smith 1988; Panofsky 1958; Roy 1988; Marijnissen 1967; Taubert 1956, 1959; Verougstraete and van Schoute 1997). The approach has been particularly popular in examining 15th Century Flemish paintings. The method is based on the fact that different elements and compounds vary in their reflectance of IR waves when illuminated with incandescent light, allowing areas of different material composition to be distinguished and some materials to be seen through. False-color infrared photography, which combines information on visible and near-infrared light, was used by Hirsch (1987) with incandescent lighting to reveal floor-tile paintings, and by Salzer (1987) with ultraviolet lighting causing material fluorescence to distinguish the pigment of rock art images from natural mineral stains and plant growth on sandstone cave walls.

In art-historical and archaeological IR applications such as these, a wide range of wavelengths--from near to mid-range infrared--are typically sensed in combination to produce a single image. In contrast are some approaches used in aerial and satellite remote sensing, where the infrared spectrum is broken into multiple bands of varying wavelength. Only certain bands relevant to the spectral response of a particular material may be monitored, as in mineral prospecting (e.g., Goetz 1976, 1984; Goetz et al. 1985; Hunt et al 1971 Nicolais 1974; Smith 1977), vegetational mapping (e.g., National Academy of Sciences 1970; Sadler 1987; Savastano et al.1984), or military surveillance. An alternative approach especially relevant to this project is "hyperspectral imaging" or "image spectrometry". A very large number of narrow bands (e.g., 10 nm) covering a wide range of wavelengths (e.g., .4 - 2.5 microns) are sensed simultaneously, resulting in a digital image where each pixel documents a spectrum of wavelengths. Pixels can then be characterized for their spectra in order produce compositional maps of mineral or forest-canopy species distributions, which are most interpretable when reference spectra for minerals or plant species are known (e.g. Kruse 1990; Hook and Rast 1990; Johnson et al 1992). This approach was used by Bearman (Bearman et al 1993; Bearman and Spiro 1996) to read faint lettering on darkened sections of the Dead Sea Scrolls. Bearman is one of this project's team members.

Ultraviolet photography has been found in art history to be optimal for detecting discontinuities in painted surfaces. Ultraviolet light incident on a material may produce fluorescence or phosphorescence in the visible spectrum, and/or ultraviolet radiation, any

of which may be sensed and recorded (Derbiere 1947; de Wild 1929; Eastman Kodak 1998; Radley and Grant 1954).

Literature Review of Digital Image Enhancement Methods. Computerized digital image enhancement methods involve analyzing and/or modifying the grey-scale values, or red, green, and blue-scale values, or other nonvisible spectral values of the pixels that comprise a digital image. Enhancement methods include several major classes of display and mathematical routines, which are designed primarily to improve the information content of a digital image. They can be used to: (1) increase image contrast, (2) sharpen boundaries within images, (3) determine the spatial scales at which image information is richest, (4) partition and remove high frequency noise or low frequency trends or disjunctures, and (5) partition overlaid images (Carr 1987; Castleman 1979; Gonzalez and Winz 1977). Image enhancement can be done in either an exploratory or deductive manner. Either the image pixel values themselves, their histogram, or their Fourier transform are operated upon. Among the most essential methods of image analysis are: band selection, interband calculations, contrast-stretch histogram modification, histogram equalization, spectral analysis, and mathematical filtering with high-pass, low-pass, band-pass, and gradient-sensitive operators.

Image enhancement methods have been used for about thirty years for remote sensing by satellite and airplane (see above), geophysical prospecting (Davis 1973; Holloway 1958; Robinson et al 1970; Zurflueh 1967), archaeometric prospecting (Carr 1977, 1982; Linington 1969; Scollar 1969, 1970; Weymouth 1985), and/or intrasite archaeological spatial analysis (Carr 1987; Lang 1992). Applications to archaeological photography are not yet common. Haigh and Ipson (1989) used a combination of Fourier analysis, linear contrast stretch, and histogram equalization to compensate for fogging and uneven partial darkening of an aerial photo of a hillfort in Scotland. Bearman (1996) applied convolution, sharpening, and histogram adjustments in Adobe Photoshop and NIH Image to a series of narrow, near infrared bands recorded from the Dead Sea Scrolls, in order to read lines of text that were hidden by the fading of carbon ink and the darkening of the papyrus. Salzer (1987) and Valiga and Scherz (1987) used image enhancement methods to improve the resolution of false-color infrared and color photographs of rock art, respectively. Stewart (1991) did the same on underwater photographs of the U.S.S. Hamilton (above). Carr (1987) and Lang (1992) used many image enhancement methods to resolve patterns in intrasite artifact distributions likened to poor quality photographs.

Preliminary Digital Photographic and Enhancement Studies. In preparation for the NCPTT research project, many of the methods of image capture and enhancement reviewed above were explored for their capability in clarifying potential images on copper objects bearing a variety of material types. State-of-the-art digital cameras, computer image processing hardware and software, and printing systems were employed - the same to be used in the proposed project (see Facilities and Equipment). Work was funded by Eastern National Parks and Monuments Assoc. and Arizona State University.

(1) Color slides were taken of both sides of all 320 extant copper plaques, headplates, and celts from Ohio. Color and textural differences over each item were enhanced by printing the slides with a Canon color copier. All potential images showing on the original items and the prints were sketched.

(2) A diverse sample of 105 item-sides of copper plaques, celts, and headplates was selected for study, based on step 1. The artifacts vary in the classes of apparent images they bear and span many of the kinds of materials and apparent artistic processes described above.

(3) Color (RGB) digital photographs were taken of the 105 item-sides using an ultra-high resolution portable (Leaf Lumina) digital camera with 3360 x 2253 pixels and incandescent illumination. Curved headplates were photographed with minimal distortion using an adaptation of “photomosaicing” techniques pioneered in aerial landscape mapping. Photomosaicing is a procedure for piecing together a flat layout photograph of a curved surface from multiple photographs taken of it from different vantage points. As applied here, the digital camera was held secure in one position and the curved headplate was rotated to several different photographing positions about its approximate center of curvature on a formed, Styrofoam support, keeping the lens-to-object distance constant. The photographs taken at different rotation positions overlapped in coverage. The multiple photographs were then spliced together in the computer using Adobe Photoshop’s scaling, rotating, skewing, and stretching routines. This approach was successful (Carr and Lydecker 1997).

(4) A large suite of image enhancement methods was tested on the 105 item-sides for their effectiveness in improving the contrast, boundary sharpness, and definition of potential compositions, and in revealing previously unnoticed figures of kinds known or thought to occur on other copper objects. The current version of Adobe Photoshop was used to make the enhancements.

One general strategy of enhancement was found most useful, and subsequently tested in the NCPTT-supported research. (a) Two copies of a given potential image were made on the CRT screen. (b) Image contrast of the two copies was optimized using two different routines: “contrast-stretch histogram modification” operating on the red, green, and blue bands, first together and then individually. (A third contrast-improving routine--histogram equalization--was seldom found effective.) (c) The optimized red, blue, and green bands of both enhanced images were assessed for which ones contained the greatest information about potential figures. Often, the red and blue bands proved most revealing, apparently because they minimized the noise of any greenish, natural corrosion products. (d) The most informative color bands and their inverses were multiplied by, divided by, added to, and subtracted from each other, in order to bring out suspected or unsuspected material types and images. (e) Each resulting calculated band had its contrast optimized using contrast-stretch histogram modification. (f) The bands were compared to each other in search for either quasi-stable patterns that repeated over several bands, or for figures that occurred uniquely in one band but that were known to resemble figures on other copper objects. These two criteria afforded a level of

confidence in the reality of the images found. (g) Found images were ground-truthed for their visibility in the original copper objects as a final test of their reality. (h) High, low, and band-pass filtering were not found effective. This effectiveness of this routine was tested in the NCPTT research project with better information on the nature of the materials on the artifacts and how material type affects image enhancement.

This strategy outlined in steps *a - g* almost always led to the clarification of images seen directly by eye on the objects. It also allowed us to find images that were not at first seen visually, but that became recognizable once the naked eye's attention was brought to them. Finally, on 22 of the sample items (ca. 19%), apparent "underpaintings"-were observed-layered sequences of paintings, corrosion, or patination. Different calculated bands revealed the same or similar human or animal figures, but significantly offset from each other, different in size, and or different in orientation. The possible "underpaintings" remain to be verified physically. The IR photography used in the NCPTT research helped resolve these possible painting sequences.

(5) A strategy was developed for separately displaying each of the multiple, individual design aspects (layers of information) found in a composition. This was necessary because the potential compositions, like much of Hopewellian art, often involve multiple conjoined, nested, and/or overlaid figures, with figure-ground reversal; these figures are hard to see and make sense of when displayed simultaneously. The display strategy involved: (a) laying acetate sheets on the enhanced image and making line tracings of each individual layer of information/figure on its own sheet; (b) raster-scanning each tracing into the computer; (c) autotracing each raster scan into a vector version, so as to produce a line drawing of consistent line width; (d) reconverting each tracing to a raster images and superimposing it on the enhanced image; and (e) printing a combination of the image enhancement and a tracing, one for each layer/tracing made.

(6) Near-infrared (.715 - 1.1 microns), midrange infrared (1.0 - 1.8 microns), thermal infrared (8 - 14 microns), and ultraviolet (.35 - .38 microns) cameras of military quality at Battelle Laboratories were used to photograph 6 sides of 6 items bearing the 11 potential pigments/binders described above, and certain organic materials. The work showed that only near and midrange infrared wavelengths are useful. These allowed the boundaries of artistic images to be sharpened, the revealing of some largely hidden images, and the mapping of sparse pigment distributions that were invisible to the naked eye. Near and midrange infrared photography are complementary in these regards relative to each other and visible light photography.

(7) Short and long-wavelength ultraviolet black lamps (.254 and .366 microns) were found ineffective in revealing imagery on 20 items with the 11 potential pigments and binders.

(8) Various hardware and software for printing enhanced color and infrared digital photographs were compared for the resolution, contrast, and texture they offer. The Canon 800 series color copier, with its good resolution (400 dpi) and an important edge enhancement routine, was found to offer the most information-laden images.

Chapter That Follow

The subsequent chapters of this final report summarize research directly supported by NCPTT. Chapter 2 identifies and maps the distribution of minerals found on the surface of a sample of Ohio Hopewellian copper artifacts, and begins to posit the kinds of formation processes (purposeful or otherwise) by which the materials came to reside on the artifacts. Chapter 3 evaluates theoretically and quantitatively whether the varieties of copper corrosion products found on individual headplates, breastplates, celts, earspools, and other copper items of the Ohio Hopewell were likely the result of fully natural, random, in situ corrosion or, instead, the product of some kind of intentional, cultural, artistic activity (e.g., painting, patination). It also assesses whether the broken edges of some copper breastplates were relatively modern or ancient in age, in order to determine whether the artifacts may have been decommissioned by breaking them into culturally prescribed forms found elsewhere in Hopewell art. Chapter 4 establishes visual criteria for identifying kinds of organic materials that are found on Ohio Hopewellian copper artifacts, identifies and maps the distribution of those materials on a sample of such artifacts, and begins to posit the kinds of formation processes – purposeful or otherwise – by which the materials came to reside on the artifacts. Chapter 5 identifies the occurrence or lack of occurrence of textiles on Ohio Hopewellian copper artifacts, maps their distribution on such items, describes their various textile characteristics, and determines how textiles came to occur on the artifacts, intentionally or otherwise. Chapter 6 reports the replication of Hopewellian copper artworks using patination techniques available to Hopewellian peoples. The chapter verifies patination as a process by which Hopewellian copper artworks were commonly made, as concluded from the materials analyses reported in Chapter 2, 3, and 4. Chapter 7 reports how information from color and infrared digital photographs of the copper artifacts were made and evaluates them qualitatively for their effectiveness in revealing Hopewellian artistic compositions. Discussions consider photographic hardware and software, image capture for flat and curved objects, photographic enhancement, registration of color and infrared images, and the utility of particular spectral bands, band calculations, and hybrids of bands. Chapter 8 develops a digital photographic, quantitative model for identifying different kinds of surface materials found on Hopewellian copper artifacts from their spectral responses. The model clarifies which surface materials are more or less resolvable from each other photographically, and thus which aspects of artistic compositions contribute to their photographic clarity or obscurity. The model also reveals the particular spectral bands more and less effective in discriminating among surface materials and in revealing artistic compositions.

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CHAPTER 2

MINERALOGICAL ANALYSIS

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Statement of Research Goals and Research Questions

This component of the research project had two major goals: (1) to identify and map the distribution of minerals found on the surface of a sample of Hopewellian copper artifacts, and (2) to begin to posit the kinds of formation processes (purposeful or otherwise) by which the materials came to reside on the artifacts. The second question involved considering the surface materials' physical characteristics; distributions; diversity; the degree of correlation among materials of different kinds, among materials and artifact classes, and among materials and sites; and the distribution of materials on opposite sides of the artifacts. The following questions were asked to address these three major areas of study:

- (1a) What kinds of minerals occur on the surface of the copper items?
- (1b) What are the best examples of each of the kinds of materials identified?
- (2) How commonly do these minerals occur on the surface of copper items, as measured first by the number of examined item-sides having them present on them and, second, by the average areal expanses of the minerals on those item-sides?
- (3) Do sites vary in the commonality with which minerals of various kinds are present on their copper items, as measured first by the percentage of examined plates within sites having those minerals and, second, by the average rank areal expanses on those item-sides?
- (4) Do artifact classes of different kinds (i.e. breastplates, celts, and headplates) vary in the kinds of surface materials present on them, considering all sites? Considering individual sites?
- (5) Which minerals of different kinds tend to commonly occur on the same item-side, and which kinds do not?
- (6) Are there systematic differences (or tendencies toward differences) between the kinds of minerals found on opposite sides of an item?
- (7) Which minerals tend to occur with organic materials, and which kinds of organic materials?
- (8) Which minerals tend to occur with cremation materials, on the same side or on opposite sides of the item?

(9) Do any of the above patterns or lack of patterns, or other observations, suggest the nature of the processes (cultural or natural) that led to the development of the mineral surface materials?

(10) Are there item-sides that have a diverse range of kinds of corrosion minerals, suggesting that not all of them developed naturally on an unaltered copper surface? If so, which item-sides?

(11) Are there item-sides that have sharp and linear boundaries between different kinds of corrosion minerals, suggesting that the minerals did not develop naturally on an unaltered copper surface? If so, on which item-sides?

(12) Are the occurrences, and broad and sometimes homogeneous expanses, of azurite or other corrosion minerals that are found on some item-sides unexpected for the natural corrosion of an unaltered slab of copper? Which item sides would suggest this, and for which kinds of minerals, if any item-sides do?

(13) Was any evidence of “drying lines” or meniscus phenomena observed? On which item-sides?

(14) Were any examples found of particulate matter, versus crystalline growth, suggestive of applied pigments? On which item-sides?

(15) Are there any common (or unique) stratigraphic relations between kinds of minerals that are telling of the processes by which they formed? If so, for which item-sides?

Sample Selection and Criteria for Selection

A sample of 11 sides of breastplates, 5 sides of celts, and 3 sides of headplates, totaling 19 item-sides, was selected for in-depth examination of all observable minerals and formation processes. A second sample of 21 sides of breastplates, 2 sides of celts, and 2 sides of headplates, totaling 25 item sides, was chosen for partial examination, focusing on specific areas of interest. The samples were chosen so as to include: (1) a full range of the easily observable mineralogical diversity of the breastplates, celts, and headplates in the Ohio Historical Society’s collections; (2) items that had well defined artistic imagery, in the opinion of Carr; and/or (3) items that had unusual material distributions (e.g., “drying” or “meniscus” lines), which might indicate the origin of the minerals on the items.

Reporting

This report describes largely the results of the in-depth examination of the 19 item-side sample. However, it benefits from what was discovered through the more focused and partial study of the 25 item-side sample. Detailed descriptive and interpretive notes for both samples are provided as a separate document, submitted to the Ohio Historical Society. References here to locations on artifacts, using a grid system or letter designation, are defined in the detailed notes.

Observational Methods Used

Only non-destructive, visual methods were used to study the artifacts. Observations were performed at 10x and 30x magnification using a binocular microscope and at no magnification by naked eye.

Identification of materials was based on habit, mode of occurrence, and on other physical properties when identifiable. The habit of the material refers to the shape of a crystal or aggregate of crystals, when considering a mineral, or the shape and consistency of a mass when referring to some other material. The mode of occurrence refers to specific details regarding the location of materials on the artifact (e.g. a material only occurring atop another material).

A variety of criteria were used for identifying minerals and distinguishing natural growth from materials applied. The identification of minerals was based mostly on observed properties, habits and modes of occurrence. Clear signs of crystalline growth, when identifiable, provided evidence of identity and natural, *in situ* growth (as opposed to application). Signs of crystalline growth include such factors as crystal habit, cleavage, translucency or transparency, and textural features that represent either chemical interaction with or spatial limitations imposed by neighboring materials.

Identification of applied materials relied mostly on the presence of unnatural textures, including but not limited to even distribution over a region, drying lines, shrinkage cracking, even surfaces and unnatural distributions.

Chemical and structural data from previous studies (scanning electron microscopy, electron microprobe analysis, x-ray diffraction, see report by C. Carr, on file with the Ohio Historical Society) were used when available in addition to observations made during this study.

Results

This section answers the questions raised at the beginning of this report.

(1a) What kinds of minerals occur on the surface of the copper items? Twenty-one material forms were identified on the 19 item-sides examined formally and in full. The materials and their distributions among the item-sides surveyed are shown in Table 2.1. Many of the various forms of materials can be grouped together to represent one or another family of materials. For instance, five material forms represent malachite: pseudomorph after organic (MPS), stalactitic habit (MST), cauliform habit (MCA), bubbles (MBU) and pseudomorph after cuprite (MAC). Five material forms represent cuprite: *in situ* replacement of copper (CIS), chalcotrichite (CHA), iridescent (CIR), single crystal (CXL) and pseudomorph after unknown (CPS). Native copper (CU) was visible on several item-sides (but was present in all artifacts as original material, even when not exposed). Stalactitic growths of azurite (AST) occurred on both sides of three artifacts examined. A total of nine materials are lumped in a miscellaneous category. These include minerals or materials that occurred on three or fewer of the formally examined item-sides and are not copper minerals. Miscellaneous materials include soil

not removed during cleaning (SOIL), mother-of-pearl beads, disks, and shells (MOP), calcite and/or aragonite (CAR), bone pigment (PIG), powdered talc/serpentine (TSE), and four unknowns (LBS, LGS, and ORS which are intimately associated and UNK).

Materials of obvious historic origin were not included. Such materials include varnish or other coatings, glues, fills and efflorescent growths that occurred after excavation and cleaning. Efflorescent growths were fairly common on many of the pieces and were highly reflective, resulting in some brightening in several of the photographs (B020A and B053A especially).

Twelve of twenty-one materials are copper or copper oxidation minerals. If the four unknowns (LBS, LGS, ORS and UNK) are copper minerals, then as many as sixteen, or three-quarters, of the materials occurring on formally examined item-sides are copper oxidation minerals. Of the remaining miscellaneous materials, the calcite/aragonite (CAR) represents *in situ* growth, the soil (SOIL) represents incidental contact remaining on the item-side, mother-of-pearl (MOP) represents incidental contact or purposeful application, and the pigment (PIG) and powdered talc/serpentine (TSE) represent materials purposefully placed on the item-side.

(1b) What are the best examples of each of the kinds of materials identified?

Best Examples

MPS B015A, B020A&B, CO26B
 CIS C006A, C026B (for foil)
 MST H002A, B020A&B(meniscus), B025A (beads)
 MCA C013B
 SOIL C027B, H002B
 CU C006A
 AST H002A
 MBU C013B
 MAC C015A
 CIR C013B
 MOP C027B
 CAR C027B
 CXL C013B
 LBS B050A
 LGS B050A
 ORS B050A
 UNK B025A
 CPS B025A
 PIG B031A
 CHA B031A
 TSE B031A

(2) *How commonly do these minerals occur on the surface of copper items, as measured first by the number of examined item-sides having them present on them and, second, by the average areal expanses of the minerals on those item-sides?*

Table 2.2 shows the commonality of the 21 material forms relative to the number of item-sides on which they are present and their average areal expanses. Copper minerals are the most common minerals found on the artifacts examined. Malachite is found on all item-sides formally examined as at least one of the described forms (MPS, MST, MCA, MBU and MAC). Copper (CU) is present in all artifacts as the original material, although it is only exposed on seven item-sides, along recent bends or breaks, or when the piece has been vigorously cleaned and overlying mineralization has been removed (all historic in occurrence). Cuprite (including CIS, CIR and CHA) is also present on all pieces as a basal, *in situ*, oxidation product of the original copper surface. Cuprite is exposed in one form or another on all item-sides except the two breastplates from the Ater site (B052A and B053A). These two pieces were difficult to interpret because of the high degree of varnish and possible reconstruction, so the lack of exposed cuprite may not be significant.

Soil and stalactitic azurite come second in terms of commonality, occurring on nine and six item-sides respectively. Miscellaneous materials occurring on three or fewer item-sides include mother-of-pearl (MOP); calcite/aragonite (CAR); cuprite single crystals (CXL); the light blue, light green and orange stalactitic materials (LBS, LGS and ORS); the unknown mineral and the associated cuprite pseudomorph (UNK and CPS); the bone pigment (PIG); and the talc/serpentine (TSE).

In terms of presence on item-sides, the total count falls into three groups. The malachite pseudomorphs (MPS), *in situ* cuprite (CIS), stalactitic malachite (MST), and cauliform malachite (MCA) occur on 16, 16, 14 and 12 item-sides, respectively. These materials are also the highest ranked based on areal expanse. The next group of materials is the soil (SOIL), copper (CU), stalactitic azurite (AST) and malachite bubbles (MBU), occurring on 9, 7, 6 and 6 item-sides, respectively. These include fairly and moderately widely distributed materials. The last group of materials includes those occurring on three or fewer item-sides. These are malachite after cuprite (MAC); iridescent cuprite (CIR); mother-of-pearl (MOP); calcite/aragonite (CAR); cuprite crystals (CXL); light blue, light green and orange stalactitic material (LBS, LGS and ORS); an unknown mineral and corresponding cuprite pseudomorph (UNK and CPS); the bone pigment (PIG); chalcotrichite (CHA) and talc/serpentine (TSE).

No materials had an average areal rank higher than 2 over all of the 19 item-sides examined. Those materials that had an average rank less than 4 typically covered a moderate to large portion of the item-side and included MST (2), MCA (2), MPS (2.19), MAC (2.33), AST (3.17), CIR (3.33) and CIS (3.56). Materials with a rank of 4 or higher typically had a lower areal rank (low coverage to trace amounts). In general it is true that those minerals that occurred on the most item-sides also had the highest average areal ranks. The only real exception to this rule is the malachite pseudomorph after cuprite

(MAC). MAC occurred on 3 item-sides but was ranked 2.33. This can be explained by the tremendous cleaning that occurred on all three item-sides on which MAC occurred.

(3) Do sites vary in the commonality with which minerals of various kinds are present on their copper items, as measured first by the percentage of examined plates within sites having those minerals and, second, by the average rank areal expanses on those item-sides?

Tables 2.3A and 2.3B record the distribution of minerals across items from different archaeological sites, relative to the number of item-sides on which they are present and their average areal expanses. Of the highest ranked minerals in terms of occurrence (MPS, CIS, MST and MCA), only MPS occurs at all sites. MST is absent from the Harness site and MCA is absent from the Esch and Liberty sites; however all of these sites are only represented by one artifact. CIS is absent from both artifacts (B052A and B053A) found at the Ater site, but these artifacts were heavily coated with some varnish and may have been reconstructed. Aside from the above exceptions, these minerals are all well represented at the various sites, occurring on most or all of the artifacts found at those sites.

Of the middle ranked minerals (SOIL, CU, AST and MBU), SOIL and CU occur at roughly half of the sites and also on half of the item-sides. AST occurs only at two sites (Fortney and Hopewell). MBU occurs at nearly half the sites. There does not seem to be any dependence of minerals on the site they at which they are found, the possible exception of AST, which had an occurrence on six item-sides at two sites. However, it is important to keep in mind that AST only occurred on three distinct artifacts, occurring on both sides of each.

For the low ranked minerals (those that occurred on 3 or fewer item-sides), it is impossible to make any statement in regards to their commonality by site.

There was no discernible difference from the above observations in commonality of minerals among sites when commonality is measured by average areal rank.

(4) Do artifact classes of different kinds (i.e. breastplates, celts, and headplates) vary in the kinds of surface materials present on them, considering all sites? Considering individual sites?

Tables 2.3A and 2.3B show the distribution of minerals across items of different morphological types, relative to the number of item-sides on which they are present and their average areal expanses. There tends to be a similarity in the kinds of minerals found on the different kinds of artifacts when all sites are considered. There are some exceptions. Malachite pseudomorph (MPS) is slightly more represented on breastplates (occurring on all those formally examined), than on the other artifacts, on which it was represented about two-thirds of the time. Cauliform malachite (MCA) is represented on one third of the headplates, but on two thirds or more of the breastplates and celts. Soil (SOIL) was found on about one third of breastplates and on about two thirds of the

headplates and celts. Azurite (AST) was absent from the celts but occurred on one third of breastplate sides and two thirds of headplate sides (it is important to note that when azurite was present on an artifact, both item-sides were formally examined). Malachite bubbles (MBU) and malachite after cuprite (MAC) occurred on about two thirds of the celts, but were absent from headplates and breastplates (except MBU which occurred on two breastplates). The other minerals did not have enough occurrences to make a meaningful comparison and are not commented on.

Only the Hopewell site has enough artifacts represented to answer the second part of this question. The trends for artifacts from the Hopewell site follow those for all sites.

(5) Which minerals of different kinds tend to occur commonly on the same item-side, and which kinds do not?

Table 2.4 lists the associations of minerals with each other on the same item-side, for the 19 item-sides examined fully. The malachite pseudomorph and *in situ* cuprite are nearly ubiquitous and are associated with most other minerals when present. MCA was present only half the time when MST was present. Also, AST was typically not present when MCA was present. This may reflect that MCA was a corroded form of malachite on some pieces and such conditions would not be conducive to MST or especially AST being present. AST was also not present with MBU or MAC, which also occurred on extremely corroded pieces.

(6) Are there systematic differences (or tendencies toward differences) between the kinds of minerals found on opposite sides of an item?

Table 2.5 lists the dissociations of minerals from each other on opposite sides of a same item, for the 19 item-sides examined fully. There is no tendency towards differences between the kinds of minerals found on opposite sides of an item. Rather, there is a general tendency towards similarity. The only general exceptions to this tendency are those minerals for which there was a single occurrence on an item-side. (B025A and B031A are examples of this.)

The major copper oxidation minerals (malachite, cuprite and azurite) always occurred on both sides of an item, although not necessarily to the same extent or in exactly the same form.

The only cause of differences between light and dark malachite and cuprite that was noted was caused by the amount of organic matter present and the amount of malachite forming on the cuprite. If the organic matter is the control, then the differences could result from topside/downside differences in moisture retention.

(7) Which minerals tend to occur with organic materials, and which kinds of organic materials?

The only mineral that has any correlation with organics is malachite. This is not to imply that malachite only occurs intimately associated with organics or only on those item-sides that have organics. Malachite in all of its forms occurs above, below and at the plate surface of all pieces, regardless of the types or coverage of organic materials present.

The malachite pseudomorph (MPS) is by definition associated with organics. MPS ranges from a lighter or olive-green color to a bright green and may blend into other forms of malachite, such as cauliform malachite (MCA) or stalactitic malachite (MST). MCA, the olive-green to brownish green form of malachite, is most commonly observed situated amid or atop organics or organic pseudomorphs, although MCA is observed growing directly on the surface of several item-sides. (It is likely that such item-sides had significant organic coverage that was historically removed, such as C006A.) MCA strongly correlates with MPS, occurring together in all instances except when extremely heavy mechanical cleaning has occurred (as is the case for C006A, C015A and C027B).

MST and the malachite bubbles (MBU) have no correlation with organics. MST typically occurs growing atop the surface of the item-side, although it can be found forming atop MPS and MBU always occurs directly on the surface of the item-side.

The stratigraphic relation of the different forms of malachite with respect to each other and the surface of the item probably indicates more of a transport model for copper rich fluids rather than any specific relation to organic materials. The presence of organic materials such as hide or textile presented a vehicle for transporting copper rich fluids away from the surface of the item and holding those fluids while copper mineralization occurred at the fluid-air interface. This wicking action allowed for intimate replacement of various organic materials with MPS and also for the formation of malachite growths between and atop the organics themselves.

(8) Which minerals tend to occur with cremation materials, on the same side or on opposite sides of the item?

No tendency for materials to associate with cremation remains was observed on those item-sides formally examined. Of those item-sides, no materials occurred only with cremation remains. However, only three of the item-sides formally examined had any kind of cremation remains present, and these were mostly in the form of small particles of charcoal and some small calcined bone fragments, less than 1 mm in diameter.

Other copper breastplates with large pieces of bone and charcoal were informally examined early in the research period. These did show several mineral forms that were not seen on the pieces formally examined. One was a waxy form of malachite that could form rather large bubbles of up to several cm. The closest material to this among the formally studied items was MBU; however, but the bubbles in MBU were all smaller than about 2mm. Also present was some kind of bright blue acicular copper material, probably chalcantite or brochantite, both of which are copper sulfates. These minerals

probably correlate with cremation remains, but formal observation on a wider sample would be necessary to be certain.

(9) Do any of the above patterns or lack of patterns, or other observations, suggest the nature of the processes (cultural or natural) that led to the development of the mineral surface materials?

The single largest control to patterns of mineral growth was the surface area upon which minerals could form. This surface area was provided by organic layers or by foil layers (or sometimes both). Most of the remnant organics were removed during cleaning (on the pieces formally examined) and only remained when replaced by malachite or significantly overgrown with malachite.

A second control seemed to be the degree of corrosion, which was influenced by the presence of cremated remains (and probably other factors as well). Vigorous corrosion created a tendency towards more MST and MBU, as well as more iridescent cuprite or chalcotrichite.

(10) Are there item-sides that have a diverse range of kinds of corrosion minerals, suggesting that not all of them developed naturally on an unaltered copper surface? If so, which item-sides?

Most of the item-sides studied showed a clear sequence of mineralization, starting with a basal cuprite, atop which malachite (and perhaps azurite) formed. Any physical stratigraphy of the pieces was typically due to malachite mineralization wicking up or forming atop some organic layer or foil. B050 is the only piece that has a diversity of minerals and textures that does not completely fit into this model.

B050 has more materials than any other piece (9 on each side, though several others have 7 or 8). There does appear to be a complexity in physical stratigraphy of the plate formed by layers of both foil and organics. Many of the minerals occur sporadically over wide areas and there is no clearly defined sequence of mineral formation as is typically evident on other item-sides. The physical texture of the surface (CIS) and the occurrence of the mesa-like structures of stalactitic material (LBS, LGS and ORS) are unique compared to all artifacts studied, formally or informally. In sum, although the kinds of minerals present on B050 are natural, their areal distributional variation and stratigraphic variability are hard to explain by natural processes.

(11) Are there item-sides that have sharp and linear boundaries between different kinds of corrosion minerals, suggesting that the minerals did not develop naturally on an unaltered copper surface? If so, on which item-sides?

There are no sharp boundaries between corrosion products that formed, suggesting an unnatural origin. Most of the boundaries are controlled by primarily the presence and location of organics and/or foils.

(12) Are the occurrences, and broad and sometimes homogeneous expanses, of azurite or other corrosion minerals that are found on some item-sides unexpected for the natural corrosion of an unaltered slab of copper? Which item sides would suggest this, and for which kinds of minerals, if any item-sides do?

The only two materials that had an unnatural spatial occurrence were the pigment (PIG) and stripes of talc or serpentine (TSE) on B031A. In addition to their unnatural spatial occurrence (TSE occurs as evenly spaced stripes and PIG occurs in an even arc, bordered by foil edges), TSE and PIG are both composed of materials that would not form during the corrosion of copper.

(13) Was any evidence of “drying lines” or meniscus phenomena observed? On which item-sides?

The only example of what may be drying lines was observed on the pigment (PIG) on B031A. No other material exhibited drying lines per se, but there were several examples of minerals forming from an aqueous solution.

B020B and perhaps C026B have examples of lines of MST growing along the edges of some organic material. These would have grown from the meniscus of water formed at the edge of the organics.

There are examples of what appear to be pooling effects on pieces (B020A, B044A and H001A). These typically result in changes in mineral texture rather than changes in mineralogy, although B020A shows a difference in mineralogy, partially around a root cast.

A third fluid effect, which is probably not truly a meniscus phenomenon, is the reaction front between AST and MST that occurs on H002A. This certainly was a fluid based chemical reaction.

(14) Were any examples found of particulate matter, versus crystalline growth, suggestive of applied pigments? On which item-sides?

B031A was the only item-side formally studied that had materials and patterns suggestive of applied pigments. The pigment (PIG) had several characteristics that really indicated it was unique from the other minerals. It was very homogenous in texture and had a very even surface (though cracked by shrinkage). The shrinkage suggested it was not natural in occurrence. It flaked off the item-side without leaving a trace, unlike the malachite and azurite growths which would leave a mark on the surface to which they were attached. None of these characteristics by themselves indicated an unnatural origin but, taken collectively, they do. Another applied material occurring on B031A are the streaks of talc or serpentine (TSE). The pattern of several parallel lines, the powdered nature, and the chemistry of the material indicate an unnatural origin.

(15) Are there any common (or unique) stratigraphic relations between kinds of minerals that are telling of the processes by which they formed? If so, for which item-sides?

The most common sequence of mineralization is that of the copper corrosion products. The typical sequence is cuprite replacing copper (CIS) at the surface of the artifact. This is a largely *in situ* process with little or no increase in the physical relief of the artifact. Next is the formation of malachite or azurite (typically malachite) on the surface of the plate. The formation of these growths creates a 'zone of attachment' on the underlying cuprite. This area is revealed as a pitted scar when the overlying mineral has been broken away during cleaning. If there is an overlying organic layer and a suitable vehicle for transport of a copper-rich solution, then a malachite pseudomorph (MPS) may occur stratigraphically above the surface of the plate. In turn, stalactitic growths of malachite (MST) may form atop the MPS. This general sequence of copper mineralization occurs on every item-side formally examined. The introduction of greater complexity resulting from layering of organics and foils (as is the case on C026B) is explained by the increase in stratigraphy and surface area offered by the layers. Even with its greater complexity of layers, C026B follows the general sequence of formation.

Plate B050 is the only piece that may diverge somewhat in this model. The sequence of mineralization was impossible to determine because of the complexity of the surface. The surface was both uneven in places and the layering that was present did not extend far enough to determine the relationship of the layers to each other). This plate had a complexity not exhibited by any of the others.

Commentary on Artistic Processes by Christopher Carr

The mineralogical studies made by Jeff Nicoll indicate that, for the 32 sides of copper breastplates, celts, and headplates examined fully or in part, only one case unequivocally evidences painting as the method by which artistic imagery was created. This is B031 side A, from the Seip site. A yellow pigment of probably bone and carbonate was applied to this specimen. That the material is a pigment was concluded by six macroscopic characteristics: its homogeneous, very fine grain; its lack of chemical interaction with the underlying copper, leading to it flaking off without leaving any physical trace; its unnaturally flat top; the shrinkage cracks within it; possible drying lines within it; and its constraint to well-defined areas with sharp borders. The bone and carbonate composition of the paint was concluded by electron microprobe assays made by Carr and Mitchell (1997). In addition, the yellow pigment was concluded by Nicoll, with certainty, to have predated most or all of the corrosion mineralization that occurred on the plate, i.e., it is old and can be attributed to a Hopewell artisan.

B031 also bears a white serpentine or talc was also applied intentionally to this artifact, but whether as a paint or powder is unclear.

There are three additional item-sides that have yellow to yellow green surface materials that resemble the yellow pigment on B031 in their color, chemical composition

as determined by electron microprobe, and microscopic characteristics. These items are B052A, B053A, and C023A. The yellow-green surface materials on all four item sides are predominated elementally by copper, phosphorus, and calcium, in that order of atomic percentage. In addition, B031, B052A, and C023A also share magnesium as their next most common element. The elemental spectrum of the yellow-green material on the surfaces of the four items was not like any of the other spectra derived for surface materials of other colors found on ten copper breastplate, headplate, and celt sides that were sampled. Microscopically, the samples of yellow to yellow-green surface materials that were taken from the four items all were very fine-grained ($\leq 10 \mu\text{m}$) and granular in texture, as determined by Hoffman (1998). Finally, C023A also had a powdery, blood-red surface material which was identified as hematite by electron microprobe analysis (Carr and Mitchell 1997). Its distribution is well bounded, limited to the edge of the celt, suggesting that it was applied. However, it is unknown whether it was applied as a paint or a powder.

The chemical and physical similarity of the yellow-green surface materials on B052A, B053A, and C023A to those on B031A suggest that they all are the same pigment. They may all have been applied by painting, with the paint surfaces on B052A, B053A, and C023A having been degraded by weathering. Alternatively, the pigment on B052A, B053A, and C023A may have been applied as a powder. The co-occurrence of the yellow-green surface material on C023A with a red hematite pigment reinforces the inference that the yellow-green surface material on this item-side is a pigment.

The electron microprobe and microscopic observations made on B052A, B053A, and C023A by Mitchell, Hoffman, and Carr should be given priority over the macroscopic observations of them made by Jeff Nicoll in identifying the nature of the yellow-green surface materials. The former methods are more precise means for identifying material type. In addition, B052A and B053A were very hard for Nicoll to examine macroscopically because they were covered with a varnish of a kind.

The remainder of the items examined by Nicoll strongly suggest that imagery, where present, was produced through a process of copper patination, as is done in contemporary copper working. Several kinds of observations support this inference.

(1) Almost all of the inorganic materials identified on the artifacts are copper or copper corrosion products. The corrosion products have natural growth patterns that are linked directly or indirectly to the copper substrate, as one would expect in patination. The exceptions to this generalization are occurrences of bone which apparently derived from the cremation process, mother-of-pearl which in at least one instance (B052 side A) was a part of an artistic composition, and calcite and aragonite.

The most likely source of the calcium which comprises the calcite and aragonite surface materials is the soil itself, rather than culturally introduced materials. Most of the bedrock throughout the Midwest and the Scioto Hopewell culture area consists of carbonates or calcareous sedimentary rocks. The glacial tills found in the area derive much of their content from this material. Thus, groundwater and local soils can contain

large amounts of Ca^{2+} released during the weathering of the bedrock or till. The concentrations of calcium derived from weathering should be orders of magnitude greater than any released from ashes of cremation or cremated bone placed nearby or on top of some copper items.

(2) No evidence was found for particular kinds of copper corrosion having originated unintentionally through growth under paints of different kinds. Nor was copper corrosion growing through paints or pushing paints off an artifact (except in the case of B031 side A) observed. The development of copper corrosion of diverse kinds in response to the kinds of paints applied to an artifact is an alternative explanation of imagery production that apparently can be set aside.

(3) Very significantly, where soil remained on an artifact, corrosion was seldom observed penetrating the soil. This situation implies, particularly for objects with well-developed corrosion products, that the corrosion formed before burial in soil. One can expect that corrosion developing on a buried copper artifact would have grown into the covering porous soil, which was a passage for the corrosive water-electrolyte, much as corrosion was observed frequently here to have grown into coverings of porous organics (hide, bark), which likewise served as passages for the water-electrolyte. In fact, on occasion, the phenomenon of corrosion penetrating soil was observed (C015A, C027B, H002A and H002B).

In an experiment by D. Pimentel and C. Carr (Chapter 6), when soil wetted with an acid-salt solution was applied to copper plates to induce corrosion, the soil was typically hard if impossible to remove in its entirety from the plates because the corrosion had grown into the soil. This effect occurred in only 3 weeks of development time, using very mild acids (e.g., apple vinegar). Had corrosion of the Hopewell artifacts studied here formed primarily in a soil-burial environment, rather than largely through a patination method before burial, more cases of corrosion growing into and fixing with soil should have been observed.

(4) Half of the copper breastplates, celts, and headplates surveyed by Wimberley and Wymer (Part IV of this report) have remains of textiles on them, and additional copper items have bark or other adsorptive organic materials on them. Soaking an organic with a salt-acid mixture and applying it to a copper artwork is a modern method for developing patinas, and may be indicated by the presence of organics on the studied Hopewell artifacts. In cases where the organics still remain on the artifacts, the patinas may have been produced unintentionally or intentionally. It is possible in these cases that the artistic rendering that was desired by Hopewell artists was a cut-out made of organics, rather than any patina that might develop under it. The patina would have developed after burial, unintentionally. Alternatively, in cases where organics still remain on an artifact, patination by putting an acid-salt solution on an applied organic material cut-out, as well as the organic cut-out, itself, may have been desired. In non-Western artistry, some aspects of an artwork may not be meant for display (e.g., a hidden patina). The work of Heather Lechtman (1975) on Peruvian metallurgy is most a well known example of this artistic strategy.

(5) Six item-sides, or 32% of the sample of 19 item-sides studied here, have mesa-like corrosion growth habits that suggest the formation of corrosion underneath a growth-limiting boundary of a kind, or meniscus phenomena that suggest corrosion next to a liquid-wicking material. B050A, B050B and B025A (in decreasing abundance) have the mesa-like structures. B050A is by far the best example, having mesa-like structures with the widest distribution and the highest relief. B020A, B020B and B031A have meniscus patterns of growth of malachite. On B020, the malachite forms along edges of strips of hide(?) and on B031A along the curved strip cut out within which the pigment occurs. All of these cases, except perhaps B031A, may indicate the placement of a material at large or a cut-out, soaked with a corrosive acid-salt solution, on the artifact by a Hopewell artisan in order to induce a patina, followed by removal of the material by the artisan or historically during cleaning. B031A possibly evidences the pigment as the liquid-wicking material rather than the more common textile or hide covering.

(6) The diversity copper corrosion products found on the single sides of some artifacts is not what one would expect from chemical equilibrium relations. This point is discussed in detail in Chapter 3, by Colwell.

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Insert Tables 2.1 - 2.5 here

CHAPTER 3

**QUANTITATIVE MODELING OF CORROSION PROCESSES
ON COPPER ARTIFACTS, AND
ASSESSMENT OF THE RELATIVE AGE OF BREAKAGE OF COPPER
ARTIFACTS**

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Statement of Research Goals and Research Questions

This component of the project had two major goals. First was to evaluate theoretically and quantitatively whether the varieties of copper corrosion products found on individual headplates, breastplates, celts, earspools, and other copper items of the Ohio Hopewell were likely the result of fully natural, random, in situ corrosion or, instead, the product of some kind of intentional, cultural, artistic activity (e.g., painting, patination). The second aim was to assess whether the broken edges of some copper breastplates were relatively modern or ancient in age, in order to determine whether the artifacts may have been decommissioned by breaking them into culturally prescribed forms found elsewhere in Hopewell art. This report is divided into two sections that address these two issues.

Corrosion on the Copper Artifacts

The general problem of the natural or cultural origin of the copper corrosion minerals on the artifacts was approached with the following specific questions in mind:

- (1) Under what soil conditions (pH, free energy, temperature, dissolved ionic species) are corrosion products of various mineral species formed?
- (2) Are any of the kinds of copper corrosion products on the artifacts different enough in the conditions under which they form that they would not likely have developed together naturally, even though they might in actuality be found together on the copper artifacts?
- (3) What is the length of time required to form the various kinds of copper corrosion products found on the artifacts, assuming common soil conditions in the Scioto valley of Ohio? Could copper corrosion minerals be culturally induced to form (e.g., as in patination) in a short amount of time that could represent a single artistic venture (a few days to months), or a staged venture within a charnel burial house (months to years)?

(4) Are there scenarios that can be envisioned whereby simple, naturally occurring substances (i.e., natural salts and acids) readily available to the Hopewell might have been used to intentionally create corrosion products to make artistic imagery, perhaps with the aid of heat, water, and/or some other accelerating method?

Corrosion Products on Copper Buried in Soils

The corrosion of copper in soil is a complex interplay among many variables. Corrosion is an electrochemical process that requires an electrolyte, i.e., water, to be present in at least minimal amounts to provide some conductivity within the soil. The corrosivity of a soil is a function of its water content, but also the local mineral content and the dissociation of those compounds into cationic and anionic species. Given the variability of the water content of a Midwestern soil throughout the year as a function of season, the corrosion rate of buried artifacts is a process that is not continuous and in fact varies over time.

The development and stability of corrosion products on copper thus depends on many local environmental variables: e.g., pH, the composition of dissolved ionic species, temperature, and time-of-wetness, to name just a few. Notwithstanding the expected variation over time in the macro-environment that is present over an entire copper artifact in relation to general soil composition and soil water conditions, there may also be variation in the micro-environment across the surface of the artifact. This variation may result from materials (e.g., textiles, feathers, hide, paints) that were intentionally fixed to the artifacts, or that were fortuitously in contact with them, or that were in the native soil but different significantly in chemistry from the surrounding soil. Such materials may hold water differently than the surrounding soil, allow dissolution of ionic species that would contribute to local chemical or electrochemical processes, or may themselves participate in reactions on the surface of the copper.

Corrosion behavior is comprised of two factors: (1) the compounds, if any, that form and (2) the rate of that formation. The rate of formation of those compounds on the sample of artifacts of concern would be very hard to predict, given probable variations in environmental conditions over long exposure time. However, the kinds of copper compounds that might be expected to develop can be evaluated using thermodynamics.

Quantitative Modeling

Thermodynamics can be used to show what compound, metal, or cation of a metal, is stable under what defined set of conditions. One method of visualizing this aspect of the corrosion behavior of metals was pioneered by Pourbaix. The method uses graphical representations, which are called Pourbaix Diagrams today. For our purposes, the copper-water diagram at 25 C° is of most importance and is shown in Figure 1. The sloped dotted lines in Figure 1 represent the zone where water is stable, which bounds the potential for this case. At potentials lower than the bottom dotted line, water decomposes, generating hydrogen. Above the upper dotted line, water decomposes to

generate oxygen. As can be seen, the diagram maps the range of pH and free energy (as potential, E) where copper metal and copper corrosion products are stable.

Diagrams such as these are constructed purely from Gibbs free energy data and represent the expected compounds *at equilibrium* under those conditions. Thus, the formation of specific compounds will occur only under the specific mapped conditions of pH, potential, and temperature. There are computerized techniques today that can be used to extend the Pourbaix format to multiple components, but only if data from the additional compounds that might form are available.

An important distinction to be made from the diagrams is that only one compound can be stable in one zone. Two compounds can coexist only along lines between the stable phase fields, which is not very likely if they form as corrosion products, given the requirement that the conditions remain constant at that very specific pH and/or electrical potential. For both adjacent compounds to be in equilibrium, excess quantity of each must be present to allow for buffering the aqueous phase and fixing the pH, for example. This could occur practically only by the addition of both compounds intentionally, because it is likely that soil conditions would not be so highly variable over small distances, and even small variations would be averaged as the soil components dissolved in water on the surface of the artifact during corrosion.

A suite of Pourbaix diagrams was constructed for the addition of multiple species to water in order to determine whether specific compounds might have formed on the artifacts as a result of corrosion. These are provided in Figures 2 through 9. The Cu-H₂O diagram baseline case shows that for near-neutral pH's of soils (between 7 and 7.5 at the Hopewell site, for instance), copper metal, or either one of the two oxides of copper can be stable, depending on the oxidizing power of the water phase. However, the potential can be assumed to be higher than the Cu/Cu₂O dividing line because bright, uncorroded copper metal (Cu) is not found on the surfaces of artifacts within Ohio Hopewell archaeological sites. Cu₂O is found, instead. Furthermore, oxides are in general very stable thermodynamically, and more so than other compounds. Thus, when adding additional components to calculate new diagrams, it is not surprising to see the oxides of copper still to be the dominant stable phase in the range of pH of archaeological interest.

One exception to the formation of copper oxides is when carbon, which forms carbonates, is added to the chemical system (Figure 10). In this case, malachite (CuCO₃)(OH)₂ is the thermodynamically favored phase in addition to Cu₂O. Indeed, malachite and cuprite are the two most common corrosion products found on the surfaces of Hopewell copper artifacts (see Part I). Note, however, that these phases are predicted from thermodynamics to coexist at only a very specific potential at a very specific pH, which is statistically unlikely.¹

The importance of these types of diagrams is very significant to the interpretation of the compounds found and identified on the Hopewellian plates. As stated previously, each zone on the diagram shows a zone of thermodynamic stability of a single compound. In the case of a corrosion reaction, for example, copper metal would form either a single oxide or sulfide or carbonate of copper, depending upon the potential and

pH. Consequently, if one or more compounds are found in the same location on a copper plate, it is not likely that they resulted from naturally occurring and random corrosion reactions. Other formation processes, such as painting with multiple copper corrosion pigments, or artistic patination, would be suggested. If corrosion had indeed caused the formation and distribution of those different minerals, then it would indicate radically different environmental conditions in very close proximity on the surface of the plate. This situation is highly improbable in nature.

One might postulate that another plausible hypothesis for natural occurrence of adjacent compounds on one plate: that environmental conditions changed over time and allowed different equilibrium phases to form in close proximity. However, had this occurred, with for example an initially stable oxide condition then altered to a carbonate-stable condition, then the oxide would become unstable and would be converted to carbonate at equilibrium, thus leading to a single phase after some period of time.

In summary, by using thermodynamic arguments, it has been shown that random corrosion processes is not a reasonable explanation for the observed diversity of copper compounds on the Ohio Hopewellian artifacts. A reasonable explanation of the diversity is that specific minerals were added at specific locations to generate the artistic imagery, i.e., paints. Another possibility is that local micro-environments on a plate were intentionally changed to create the imagery using readily available chemicals, or materials that had the same effect, i.e., artistic patination.

Independent experiments have been conducted by Christopher Carr and David Pimentel at Arizona State University on bare copper to test the hypothesis that “forced corrosion” (i.e., patination) could have been used to alter the copper plates and form a diversity of specific corrosion compounds, thus creating the imagery. The results of that investigation answer to the positive, and will be discussed elsewhere.

Broken Edges of Copper Artifacts

Several dozen breastplates and headplates from Ohio Hopewell sites have broken edges that occur in repeated patterns. To C. Carr, the items appear to have been broken deliberately, in the course of decommissioning them, into culturally prescribed forms – especially human heads with headdresses and various animal forms of kinds that also appear to have been painted or patinated on such copper items. In addition, according to Carr, the forms are repeated among the shapes of many Ohio Hopewell mica mirrors found within Mound 25 at the Hopewell site and curated at the Chicago Field Museum of Natural History.

In order to determine whether the hypothesis of intentional prehistoric breakage is true, or whether alternatively the breaks were recent and fortuitously matched known artistic patterns, twenty copper artifacts that had broken edges and that appeared to represent culturally prescribed forms were examined. The sample included sixteen breastplates and four headplates (Table 3.1). The surfaces, edges, and internal fractures of the plates were examined using low power microscopy (about 10-20X).

Twenty artifacts were examined and, for the most part, the fracture edges were judged to be corroded. Some fresh, i.e., modern, fractures were seen (indicated by bright uncorroded copper), but primarily in small locations or corners where pieces of the object had undoubtedly been broken during the archival of the objects. There were also several cracks observed that have not fractured through, but were clearly “old”. The old and new cracks and fractures have been noted in the figures on file at Arizona State University with the PI.

The corrosion products identified by this visual examination of the edges of the artifacts were cuprite and malachite. In most cases these were mixed along the edges, but generally in zones where either one or the other was predominant. Referring back to Figure 10, it can be seen that these two compounds would be the ones expected under long term exposure to near neutral pH water if carbonates were the dominant soil species.²

The fact that only malachite and cuprite were seen on the fracture edges indicates the very strong likelihood that the edges corroded in the soil according to the expected thermodynamics, and that the edges were fabricated to specific artistic shapes prior to burial of the artifacts.

Endnotes

¹A second minor exception to when two corrosion products may coexist in equilibrium adjacent to each other is when sulfur is added to the system. Then, the CuS and Cu₂S phases do appear together over a very narrow range of potential within the pH range between 7 and 7.5 (Figures 2 - 9). This case is not especially significant to the case of Ohio Hopewell artifacts, because copper sulfides were not identified on their surfaces (see Part I by Nicholl).

²In addition, from the Pourbaix diagram in Figure 10, one would not expect pure copper metal to ever co-exist with malachite under natural conditions. In other words, malachite does not form directly on the surface of copper, because the diagram shows that there are no conditions where copper and malachite are in equilibrium. Instead, as copper is converted to malachite, there will always be at least a thin layer of Cu₂O between the uncorroded copper and malachite. There was one plate in particular, B060, where an edge fracture could be seen that confirmed this. An oblique view of the edge showed malachite on the surfaces above and below the copper plate, but with cuprite between the copper plate and malachite. Other examples of this stratigraphic relationship are given by Nicoll in Part I.

Insert Figures 3.1 - 3.10 and Table 3.1 here

CHAPTER 4

ORGANIC MATERIALS ANALYSIS

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Statement of Research Goals and Questions

This component of the research project had three major goals: (1) to establish visual criteria for identifying kinds of materials that are found on Ohio Hopewellian copper artifacts, (2) to identify and map the distribution of those materials on a sample of such artifacts, and (3) to begin to posit the kinds of formation processes – purposeful or otherwise – by which the materials came to reside on the artifacts. The last using correlations among materials of different kinds, materials and artifact classes, materials and sites, and the distribution of materials on opposite sides of the artifacts. The following questions were asked to address these three major areas of study:

General Methodological Questions:

- A. What visual criteria were found useful for identifying each of the kinds of materials found on the copper artifacts studied? At what magnification?
- B. What materials are most likely to be confused for each other when making their identifications, and why, for the corpus examined?

Corpus-Specific, Descriptive Questions:

- C. What kinds of organic materials occur on copper items?
- D. How commonly do these organic materials occur on copper items?
- E. Do sites vary in the commonality with which organic materials of various kinds are present on their copper items?
- F. Do artifact classes of different kinds vary in the kinds of organic materials present on them, considering all sites? Considering individual sites?
- G. Which organic materials of different kinds tend to occur together commonly on the same item-side, and which do not?

- H. Which organic materials of different kinds tend to occur on opposite sides of the same item.
- I. Do organic materials ever occur with cremation materials, on the same side or on opposite sides?
- J. Do any organic materials tend to occur on both sides of an item? Do any tend to occur on only one side?
- K. Other patterns?

Questions on Formation Process:

- L. Do any materials point toward certain formation processes (cultural or natural) having occurred?
- M. Do any of the patterns found in answering Questions E - K point toward certain formation processes (cultural or natural) having occurred?

Samples Selected, Criteria for Selection

A total of 77 copper objects archived in the Ohio Historical Society collections were selected for study (Table 4.1, see also Table 5.2). The selection process was begun by examining Canon color prints of nearly all breastplates, celts, and headplates in the Society. The prints had been made by Carr, from color Ektachrome slides and high-resolution digital photographs between 1994 and 2000. Items that potentially had various categories of materials, such as hide, bark, feathers, plant masses, bone, and textiles, were recorded. The items were then prioritized for direct visual examination according to the following criteria: (1) the presence of substantial pieces of each of the kinds of materials thought to occur on the items; (2) the potential of the item for bearing artistic imagery, as assessed by Carr.

Within the time limits of the project, 59 copper breastplates, 14 copper celts, and 4 copper headdresses were examined (Table 4.2). The larger number of breastplates reflects both the greater quantity of these artifacts in the archived collections and their greater tendency to have retained organic materials in a fairly good state of preservation.

Seven sites are represented in the analysis (Table 4.2). These exemplifying prominent Hopewell sites with large collections of copper artifacts (Seip, Hopewell) as well as sites with smaller numbers of archived artifacts (Edwin Harness Mound of the Liberty Earthworks, Ater, Fortney, Fort Ancient, and Rockhold). Both Seip and Hopewell are fairly well-represented, with many examples of breastplates and celts; the Hopewell site includes three headdresses as well. Collections from the other sites include primarily breastplates; Fortney did have one celt.

Analytical Techniques

The detailed examination of the copper artifacts followed a specific format created for this project. The procedures were adapted from and improved upon a pilot

study undertaken during the summer of 1999 in Chillicothe Ohio at the Ross County Historical Society and the Hopewell Culture National Historical Park. The search for organic materials preserved on the copper artifacts consisted of carefully scanning the surface of each side with the aid of a stereobinocular microscope with magnifications ranging from 7x to 30x -- the standard "tool" of paleoethnobotanical research. The scan usually followed a set pattern where I would begin at the upper right edge/corner of the artifact and slowly move the piece to the right until the entire upper edge had been examined; the next pass, moving from left to right, included an overlap of the field of vision of the first transect to ensure that nothing was missed. I continued in this pattern of overlapping transects until the entire side had been viewed. Once the entire side had been inspected and notes made (see below), select areas that revealed complicated layers of materials, unusual substances, or particularly well-preserved fragments were re-examined in detail. Each side was treated independently and forms and notes were kept by object-side.

The location and identification of materials was facilitated by the use of transparencies that were marked in a grid layout of one centimeter squares that was placed on top of Canon color prints of photographs of each side of each object, when available. The outline of the object, such as the edges of a breastplate, was marked on the transparency with black permanent marker pen and the object catalog number and side number were also identified on the transparency. Materials identified on the object with the microscope were then directly outlined and drawn on the transparency along with written comments. An assortment of different colored marker pens were used, with commonly encountered materials represented by selected colors (e.g., the outline of hide marked in orange ink, plant textiles in purple, and wood charcoal and other macrobotanical specimens in red ink). Thus, this method created an immediate visual impact of the type, location, and nature of the preserved organic materials still extant on the surface of the copper. In addition, the use of a grid system on the transparency allowed for precise locations of materials or items (or edges/boundaries of substances) in the hand-written or typed notes for each object-side.

An extensive five-page form (Appendix 4.1) was used to ensure that uniform and accurate notes were kept for each object side. The forms included requests for objective data, such as a series of checklists recording the presence of specific organic categories (e.g., hide/leather, plant textiles, feathers, fur, and others). Subjective data, which may be some of the more important descriptions of the material, included extensive and detailed notes and impressions indicated on the last page of the form.

Ten copper objects were simply "scanned". By this I mean that, due to time constraints, the individual sides of the objects were more rapidly assessed. This was often done with objects that a preliminary visual examination suggested may not have much organic material remaining. Broad comments and forms were also kept on these objects and I am fairly confident the materials identified on these artifacts accurately reflect what is still extant on their surfaces. Also, several specimens could only be assessed for a single side. For example, one breastplate (specimen B010 - side 2) had been historically glued to a wooden back and thus only the visible side could be analyzed.

Typically, I first assessed and described the organic materials on each artifact and then would pass the object on to the project textile expert, Dr. Virginia Wimberly, if traces of textiles were present. The partnership of a paleoethnobotanist and textile analyst proved to be extremely advantageous. I believe that our assessments of the objects were strengthened by the interaction and discussion while reviewing the same artifacts at the same time.

A wide variety of organic materials were surprisingly still present on the copper artifacts and the first phase of my research consisted of developing macro and micro level characteristics useful for materials identification (Appendix 4.2). Some materials, such as hide and bark, revealed surprisingly similar attributes at first glance; however, closer micro-level examination along with an increasing familiarity with the materials as the project progressed, produced consistent and distinctive criteria that could be used to identify and differentiate among the materials (Appendix 4.2). Identification was especially hindered in some cases by the degree of copper corrosion replacement of organic materials - some substances, such as feathers and hide, seem to more readily uptake and absorb corrosion products thus obscuring macro and cell structure. Other substances, such as wood charcoal, seemed little affected by corrosion by-products. However, increasing experience and the development of a comparative collection geared specifically towards the project greatly facilitated the identification of materials on the copper surfaces.

Materials Identified

All artifact classes exhibited traces of preserved organic substances. In fact, virtually every object analyzed in this project produced at least some residue of organic material. Breastplates, however, revealed the greatest quantity and diversity of identifiable materials. The substances on celts and headdresses reflected what was identified on the breastplates; the only item not observed on the breastplates that was unique to the celt artifact class included a single specimen of a small copper bead adhering to a celt from the Hopewell site (Specimen C020).

One difficulty in discussing the materials on the copper artifacts examined is the sheer diversity of the materials. To deal with this, I have grouped the substances into twelve basic categories; (1) textiles; (2) feathers; (3) leather/hide; (4) hair/fur; (5) hide/bark?; (6), macrobotanical remains; (7) bone; (8) pearls; (9) beads other than pearl; (10) prehistoric pigments; (11) historic repair materials, e.g., glue; and (12) unidentified organic. I will first discuss the nature of the materials in these categories and then follow with a review of the pattern of their occurrence by artifact type and site locality. I will begin with the materials found on breastplates, since they had the greatest diversity of materials, and proceed to celts and headplates.

Breastplates

Tables 4.3 and 4.4, and Figures 4.1 and 4.2 summarize the data to be presented here. Raw data for breastplates are given in Appendix 4.3.

Textiles. Textiles include materials that exhibit traces of an intact strand or yarn pattern, such as the presence of interlocking strands, often with active and passive components ("woven"). This included frequent examples of a beautiful finely-woven plant textile composed of the yarns from Group 1 fibers – herbaceous plants such as Indian hemp or milkweed, for example. These specimens were often well-preserved, retaining a golden hue, and a closely-spaced well-constructed woven pattern (e.g., B039B from Seip and B070 from Hopewell are good examples; see Part IV, Wimberly's textile report, for further description). This class of organics was the most common material identified during the analysis and a significant number of breastplate specimens incorporated large well-preserved fragments on their surfaces. It seemed apparent during the scan and analysis that some of the breastplates had been entirely covered (sometimes on both sides) with this material. As seen below, the Group 1 textiles were often found in association with other materials and, in fact, may have functioned in some cases as the backing for the attachment of other items (see below).

Another common surface material were textile fragments created by interlacing fur. Strands of fur had been worked together in a simple braiding or interlacing pattern. In some cases, residue of eroded hide was associated with the fur; perhaps the textiles were made from fine strips of fur with the hide still attached, or the interlaced fur textile had been sewn onto a backing of hide (e.g., Specimens B034, B036, and B044 from Seip). The second possibility may be the case in at least one occurrence (Specimen B036 from Seip). In this case, I observed in a small well-preserved section of the interlaced fur textile Group 1 plant yarns looped over and around individual segments of the interlaced fur strands that seemed to be attached to hide. Some examples of the interlaced fur may have been attached to a Group 1 plant textile as well (e.g., B027; B039A; B062). Also, at least one breastplate had interlaced fur on top of a felted bark textile (e.g., B034). The majority of the interlaced fur specimens – for those pieces that had not severely absorbed copper corrosion – were a fine light-colored fur, which may be rabbit (e.g., B039A; B044; B067). Some specimens exhibited a longer coarser more golden-colored/reddish strands which may be fox (e.g., B007; B027; B067; C026), and others a dark-colored fur that could very well represent bear (e.g., B067; B079). It will take analysis by a fur identification specialist to verify the taxa represented by the various hair/furs. I do believe that at the least three different types (and probably more) of fur/hair are extant on the copper objects.

The other examples placed in my textile category loosely match the traditional use of the term "textile". For example, two different types of "bark textile" (for want of a more appropriate term) were noted on the breastplates. First, several examples of what appeared to be thin strips of a pliable bark that had been interwoven were noted (e.g., Specimen B079). Secondly, some specimens revealed a "felted" bark – a soft, pliable bark that had been pounded into a substance best analogous to felt (e.g., Specimens B004, B010, and possibly B018).

Other examples not traditionally demarcated as textiles were also included in this broad category. This includes one example (e.g., B048) of a fairly intact plant matting.

The mat fragment was perhaps made out of a long, linear grass leaf – some pieces verified as cane, and others possibly cattail, *Typha* – interlaced in a under-over pattern. Isolated or non-patterned twisted plant yarns, and unidentified processed plant strands were also observed.

Feathers. Another common substance identified on the breastplate specimens were bird feathers. At least 15 breastplate sides revealed confirmed identifications of this material. I do not have the expertise to identify the feathers to bird taxa and, in fact, since this material readily absorbed copper corrosion by-products it may be difficult for feather identification experts to ascertain the original species or genera. Minimally, I did note that both long 'sweeping' (mature?) feathers had been utilized (e.g., B026; B057) as well as down feather (e.g., B079) The longer intact feathers seemed to be the most common and included the shafts as well as the individual feather segments and possibly barbs. In most cases, it appeared that the entire surface of the breastplates were covered with feathers (e.g., Specimen B026) with no obvious complicated pattern discernable to the feathers nor hints of a formal backing. However, several breastplates did exhibit a general orientation of the feathers (e.g., B057; B070). In such cases, the shafts and feather segments, for example, were generally oriented in the same direction, often "starting" from one of the lengthwise edges of the plate and sweeping downward across the body of the plate. It should also be noted that one specimen (C011)) of a celt did produce what appeared to be pigmented short feathers in alternative bands that may have been originally backed to some material (see below). On some breastplate specimens, it was apparent that the feathers had formed part of a larger, more complicated item made out of diverse materials that had adhered to the plates and had thus been preserved (e.g., Specimen B079).

Leather/Hide. Specimens of napped and worked leather/hide were frequently encountered during the project analysis. The hide specimens included two versions: (1) the outer or "skin" side of leather (e.g., B007), and (2) the interior napped or "sueded" portion of hide (e.g., B007; B010; B079). Both types produced distinctive characteristics and could thus be discerned during analysis. For example, the interior suede specimens had unique fiber characteristics and, I suspect, probably were created from deer hide. Most of the extant examples appeared to be from the interior suede of hide rather than the outer worked skin area.

The "Leather Unidentifiable" category listed incorporates examples that were definitely leather/hide but which could not be differentiated between the interior or exterior portion. Finally, leather/hide eroded in a characteristic fashion, which left behind a distinctive rust-colored substance, and many other examples listed under the "Possible Leather" category, include heavily eroded examples in which identification to this particular material could not be absolutely definite. However, I believe that this material does indeed represent leather/hide. If confirmed, and possible examples of hide are included, then this material was extremely common on the breastplates.

The leather/hide specimens, like the various examples of the "Textile" category, seemed to represent a number of different uses of this material. First, several breastplates

had one or both sides completely (or nearly) covered with hide; they may represent objects that had been wrapped in the material or had been laid adjacent to the material, thus preserving this organic substance (e.g., Specimens B007 and B030). In some cases, some portion of the leather/hide had fur or hair still attached and may thus represent a fur item in contact with the copper artifact ((e.g., B005; B007; B063; see below). Second, some of the items with leather/hide may have the remnants of hide backing in which a textile (plant or interlaced fur) or other objects, such as pearls or bone beads, had originally been attached or sewn to the leather (e.g., C011; B044; B078). Finally, another common occurrence seemed to be leather/hide strips or segments that had been a component of a more complicated piece or item that had been in contact with the copper (e.g., B079).

Hair/Fur/Undifferentiated Fur. This category represents fur or hair (most likely animal fur) that was present but had not been worked into a textile. Thus, some of this material had been associated with hide specimens and were probably remnants of an animal fur object; some breastplates (see Specimen B005 for an example) had sides entirely covered with fur. Some breastplates had areas that seemed to simply be a low-density scatter of single or grouped strands still preserved on a few random or isolated locations on the surface (the "undifferentiated" group). These may represent either animal skin objects in which erosion and degradation have removed much of the original surface or that the breastplate had been in close proximity or contact with a fur object at some time. At least four of the fur examples exhibited the same reddish-brown color and may represent the same animal taxon (fox?).

Macrobotanical. Materials placed in the "Macrobotanical" category include a wide variety of distinctive plant masses or portions. Perhaps the most widespread of this group is the identification of wood charcoal adhering to the surfaces of many of the breastplates. A number of wood charcoal pieces are small, scattered flecks, but a goodly number of the breastplates exhibited masses of large (1 - 4 centimeters in size) fragments of wood charcoal (e.g. Specimens B004, B007, B005, B034). There was no obvious orientation to the large wood charcoal fragments and they did not seem to be part of any larger wooden object that may have burned. The large masses of wood charcoal were often associated with the presence of calcined (burned) bone and undoubtedly represent the placement of copper breastplates within a cremation. At least one case (Specimen B007) included human facial bones. I suspect that the breastplates with calcined bone had been placed in their final context after the initial crematory episode because the plates did not exhibit burning; in addition, other than the presence of wood charcoal and calcined bone, the other organic materials present (e.g., plant masses, flower masses, seeds) typically did not reveal any evidence of carbonization and burning).

Unfortunately, it was extremely difficult to ascertain the wood taxa from the charcoal specimens associated with the copper artifacts. In order to confirm wood identifications a fairly 'clean' cross-section, revealing the vessel structure and arrangement unique to different taxa, must be viewed and assessed. I was able to determine for a few fragments that walnut (*Juglans* sp.; B007), hickory (*Carya* sp.; B004;

B005), ash (*Fraxinus* sp.; B004; B005; and B042), oak - white group (*Quercus* sp.; B005 and B059), and possibly a conifer (pine??) had been used as a fuel source.

Bark (uncarbonized) also occurred fairly frequently on the breastplates. In these cases, the bark specimens typically appeared as random strips or fragments without any clear orientation or any evidence of purposeful modification (e.g., B004; B0010; B012; B056).

Seeds specimens usually occurred as isolated examples in low density on a number of breastplates. Unfortunately, they had been so readily absorbed copper corrosion that identification was difficult or impossible. The seeds and seed cases may have been incorporated into the copper from the surrounding sediment. At least rush (*Juncus*; B024; B031)), grass (Graminae - probably panic grass [*Panicum* sp.]; (e.g., B059)), and possibly ragweed (*Ambrosia* sp.; B059) were present. No obvious specimens from the Eastern Agricultural Complex were identified.

A rather unusual plant category included entire copper plate sides covered with masses of stem and leaf fragments. Many of the stems look to be from medium-sized grasses, and several grass florets were in fact identified. In one case a breastplate from Hopewell, Mound 25 , Burial 6 (Specimen B028) had one entire side completely covered with the preserved remains of thousands of small flowers (approximately 3 mm in size). The small flowers were multi-petaled and appeared to be on top of a disc that itself was lying upon the breastplate's surface. The inflorescences contained mature seeds still incorporated into the flower, revealing distinctive linear seeds, many still embedded in a honey-comb shape within their attachment site on the developing seed head (imagine a sunflower 'disc' on an extremely small scale). I am still trying to verify the taxon of the plant but, given the seeds and flower structure, my preliminary assessment is that the flowers are from one of the Compositae (Aster family). Given the apparent fresh state of the flowers upon their placement on the breastplate, and the maturation period of the seeds, it seems evident that at least this particular ritual or burial episode occurred in late summer or early fall. Unlike the seeds noted above that most likely represent accidental inclusion on breastplates, and certainly given the nature of this flower mass, it appears that this was a very deliberate and purposeful inclusion with the breastplate at its ultimate burial.

Six breastplates sides from the sites of Seip and Hopewell yielded fragments of large monocotyledon leaf segments. The majority of the specimens seem to represent remnants of split cane matting or isolated cane (or cattail) leaf fragments. At least one breastplate (Specimen B048 from the Hopewell site) – an unusual item with corner cutouts in the "classic", stylized raptor claw shape, had been apparently covered with a series of long monocotyledon leaves (cane? cattail?).

Bone. As mentioned above, a commonly occurring material on the breastplates was calcined bone. The bone fragments tended to range in size from as small as 2 mm. to several centimeters. The larger size range was more typical. The bone appeared to be scatters of material probably from cremation burial events. This seems likely when it is

noted that calcined bone was never found without accompanying specimens of wood charcoal. Intriguingly, several breastplates with calcined bone and wood charcoal on one side had Group 1 plant textiles on the opposite side or textiles mixed in with the bone and wood charcoal on the same side; yet in nearly all instances, the textiles were entirely uncharred (e.g., B001; B004; B006). This may indicate, that the breastplates became associated with the cremation remains after the firing of the bones, during a second, later ritual involving the deceased.

Pearls and Shell Beads A significant number of breastplates had specimens of entire and fragmented freshwater pearls – some charred and some unburned. Well-preserved specimens always revealed carefully drilled holes through the center of the pearl and many were of fairly large size (e.g., Specimens B006, B034, and B039b). Pearls seemed to have unique associations, appearing on breastplates that often had a more diverse array of materials. Four distinct patterns were noted: (1) pearls, sometimes surrounded by small circular fragments of hide, placed over the holes drilled in the breastplates (e.g., B024; B048; B079)); (2) charred and uncharred pearls often found mixed with calcined bone and wood charcoal (e.g., B039); (3) what had clearly once been strings of pearls that had lain upon the breastplate, sometimes occurring with bone and wood charcoal, and in some cases with the string still present inside some of the pearls (e.g., B006; B0039); and (4) pearls that appear to have been originally sewn onto Group 1 textiles or possibly hide (Specimens B006, B039B; B079). Lastly, a few specimens of cut, polished, and drilled shell beads were found on several breastplates from the site of Seip (e.g., B039B and B043).

Prehistoric Pigment For this category, I only included examples of traces of clear and obvious artificial pigments that could be differentiated from copper corrosion. Two of the interlaced fur textile specimens (Specimens B034 and B044) exhibited traces of a definite pigment painted on the surface of the textile. One included the colors of red and an olive green, and a second specimen (and possibly a third: B079) included the apparently same red pigment. In these cases, the red and green pigments had been applied as a solution or "wash" on top of the fur and the stratigraphy of the material substrate overlain by pigment was easily seen through the microscope. One breastplate (Specimen B031B) from Seip was quite unusual. It apparently had had a preserved portion of a painted fabric adhering to one side of the breastplate when it was originally excavated. The original fabric is now missing but traces of the fabric are still extant on the copper surface as well as the pigment; this included a complicated curvilinear design outlined in black pigment with the spaces painted with a bright yellow pigment on a Group 1 plant textile. On the other side of this specimen (B031A) was an unusual substance, cream in color, that looked like an applied liquid pigment.

Historic Repair Materials. Not surprisingly, a significant number of the breastplates exhibited traces of historic repair to them. Many of these repairs occurred at the more vulnerable thinner edges or corners of the artifacts. A variety of repair techniques and materials had been utilized during the curation histories of the copper artifacts, including green-pigmented wax, glues, tape, and new (sometimes artificially

patinated) copper replacement parts. Glues and wax seemed to be the predominant repair technique.

One interesting circumstance that future researchers need to be aware of is that several entire sides of particular breastplates (e.g., Specimen B059 from the Harness site) had been apparently covered with some form of historic cloth exhibiting a white, probably nylon, material that was then subsequently covered with plant and seed masses. At first glance, I mistook the masses as originally prehistoric in origin because they appeared to be virtually identical to the prehistoric plant and seed/flower masses noted on other breastplates. Their uniformity at first puzzled me and on closer examination I could see in eroded areas an underlying obviously historic textile underneath the plant/seed masses. The attribution to historic repair was confirmed when on one of the plates with this treatment (B059) I identified the presence of clover (*Trifolium repens*) – a plant introduced from Europe. I would be curious to find any information about this historic repair and reconstruction, given the intriguing similarity to the prehistoric plant masses identified on several of the breastplates.

Unidentified Organic A "catch-all" category used in paleoethnobotanical analysis is "unidentified organic". Here, this category includes material that has been so eroded or corroded by copper salts that no cell structure or definable characteristics are still extant.

Celts and Headdresses

Tables 4.5 and 4.6, and Figure 4.2 summarize the data to be presented here. Raw data for celts are given in Appendix 4.4 and raw data for headdresses are given in Appendix 4.5.

Overview. Overall, the same type of materials identified on the breastplates were also detected on the celts and headdresses analyzed under the domain of this project, albeit at a lower diversity (Figure 4.2). A number of distinctions do occur, however, and seem to reflect both the nature of the objects themselves as well as the excavation and/or curation histories of the artifacts. For example, it was readily apparent that materials were less well-preserved on the celts than the breastplates. There was a greater degree of copper corrosion on the celts, and this often obscured the identifying features of organic materials. Finally, a major difficulty with analyzing the headdress specimens is that after their removal from their archaeological contexts, they had been heavily repaired and cleaned. This was probably related to the intrinsic interest that this particular artifact class held for earlier curators and researchers, and occasionally to the crushing that had occurred to these complicated, three-dimensional artifacts.

Celts. Celts produced essentially the same type of textiles noted on the breastplates; both the rather ubiquitous Group 1 plant textiles and interlaced fur textiles were observed on celts like on breastplates (Figure 4.2). Feathers were also identified on two of the celts (three sides; C011 and C018) and included the unusual specimen noted above (see also below).

Specimen C011 is a large, heavy celt that has a complicated array of materials on one side (Side 1), and what appears to be the severely eroded remnant of a Group 1? textile on the opposite side (Side 2). The specimen was originally thought to have come from the site of Seip. However, the numbers 283/291-8 were observed written on the artifact, and if this accession number is correct, then the celt must be from the Hopewell site.

Material on Side 1 consisted of alternating bands of small feathers. A band that is dark in color is followed by a band of orange-colored feathers. These bands were oriented diagonally across the body of the celt. In areas that were eroded, a thin, dark "crispy" (for want of a better term) material was revealed, suggesting perhaps a thin skin-like substance or corrosion in contact with some organic substance. Finally, some of the regions on this side revealed the severely eroded presence of a textile, most likely a Group 1 plant textile similar to what was observed on Side 2. The processed strands of Group 1 yarns could be seen emerging from underneath certain sections of the feather layer; yet, in some areas, the textile seemed to be lying on top of the feather layer.

Some of the celts also yielded examples of preserved leather/hide fragments, including both interior napped or sueded remnants (e.g., C010) and exterior outer skin remnants (e.g., C10 and C026). Unfortunately, most of the hide readily absorbed corrosion, so anything beyond a basic notation of the presence of hide was nearly impossible. However, one celt (Specimen C022 from the Hopewell site) did produce a distinctive pattern of the material, which suggested that the non-bit end had been wrapped in the substance with the bit end relatively devoid of organic material.

Fragments of carbonized wood as well as uncharred bark segments were also fairly ubiquitous on the celt specimens. Cross-sections with a clear view of the vessel structure were not available for the wood charcoal so taxon identification was not feasible. Several celts (Specimens C013, C016; C022, and C023, and possibly C026) produced small areas of preserved large monocotyledon leaf/stem fragments. In at least one of the cases (Specimen C016), the material can be identified as similar to split cane matting fibers, while a second (C022) is most likely cane or possibly cattail. Thus, some of the celts may have lain upon, or been covered with, a cane matting or have been in contact with such a matting; some (such as C013) looks as if it had originally lain upon a grass matting or mass (see below).

One celt (Specimen C013) from Mound 17 of the Hopewell site had an unusual type and pattern of monocot stems and leaves. In this case, both sides were covered with a relatively thick and uniform layer of fragmented Graminae (grass) stems and leaves. These fragments were definitely not from a large grass such as cane and, in fact, a specimen of an unidentified grass seed was found embedded in the stem mass on both sides. At this point in time, the taxon represented by this grass mass is unidentified. Interestingly, the fragments exhibited a relative uniform length (a number of well-preserved specimens yielded measurements ranging from 1 to 1.5 mm. in length and around 0.5 mm. in width). It seemed clear that these segments were originally from

longer stems but did not reveal any evidence of cutting. Rather, they seemed to exhibit torn, broken, or crushed ends; the significance of this is unclear. One other celt (Specimen C026) also produced some small areas of a similar crushed plant mass on both sides. The masses included what may be some stem fragments. However, this material could not be definitively assigned to any botanical taxon.

Other than the Graminae seed noted above, all of the other seed specimens consisted of a few scattered, unidentifiable seed cases. They may represent fortuitous incorporation from surrounding sediment.

Finally, only a few of the celts yielded ornamental beads. One had a fragment of a pearl (Specimen C026). A celt from the Hopewell site (Specimen C020) produced a large number of unusual bead specimens. Both sides contained the jumbled remains of charred well-made, flat, thin, and drilled shell beads that are mixed with wood charcoal fragments. Bead diameters are around 3.5 mm., with a thickness of 1.5 mm. On Side 1, centrally located, is a very large unusual, "dumbbell" shaped, drilled bead that may be of charred shell material (35 mm. in length and 16 mm. in width). Adjacent to this bead are a series of large rectangular pieces that may be calcined bone but identification is problematical. Also, a highly-corroded copper fragment that appears to be a small bead lies next to the central bead.

Headdresses. Only four objects that are interpreted as "headdresses" were analyzed for the project. The assessment as headdresses is probably accurate, given their unusual shape (a distinctive subrectangular curved form) and the recovery of some of them from the skull region of extended burials. Three of the artifacts are from the Hopewell site and may be from burials from Mound 25, while the fourth headdress is from the Liberty site's Edwin Harness Mound. The most intact and well-preserved of the headdresses revealed a similar form: a rectangular, doubly curved shape (curved lengthwise and widthwise) with one or two holes drilled through the copper close to one of the long ends. It is most likely that the holes were utilized to attach the headpiece to a textile or other material, or to attach some other item to the copper.

Unfortunately, given the state of repair and cleaning of the pieces, most of the organic material has been removed. However, at least one of the headdresses (Specimen H011 - Hopewell, Mound 25, Burial 24?) exhibited clear traces of the sueded portion of hide on the exterior (concave) part of the artifact. The best preserved pieces of sueded hide are on the topmost (most concave exterior) portion of the piece. The other headdress from the Hopewell site (Specimen H014) also had severely eroded hide in the same location ("exterior" or concave area) as H011. The artifact from Harness (Specimen H001) had minute traces of hide on both interior and exterior surfaces. Intriguingly, Specimen H014 had a few strands of what appears to be long, dark hair near the larger central hole on the interior of the piece. I suspect that this is human hair. A similar material, either fur or hair, may occur on headpiece H003. Thus, it seems most likely that the copper headdresses were probably originally part of more complicated objects that included worked leather/hide.

Artifact Class Comparisons

One interesting assessment that can be conducted with the results of this analysis is a comparison of any similarities or distinctions that may occur in the presence of organic materials by artifact class. This evaluation must necessarily be limited to the breastplate and celt categories, given the small sample size for headdresses. For the purposes of comparison, I selected the most common material that were identified on these two kinds of artifacts: Group 1 plant textiles, interlaced fur textiles, feathers, leather/hide, non-textile bark, wood charcoal, and calcined bone. I also included pearls, which are found much less commonly on the objects (Figures 4.1 and 4.2).

Not surprisingly, the breastplates exhibited greater ubiquity for all material classes. The greatest differences between celts and breastplates appears for the Group 1 plant textiles, wood charcoal, and calcined bone. The wood charcoal and calcined bone distinctions may be due to the increased placement of breastplates with cremations, if this is indeed the context for the majority of the specimens of this artifact class. The increased prevalence of Group 1 textiles could reflect a ritual distinction between the celts and breastplates in the use of this type of textile, or may merely reflect differential preservation conditions. The flat, thinner form of the breastplates, for example, perhaps better preserved delicate fabric than did the rounded or sloped form of the celts. Leather/hide and feathers were identified nearly as frequently on celts as they were on breastplates. Whether these are significant patterns or merely fortuitous associations is impossible to assess at this time. Further research on a larger sample of celts, as well as breastplates, headdresses, and other copper objects, will be necessary.

Intrasite Comparisons

The only artifact class that had a large enough sample to compare and contrast the ubiquity of materials by site was breastplates (Figure 4.1). The three major sites that have significant numbers of archived breastplates – Seip, Hopewell, and Harness (Liberty) – were compared for the presence of ten different organic materials by plate side. I analyzed the percentage of breastplate sides that yielded Group 1 plant textiles, interlaced fur textiles, feathers, leather/hide, bark, wood charcoal, plant masses, monocotyledon leaves, calcined bone, and pearls. Some intriguing differences among the sites emerged.

Seip clearly produced the greatest percentage of items with Group 1 textiles, compared to either Hopewell or Harness. Interlaced fur textiles were more predominant for the Hopewell site, and were not identified in this sample of breastplates from the Harness site. My initial impression when reviewing the breastplates was that the Group 1 textiles were very similar in plant/yarn processing and weave among all three sites (see Chapter 5 by Wimberley). Feathers were fairly common on the breastplates from Harness, with nearly a third of the sides producing evidence for this organic material, and were much less common on the breastplates from Seip and Hopewell. Leather/hide fragments were fairly uniform in occurrence on the breastplates from all three sites, identified on approximately 20 to 28 percent of the sides. Uncarbonized bark specimens

were more ubiquitous for the Seip breastplates, and wood charcoal was also quite common on them. The Harness site also produced a significant percentage of wood charcoal by breastplate side. Plant masses ranged around 10 to 12 percent of the breastplate sides for all three sites. Monocot leaf fragments occur on only breastplates from the Hopewell and Seip sites. Finally, bone and pearls are more common on the breastplates from the Seip site and are either absent or in lower percentages for the other two sites.

In sum, the Seip site is significantly distinct in its breastplates, which have a greater ubiquity of Group 1 plant textiles, bark, wood charcoal, bone, and pearls. The Hopewell site produced the greatest ubiquity of leather/hide fragments and monocotyledon leaf fragments. The Harness Mound returned the highest percentage of feathers and a fairly good quantity of wood charcoal as well. Overall, the breastplates from Seip produced the greatest diversity and quantity of the organic material identified during the scope of this current project, often with good preservation (Figure 4.1).

I would also note that the most common materials that appeared on the Seip and Hopewell breastplates – Group 1 textiles, interlaced fur, and leather/hide fragments – were also identified on the breastplates from the other project sites of Ater, Fortney, Fort Ancient, and Rockhold. The fabrics and items made out of these materials, especially the Group 1 plant and interlaced fur textiles, seemed quite similar in manufacture and ultimate appearance among all of the project sites.

Material Associations and Object Complexity

During the examination of the copper artifacts, it was readily apparent that they were a palimpsest of diverse substances and materials, and often these materials had a complex stratigraphy. For example, reviewing the breastplates from Seip alone, which produced the greatest variety of organics among the artifact classes and the project sites, it is evident that nearly every side of each breastplate produced a diversity of materials (Appendix 4.2). Of the 60 breastplate sides examined for this site, 52 (86.70%) yielded two or more distinct organic materials.

The most common association of materials on the breastplates from Seip, as well as on the plates from other sites, included Group 1 plant textiles that were often found on the same side with traces of leather/hide. It was not unusual, for example, to find plant textiles identified with fragments of hide, interlaced fur textiles, and plant yarns. Feathers were also typically found associated with faint traces of leather/hide. The same pattern occurs with celts - interlaced fur textiles or feathers are often found with traces of hide along with the presence of processed plant yarns. These associations may indicate the faintly preserved fragments of a once more elaborate item (cloak? garment? bag??) of two different types: (1) a finely interlaced or interbraided fur (in some cases, I suspect rabbit, bear, and possibly fox) that had been attached with plant yarns to a hide backing or Group 1 plant textile backing, and (2) feathers attached to hide or Group 1 plant textile backings. In several cases (e.g., B039A; B052; B027?), I could see processed plant yarns looped over and around individual fur strands apparently attaching the strands to either a

hide or plant textile backing. Furthermore, on at least one artifact (Specimen B030 and possibly B035), I observed a fine processed plant yarn looped over the quills of feathers that had apparently once been attached to a hide backing. Two breastplates from Seip (e.g., B034 and B044), as noted above, also exhibited at least red and green pigment painted on top of preserved segments of an interlaced fur textile so these objects must have also been vividly colored during their use-life.

The stratigraphy of the materials on the copper indicated that, for some of the artifacts, the sequence may have been copper, feathers or interlaced fur, plant yarns, and hide or Group 1 textile; in some cases, the sequence was virtually the reverse: copper, plant textile or hide, and feathers or interlaced fur. This pattern may indicate that, in some cases, the copper artifact may have lain upon the outer surface of a once complicated fur or feather textile, such that the fur or feathers were first embedded in the copper followed by the backing upon the fur strands or feather quills; in other cases, something had once wrapped the copper object, with the hide or plant backing against the copper surface and feathers or interlaced fur on the outside. Further research will, of course, need to be conducted to verify these possibilities, as well as alternative ideas. At the least, the nearly identical form of interlaced fur perhaps attached with plant yarns to a hide backing (or Group 1 backing) was found on artifacts from Seip, Hopewell, Harness, and Fortney, indicating some degree of similarity in the ritual of construction and in the ceremonial items among these sites.

Going one step further, there may be some deliberate association between animal fur and bird feather in the ceremonial realm for the Hopewell and this may be reflected in the organic materials associated on the copper artifacts examined for this project. Intriguingly, during the Summer 2000 pilot project for this larger study, I examined a well-made breastplate from the archived collection at the Mound City earthwork (Hopewell Culture National Historical Park). One side was entirely covered with what looked like a carefully cut and/or applied section of fur (bear?) and the opposite side was covered with feathers; in fact, it appeared to be a nearly complete wing (skin and feathers) of a larger bird sweeping across the entire side. (I suspect, given the overall shape and topography of the breastplate, that the fur side may have been the "presentation" or "front" of the piece).

The complexity of pieces, especially the breastplates, was in some cases nearly overwhelming. One specimen from Seip (B079) is a good example of the diverse nature of these artifacts and the frustration with viewing the eroded and faint traces of what must have been a complicated object at one point in time. Side 1 was covered with an interlaced 2-ply oblique bark textile (the inner bast fibers of a non-conifer bark) with possible traces of Group 1 plant textile yarns still extant in certain sections of the bark textile. Feathers were then found on top of this material. In the center of this side, on top of the bark textile and general feather layer, had been some object or addition to the plate made of hide. On top of the hide was a thick mass of larger and down feathers. The feathers are impressed with a irregular shape that hints of a heavier form that is no longer present and that had once been attached to or covered the feathers in the center.

Side 2 is equally perplexing. This side is covered with a short dark fur (bear?) that is oriented in a linear fashion on the plate, but is not an interlaced fur textile. Some areas of this side produced traces of an eroded napped hide that had been on top of the fur. In the center of this side was a thicker area of fur with an impression of a more complicated sequence of materials. The 'edges' of the central shape were bounded with thick, flexible segments of bark (not a textile). Hide was identified on top of the fur contained within the shape defined by the bark. Unidentified (and probably unidentifiable) organic materials were also associated with this central area, often adjacent to the bark "arc" shapes. Historic glue around the drilled holes, and the presence of large pearls in a plastic bag, suggest that possibly pearls may have covered the breastplate holes on this side (but this association is not clearly known at this time). Finally, like the breastplate from Mound City, there seems to be a pattern of feathers on one side and fur on the other of the breastplate.

Conclusion

Overall, the analysis for organic components preserved on the copper artifact classes of breastplates, celts, and headdresses reveals that nearly every item had some residue. Typically, it was more common to find a mix of several different materials on a single side than just a single substance. Breastplates had the greatest material diversity and the best preservation of materials of the three copper artifact classes. Some of the more common organic materials found on breastplates include: Group 1 plant textiles (with a similar form across all of the project sites), interlaced fur textiles, hide, feathers, pearls, wood charcoal and bark, and calcined bone. More unusual categories found on breastplates include grass, flower, and unidentifiable plant masses. The breastplates from Seip revealed some of the more complicated and best-preserved examples of organic items.

Celts tended to produce hide, feathers, and interlaced fur textiles as well as the same Group 1 plant textiles noted for the breastplates. Plant (grass) masses and monocotyledon leaf segments were also identified. Headdresses tended to be severely repaired and cleaned, historically, but all specimens did produce traces of the sueded portion of hide, and at least one may have preserved a few strands of human hair.

Many of the artifacts, especially the breastplates, preserved traces of what must have been originally complicated textiles or items. The identified combinations and stratigraphy suggests that some of the items may have been interlaced fur (sometimes painted) attached with plant yarns to a hide or Group 1 plant backing. To a lesser extent, bark; pearls and other objects may have also been attached to such textiles. Feather textiles may have also been used; some specimens suggest that these too may have been attached to a hide or plant fabric.

I believe that perhaps one of the most important results of the examination of the copper artifacts is the clear evidence for the preservation of diverse and complicated organic materials still extant on these archived collections. It seems apparent that this little investigated realm of Middle Woodland archaeology may offer remarkable insights

into the ceremonial sphere of the Hopewell. Perhaps, however, it is not surprising that this analysis reveals a microscopic world of artifacts that reflects the degree and depth of complexity that has made the Hopewell culture so fascinating to both professional archaeologists and the public alike.

Commentary on Artistic Processes **Christopher Carr**

A broad array of possible explanations for the observed occurrences and spatial distributions of organic materials on the surfaces of Hopewell copper artifacts is suggested when those observations are taken in the broad context of the other studies of surface minerals, corrosion processes, and textiles made within this project. The possible explanations minimally include:

(1) Cutouts of textiles, hide, fur, and/or feathers were applied and/or plant masses were laid down on copper artifacts in order to directly and intentionally form artistic compositions as collages. The images/designs that resulted are in both positive and negative formats;

(2) Cutouts of textiles, hide, fur, and/or feathers were applied and/or plant masses were laid down on copper artifacts in order to intentionally produce copper patinas of various colors, textures, and shapes as artistic compositions. Sometimes these compositions were completed and the organic materials aiding in the patination process were removed, or largely removed to the extent that the patinas did not grow into the materials. Other times, the organic materials were left in place and the artifacts were buried, allowing patination to continue after burial as an "extended ritual";

(3) Textiles, hide, fur, and/or feathers were applied and/or plant masses were laid down on copper artifacts – over all of the surface or part of it as a cutout – and then removed in specific places to produce an image in the positive or negative, much like in carving.

(4) Small flowers, seeds, broken up plant stems, pearls and/or shell beads were intentionally placed on the copper items as part of a burial ritual. Imagery may have been intentionally produced by this process or not;

(5) Cremation remains were intentionally placed along with organics of various kinds on top of breastplates, as part of a burial ritual. Imagery may have been intentionally produced by this process or not;

(6) Feathers were arranged over the entire surface of the copper items in order to directly and intentionally form artistic compositions;

(7) Textiles, hide, fur, feathers, and/or plant masses were intentionally layered on the copper items, as part of a burial ritual, but without the production of imagery;

(8) Copper artifacts with patina imagery were wrapped for burial in textiles, leather/hide, and/or textile or hide backings with attached feathers, followed sometimes by the differential preservation of these materials where they came in contact with different patinas. This could have led to the unintended formation of organics preserved in culturally-prescribed shapes.

(9) Copper artifacts with patina imagery were laid against clothing made of textiles, leather/hide, textile or hide backings with attached feathers, followed sometimes by the differential preservation of these materials where they came in contact with different patinas;

(10) Plain copper artifacts, without patina imagery, were wrapped for burial in textiles, leather/hide, and/or textile or hide backings with attached feathers;

(11) Plain copper artifacts without patina imagery were laid against clothing made of textiles, leather/hide, and/or textile or hide backings with attached feathers;

(12) Large expanses of hide or fur were placed over copper artifacts and subsequently painted to produce an image in the positive.

(13) Any of the above processes may have been combined with differential erosion of mineral and/or organic surface materials through differential cleaning during archiving.

It is probable that many if not all of these processes, sometimes in combination, played roles in forming the surface distribution of materials now seen on the copper artifacts, as a group, in the Ohio Historical Society. What remains to be done is to determine which particular processes took place on which particular specimens.

The following are, in my current understanding of the copper artifacts, some examples of some of the above hypothesized processes. The content of the imagery on each specimen listed below follows patterns (shapes and compositions) that are repeated on multiple copper items, in shaped mica mirrors, and in copper breastplates broken (decommissioned) into such forms.

Examples of cutouts of textiles forming an image in the positive, and involved in either process 1 or process 2, above, include B073B (head of a person with a bird beak nose and headdress), B053A (heads of a person in a cat headdress and a person with a bird beak nose-eye mask, facing each other), B070A (a person with a nonraptorial bird beak), B036B (bird or bird-human composite in flight), B040A (bird head and body), B032A (nonraptorial bird head, long neck, and raised wings), B029A (raptor head), and B023A (two human and/or animal impersonator heads facing each other).

Examples of cutouts of textiles forming an image in the negative, and involved in either process 1 or process 2, above, include B078B (eyes and mouth of a face cut into a

fabric background over the whole plate) and B046A (human face and probable man with bird nose, facing each other).

Cutouts of hide forming an image in the positive, and involved in either process 1 or process 2, are found on B030A (nonraptorial bird head and body, with partially opened wing mimicked by the shape of the plate), and B020B (top half of a human head with bird nose in 3/4 perspective). A cutout of hide forming an image in the positive and negative, and involved in process 1 or process 2, occurs on B044A (negative bear face with positive hide nose and background). A cutout of hide forming an image in the positive and negative, and involved in process 1, 2, or 3, is seen in H001A (top half of a human head). This cutout may have been produced either by laying down several concentric pieces of hide or by laying down one piece of hide and removing it in places. Both B030A and H001A have the same composition as two of the few painted copper breastplates, B031A and B080A.

An applique of fur, forming an image in the positive and negative, and involved in process 1 or 2, is found in B101B (animal impersonator head bearing a copper headplate with antlers).

A collage with a complex stratigraphy, forming an image in the positive, and illustrating process 1, is B079A (a raptor head of textile with an eye of hide on top of it).

The use of an organic material cutout to induce a patina image on a copper plate, exemplifying process 2, appears to be well illustrated by C023A (human head in profile with bird beak nose and headdress). The patina is a thick layer of malachite. The material used to produce the patina may have been an open weave textile.

A cutout of textile and feather forming an image in the positive and negative through process 3, is exemplified in B101A. This plate has a long-beaked bird head facing one way in the positive, made out of textile and feather, and a long-beaked bird head facing the other way, made by in the negative by the removal of textile and feather. Breastplate B042B has a raptor's head in positive and negative with its beak encompassing a human head in negative and positive. Both the application of textile and the removing of textile (i.e., process 3) were likely involved in producing this composition. B017 has a cutout of textile and some unknown material below it, forming an image in the positive (the left three-quarters of a human face bearing an antler headdress; processes 1 or 2) and may have negative elements within it that were removed intentionally (to produce facial features – a headplate, forehead, nose; process 3). In the case of B028, the entire plate appears to have been covered with hide and seeds, and then a positive image (a human in profile, shoulder up, wearing a headdress) was produced by removing the hide and seeds to create a background of copper.

A variety of materials were used in multiple, small pieces to form positive images on copper items, illustrating process 4. The materials include: seeds and seed coats on top of hide on B047A (human face in profile with headdress); stems torn or broken into similar lengths on B056B (whole human figure with bird head, carrying a spear, and a

bird – hummingbird? – in flight in three-quarter view); pearls in a line but not on a string, since they are separated from each other, on B052B (human head from maxilla upwards, in profile, with bead-lined headdress); and partial strings of shell beads arranged, as in B038A (human face in profile with tall headdress in the form of a bird's head; see original publication photograph of the plate for the entire bead pattern).

The application of feathers in an intentional arrangement over the entire surface of a copper item is illustrated in B070B (a human head in headdress and an animal head are nested, facing each other)

Large expanses of textiles placed over and hiding images created by patination, painting, or collage (processes 1 or 2) have been revealed in several instances by infrared photography or surficial evidence. B067B has feathers laid out in the image of the head of a human in profile and wearing a headdress. The face of the human, and two thirds of the breastplate, are covered with textile, but the face could be made out through infrared photography and image contrast-improvement techniques. B001B is entirely covered by textile, but very sharp changes in the surface topography of the textile indicate the head of a bird in profile, apparently made of materials with some thickness and below the textile.

Large expanses of hide placed over the entirety of a copper artifact and subsequently painted (process 12) are shown by B005A. The head of a raptor impersonator wearing a headdress is painted on the hide covering the plate.

Large expanses of hide and textile clothing that came to be preserved on a breastplate in which they were in contact (process 11) may be illustrated in by B034B. However, there is some possibility that the textile and hide were painted (process 12).

Of the multiple ways in which organic materials may have come to be present and preserved on Ohio Hopewellian copper breastplates, headplates, and celts, as listed above, none was common in the sense of pertaining to the majority of artifact-sides examined. Group 1 textiles have the highest frequency of occurrence of any organic material, but constitute only 35% of the item sides of breastplates and celts examined. Leather, bark, feathers, and fur are next most frequent in occurrence, in frequencies in the range of 7 - 25%. When one considers that the sample of item-sides selected for study was heavily biased toward those having organic remains, the frequency of any of the above, singular processes relative to the totality of Ohio Hopewell copper artifacts is accordingly further diminished. Thus, the majority of artistic compositions on copper breastplates, celts, and headplates archived at the Ohio Historical Society appear to have been produced by patination, followed by the removal of most or all of the organic materials used to facilitate development of the patinas.

Insert Tables 4.1 - 4.2, Figures 4.1 and 4.2, and Appendices 4.1 - 4.5 here.

CHAPTER 5

TEXTILE ANALYSIS

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Statement of Research Goal and Research Questions

This component of the research project had four goals: (1) to identify the occurrence or lack of occurrence of textiles on Ohio Hopewellian copper artifacts; (2) to map their distribution on such items; (3) to describe their various textile characteristics; (4) to determine how textiles came to occur on the artifacts.

The following questions were asked in order to address these three topics.

- (1) How commonly do textiles occur on copper items of all types, such as breastplates, headplates and celts?
- (2) Do sites vary in the commonality with which textiles occur on copper items of all kinds?
- (3) Do basic artifact types differ in the commonality with which textiles occur on them?
- (4) Do textiles tend to cover 80% or more of an item-side or less than 80% of an item-side, considering all kinds of copper artifacts for all sites studied?
- (5) Does the areal coverage by textiles on items differ by site?
- (6) Does the areal coverage by textiles on items differ by type of artifact?
- (7) When textiles occur on a copper artifact, do they tend to occur on one side or both sides?
- (8) Do copper artifacts of different types differ in whether textiles occur on one side or both sides?
- (9) How many cloths of identifiably different technical construction tend to occur on copper items, regardless of their specific type?
- (10) Does the numbers of different cloth constructions per artifact type differ among the sites studied?
- (11) Does the number of different cloth constructions occurring per item differ among the artifact types studied?
- (12) Do any items having multiple textile fragments from the same or different textile construction have their textile fragments oriented differently?
- (13) How do fabric structures, fiber diameters, yarn diameters, and yarn spacing per centimeter (thread count) vary by site?

(14) How do fabric structures, fiber diameters, yarn diameters, and yarn spacing per centimeter (thread count) vary by the kind of artifact?

Questions 4, 7, 9, and 12 were asked specifically to determine whether textiles on headplates, breastplates, and/or celts derived from these objects having been placed in textile bags or wrapped in textile cloth just prior to burial, or whether the textiles had different origins. One of these alternatives is that textiles were cut out into culturally-meaningful shapes and applied to the artifacts, perhaps in the process of developing copper corrosion patinas (see Parts I and II).

In this report, the primary observations were made by V. Wimberley and D.A. Wymer. The technical, textile analysis and written report were the work of Wimberley. C. Carr was responsible for making the Canon color prints on which some observations were made, sample selection, calculating some summary statistics reported here, and the commentary at the end of the report.

Samples Selected, Criteria for Selection

A preliminary list of samples for analysis was selected through a survey conducted by Wimberley in 1997. Christopher Carr took color, Ektachrome slides of all headplates, breastplates, and celts curated in the Ohio Historical Center, from 1994 through 1996. Canon color prints that enhanced the material contrasts of the artifacts in these slides were made by Carr and surveyed by Wimberley for textiles, pseudomorphs (inorganic metallic replacements or casts of organic materials), and their prevalence, in preparation for the original grant request. In the summer of 2000, Dr. DeeAnne Wymer made a second inventory from the Canon color prints and a second list was derived for the analysis of organics and textiles. Table 5.1 lists the judgments of possible textile presence on copper artifacts made by Wimberley in 1997. Table 5.2 compiles the assessments made by both Wymer and Wimberley, along with percent areal coverage estimates made by Wimberley, in the summer of 2000, noting the presence and percent coverage of textiles on the two sides of each artifact. Of the 132 item-sides surveyed, 68, or about half, had at least some textiles present on them.

Items were prioritized for examination according to the following criteria: (1) the presence of substantial pieces of textiles or their pseudomorphs; and (2) the potential of the item bearing artistic imagery, perhaps produced in part with textiles, as assessed by Carr.

Observational Methods Used

A centimeter grid was placed over the photograph of the artifact to be analyzed. The grid had Y-axis rows labeled consecutively from A and X-axis columns labeled consecutively from 1. This grid system allowed the mapping of locations of textiles and organics as well as facilitated the calculation of percent areal coverage by textiles and pseudomorphs. The paleoethnobotanist, DeeAnne Wymer, surveyed artifacts first for organics and possible textile materials, noting the locations of these materials and pointing out unusual characteristics worthy of investigation. Wimberley then inspected

the artifacts during the weeks of July 26, 2000 through August 7, 2000 at the Ohio Historical Society storage facility. Samples were viewed by stereomicroscope with a micrometer disc inserted into one eyepiece for measurement of fiber diameter, yarn diameter and thread counts of textile constructions. All samples were handled only with gloved hands to prevent damage from perspiration, etc. The stereomicroscope had a maximum magnification of 7X power, not great enough in most cases to facilitate the identification of fiber types, and sufficient for making only general classifications of fiber characteristics.

For fiber and yarn characteristics, five measurements were made for diameters and averaged. A hand held protractor was used to determine the angle of twist for single and ply yarns. A protractor disc in an eyepiece would have been preferable but was not available. For thread counts of vertical and horizontal elements, five measurements taken by sampling over the entire sample were made, using an ocular micrometer disc and then averaged. In the case of some fragments, five measurements were not possible due to the small size of the textile; therefore, as many measurements as possible over the entire area of the sample were made and averaged.

Results

It became apparent during the textile analysis that artifacts could have the macro-appearance of a textile grid of threads but at the microscopic level there was no fiber, yarn or cloth left on the artifact. The marks could be “ghosts” of a previous textile or copper mineralization or corrosion. Copper replacement (mineralization) of organic fibers in some cases was complete, in other cases partial. Table 5.1 displays the 1997 assessment of possible textile or pseudomorph presence, based upon the visual inspection of the Canon color prints provided by Carr. Of the 116 prints of 116 item-sides, 56 (48.3%) were judged to have only textile remains, 36 (31.0%) to have only possible pseudomorphs, and 2 (1.7%) to have both. The remaining 22 items (19.0%) had neither textiles or pseudomorphs. In Table 5.1 if there is not a 1 or 2 entered in the column for an artifact side, it was not known whether it was designated side 1 or side 2 by Carr.

Table 5.2 reports the assessment by Wimberley and Wymer of a somewhat different sample of 66 items (132 item-sides) by visual inspection of the actual items, rather than Canon color prints of them. In a few instances, the assessment of textile presence was made by Wymer, alone. Due to time limitations, Wimberley surveyed in detail only those artifacts judged to possibly have textile remains, as evaluated by Wymer’s inspection, and those assessed as important for imagery by Carr, rather than every artifact. Of the 132 item-sides surveyed, 68 (51.5%) had textile remains. Of the 66 items, 23 (34.8%) had fabric on two sides, 22 (33.3%) had fabric on one side, and 21 (31.8%) had fabric on neither side. Only 3 celts of 14 (21.4%) had textile on both sides; 3 (21.4%) had textiles on one side and 8 (57.1%) had no fabrics.

Table 5.3 provides a breakdown of these results by the kind of item (breastplates, celts, headplates) and by site. The sample is definitely skewed toward Seip and Hopewell. The Hopewell Mound Group had 5 out of 10 breastplate sides exhibiting

fabric, but all with areal coverage of less than 80. Hopewell also had 3 of 5 celt sides with fabric present at 5 percent areal coverage. This would appear to indicate that the textile was not necessarily bagging or wrapping material, but without provenience information it is difficult to say more. These artifacts have been handled extensively and textiles may have broken off or been reduced to powder. The preservation of the appearance of these items in their present state by Carr's Ektachrome and digital photography will help track what happens to the textiles over time as they remain in storage and are used for research. The other sites of Rockhold, Liberty, Ater, and Ft. Ancient have few artifacts with textiles adhering to copper. These sites were represented by one to two items possessing any areal coverage of fabric, all considerably less than 80 percent, which was chosen as likely indication of wrapping or bagging. There are textiles from these sites analyzed by the author in 1997 that are not attached to copper. Breastplates from these sites have the most textile evidence, with some celts possessing textiles or pseudomorphs. Headplates, originally thought to have remains reminiscent of a textile, universally proved to have no attributes of textiles in this Ohio Historical Center sample. However, one cannot assume that headplates do not generally retain textile evidence; there is one headplate specimen at the Ross County Historical Society, Chillicothe, OH, which had much cordage on both sides.

To consider whether textiles covered one or both sides of an artifact, and the amount of areal coverage by textiles, please refer to Tables 5.2 and 5.4. Eighty percent or greater coverage of an artifact side by textile is a rare occurrence. For the 66 items examined, of the 68 item-sides having textiles, 48 (70.6%) have textiles on less than 50% of their area, 10 (14.7%) have textiles on about 50% of their area (21.2%), and only 10 (14.7%) have textiles covering more than 50% of their area.

Few artifacts had more than one cloth construction on one side (Table 5.5). Of the 84 copper items with textiles or their pseudomorphs, only two items (2.4%) had two different cloths, and only one item (1.2%) had three. There was some mixture of one textile construction with feather and/or hair or fur fiber.

Table 5.6 lists the different textile constructions found on the surveyed artifacts. The number of different textile constructions was limited to four types: oblique interlacing, spaced 2-strand twining, alternate pair twining and spaced alternate pair twining. Only two items had two identifiably different textile constructions on the same side of the artifact; these items were both breastplates, from the Hopewell site (See Table 5.5). There is a possible example of featherwork, where feathers were attached to a textile substrate. Only a few places have the feather shafts bent in the traditional form for attachment; yet there is a definite textile grid over the entire plate side. This artifact requires further analysis.

Table 5.6 shows that oblique interlacing occurred only on breastplates for the sites of Seip, Hopewell and Ater. Alternate pair twining was found on one breastplate from Seip. Spaced alternate pair occurred on ten breastplates from Seip, one breastplate and one celt of Hopewell site origin, and one Rockhold breastplate. Spaced-2-strand twining was characteristic of only one breastplate from the Hopewell site. Five breastplates from

the sites of Ater, Hopewell, Liberty and Seip had unidentifiable textile constructions. Because the sample is so biased in numbers toward Seip and Hopewell, it is not possible to generate any conclusions for between site and artifact type occurrence.

Information of more detailed technological attributes, including thread and ply diameters, and yarn spacings, are shown in Tables 5.7. The yarns were universally Z-spun singles and then plied S for all sites.. It would further the analysis of textile structure occurrence if the artifacts were put in archaeological context. There may be differences in the attributes of textiles associated with bone. There is one incidence of thicker elements or yarn diameters having been used for a textile adhering to a plate with bone, compared to the same construction adhering to plates without human remains.

Questions That Have Arisen From the Research and Future Lines of Study

While 70X magnification was not great enough to be certain of specific fiber types, it was possible to distinguish plant fiber from hair and feather. Single fiber yarns appear to be Group I fibers from the Jakes Plant Classification System - well defined and not many surface inclusions. Fibers are cream colored at their lightest. This group includes mulberry, nettles, dogbane and milkweed. These types of fibers have been recorded as having been used ethnohistorically in the area by Willoughby and Greber. Hair fibers could not be identified by the appearance of any medulla characteristics or scale structure. SEM would be required for this, but still may not be conclusive due to the degradation of the surfaces and encrusting copper corrosion. Future lines of study for these artifacts would include an effort to identify fibers as well as hair, fur, and feather. In consulting the notes made by Lucy Sibley from April 14, 1987 [provided to Wimberley by N'omi Greber], it is apparent that an investigation of the use of milkweed fibers, either the "down" or stem, should be made. Sibley thought breastplate #283/450 possibly had milkweed down instead of feather. Magnification greater than 7X is needed to check for feather barbs and other surface characteristics. Bast-like fibers identified by both Sibley and Wimberley need further investigation for more specific identification. Wimberley is currently collecting milkweed fiber for comparison to materials on the copper plates. Rabbit hair has been reported by Willoughby, Song, and Jakes for textiles not attached to copper.

Wimberley would like to compare the fiber and textile constructions that occur on copper to those textiles which were not attached to copper [studied during the summer of 1997]. This may answer the question of whether there are differences between textile structures appearing on copper and those not associated directly with copper from the same Hopewellian sites.

Finally, Wimberley noted higher or lesser twisted yarns within the textile structures on several breastplates. Table 5.7 reports yarn diameters and thread counts. This anomaly of twist per centimeter is being investigated for several possible reasons. Once a spinner is experienced, the twist per centimeter remains fairly consistent for the yarn type being produced for a particular use. In the case of the breastplates in Table 5.7, the bast-like yarns all visually appear to be of the same fiber type and were used for the

same twined construction, which would normally mean that all yarns used would have the same twist per centimeter for the entire cloth when made by one spinner. The presence of these varying yarns may indicate that more than one person provided yarn for the textile or that yarns, which had been prepared for different purposes, were incorporated into the structure, perhaps due to time constraints for quick preparation.

Commentary on Artistic Processes by Christopher Carr

The question of how textiles came to occur on the artifacts examined here has several possible answers. (1) The artifacts were wrapped in cloth or placed in cloth bags for burial, analogous to the manner in which some persons were apparently wrapped in shrouds. (2) The artifacts may have lain against clothing worn by the deceased. (3) The textiles may have been cut out of forms that were applied to the artifacts to decorate them directly (4) The textiles may have been cut out of forms that were applied to the artifacts in order to create images through the process of differential patination. This section considers these alternatives relative to the data collected. It reflects the conclusions of C. Carr.

It is possible, and actually thought probable, that each of these formation processes had roles in the occurrence of textiles on the copper breastplates and celts. Occasional items (e.g., the very large celt from Seip) have fabric remnants and/or pseudomorphs in a regular, grid-like pattern over most of their area and both sides. This pattern suggests the wrapping of the item in cloth or its placement in a cloth bag. At the same time, of the 66 items studied, only 23 (34.8%) have textiles on both sides. Thus, for the majority of items, the explanation of a cloth wrapping or placement in a bag is not likely.

The idea that the textiles were the fortuitous result of having lain against clothing, with subsequent corrosion and incorporation of the textiles in the artifact-corrosion mass, finds some support in that 22 of the 66 items studied (33.3%) have textiles on one side, alone. However, few of these items have textiles covering any large area of the side on which they occur. Of the 22 items with textiles on one side, 17 (77.3%) have textiles covering less than 50 of their area, while only 2 (9.1%) have textiles on about 50% of their area and only 3 (13.6%) have textiles on more than 50% of their area. More broadly, of 68 item-sides with fabrics present on them, 48 (70.6%) have fabrics covering less than 50% of a side, while only 10 (14.7%) have fabric covering about 50% of a side and only 10 (14.7%) have fabric covering greater than 50% of a side. These situations tend to support the alternative explanations, that textile forms that were cut out and applied to the artifacts as decorations or to create images through differential patination. The last two options cannot be separated by the kinds of data tabulated here.

Insert Tables 5.1 - 5.7 here

CHAPTER 6

REPLICATION OF HOPEWELLIAN COPPER ARTWORKS

TO VERIFY THE HOPEWELLIAN ARTISTIC PROCESS OF COPPER PATINATION

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Beyond Hopewellian copper artworks made by painting or collage, the great majority were produced by forming copper patinas – that is, by purposefully inducing corrosion with salts and acids to produce images. The NCPTT research team came to realize that this method had been used when our research led us to an empirical inconsistency. On most copper plates, such as from Fortney mound, we found distinct materials separated by crisp boundaries. A study of 63 microsamples from this piece and 10 other copper artworks, using several different chemical methods, revealed that the distinct materials were all copper-based compounds: cuprite, chrysocolla, malachite, turquoise, azurite, and perhaps others in minor amounts. The NCPTT research team initially hypothesized that the well defined areas of these very different minerals were examples of paints that had been made from different forms of corrosion, which had been scraped from readily available copper and then mixed with a binder. We discarded the idea that such areas represented natural corrosion of the copper, which would not have regularly produced such material boundaries. Quantitative chemical modeling corroborated our conclusion. The turquoise and azurite compounds that comprise some images were found to not be stable in the soil conditions of Ohio, and would not likely have developed *in situ* on buried copper (see Chapter 3 by Colwell). Their origin as a paint seemed more likely. In addition, quantitative modeling showed that the diversity of distinct copper minerals found on some single artifacts would not likely have developed naturally through simply their burial in soil. Only one or two forms of copper corrosion would have formed (see Chapter 3 by Colwell). Again, this finding was consistent with the painting hypothesis. However, when copper artifacts were examined in detail for stratigraphic relationships among the copper minerals and the substrate, the minerals were found to have developed from the substrate, as would corrosion. In all, these several, opposing observations could not be explained by either the painting hypothesis or the hypothesis of natural corrosion development

The NCPTT research team was stymied, until Carr showed the pieces to a contemporary copper worker and Head of the Metals Department in the School of Art at

Arizona State, David Pimentel. To the team's quandary, he immediately replied, "I can replicate that artwork and make sense of your observations easily. The pieces were made by patination – by inducing corrosion products of different kinds in different areas using varying acids, salts, and application methods. It is a common process in art today. Patination will explain at once the crisp borders between adjacent areas of copper minerals, the presence of turquoise and azurite on your specimens, the diversity of forms of copper minerals on single items, and the *in situ* growth of the minerals from the substrate".

To test this idea, Pimentel and Carr experimented with forming patinas on copper with various acids and salts that would have been available to Ohio Hopewell artists. For the acids, we used pure red grape juice, apple juice, citric acid, cranberry juice, apple vinegar, white vinegar, urine, and 3 strengths of tannic acid available from acorns. For salts, we used table salt, crushed gypsum, crushed shell, and bone meal as sources of corrosive chloride, sulfate, and carbonate, and phosphate ions, as well as crushed copper corrosion as seed crystals. Each salt was made into a paint slurry with distilled water. These five paints were then applied to copper test plates, and covered with textile, hide, and feather, which would help to hold the acids. Remnants of textiles, hides, and/or feather are found on a great majority of Ohio Hopewell copper breastplates, headplates, and celts. Each acid was then mixed separately in three different absorbant materials – saw dust, culturally disturbed soil from the Hopewell site, and subsoil from the Hopewell site. The soils had weakly basic pHs, and would not have produced copper corrosion readily. As in contemporary metal work, the sawdust or soil samples holding the acids were packed around the copper plates. In all we made 42 test copper plates with 15 test patches each, documenting various combinations of salts, acids, and acid absorbant materials.

The results were astounding, particularly when using soils from the Hopewell site. In only two weeks time, at room temperature, the various mild acid-salt combinations produced thick patinas of cuprite, chrysocolla, turquoise, malachite, and azurite – all of the copper minerals that predominate on Hopewell copper artworks. Some treatments produced large, one to two millimeter crystals of malchite and azurite. Crisp boundaries between copper minerals of vividly different colors and kinds were obtained where hide and textiles were applied. We also were able to reproduce the mineral impressions of feathers and textiles that commonly occur on Hopewell copper artifacts and that form that basic units of their artistic compositions.

To nail the coffin shut, we experimentally reproduced an image of bird impersonator on a copper breastplate from the Hopewell site. The bird man on the plate is similar to a mica cutout from the Turner site, with a bird nose and a three-layered turbin headdress. We cut out a copy of this bird man from burlap, placed the cut-out on a copper plate, and covered it with Hopewell soil mixed with apple vinegar and table salt. In two weeks time, we produced this red, cuprite patina in the image of the bird man. The cuprite grew from the substrate but has crisp, well-defined boundaries where the burlap cut-out ended. These are two of the characteristics of most Hopewell, copper

mineral artworks that neither the painting hypothesis nor the hypothesis of natural corrosion could explain.

Putting this experiment in cultural context, we would point out that the chemical process of patination is well suited to the Ohio Hopewell cultural and material tradition, and would have been well received by Ohio Hopewellian artists, religious specialists, and the populous. Hopewell raw materials and art are predominated by a theme of transformation – from light to dark, shiny to dull, human to animal, and back again. The ability to change a shiny copper surface into a dull patinated one, and copper color into brilliant red, green, turquoise, or deep blue in just a couple weeks time, simply by applying a cutout design, a special liquid, and soil, falls well in line with Hopewellian fascination with change.

CHAPTER 7**DIGITAL PHOTOGRAPHIC METHODS FOR
DISCERNING ARTISTIC IMAGES ON HOPEWELLIAN COPPER ARTIFACTS**

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This chapter describes the digital photographic aspects of the NCPTT sponsored research. Sections discuss the hardware and software selected for specific purposes for color and infrared imaging; image capture for flat and curved objects; photomosaicing of images of curved objects; photographic enhancement routines; registration methods in preparation for combining color and infrared images into hybrid, composite images; and evaluation of which bands, band calculations, hybrid band combinations, and hybrid combination procedures are most effective for rendering visible the artistic compositions on Hopewell copper artifacts.

Image Capture

Hardware and Software

Breastplates, celts, and headplates within the collections of the Ohio Historical Society, Columbus, OH, were digitally photographed with state-of-the-art digital cameras (Battelle Laboratories; ASC, Inc.) of three kinds: (a) ultra-high resolution color, (b) near-infrared, and (c) midrange infrared. For color image capture, we used a combination of a high resolution digital camera and a computer system. The camera, a Leaf Lumina manufactured by Leaf Systems, uses a CCD array to produce images with a spatial resolution of 3380 X 2254, and a color depth of 36-bit, and uses standard Nikon bayonette-mount lenses. During all phases of this project, we used a Nikon 60 mm 1:2.8 lens. Two different computers were used during the course of image capture, both running the Macintosh OS. Computer #1 consisted of a Power Computing PowerCenter 132, with a 132 MHZ Power PC 604, 80 MB of RAM and a 1 GB HD. Computer #2 consisted of a Power Macintosh 7100/66, with a 66 mhz Power PC 601, 56 MB of RAM and 6 GB worth of hard drive space, and a recordable CD drive. Software used for the capture (and subsequent analysis) included both NIH Image and Adobe Photoshop versions 3.0 and 4.0, as well as the Leaf Lumina Photoshop plug-in Twain scanning utility. Previously, we had used Leaf's twin compatible scanner plug-in EasyScan 1.2 written for Macintosh. The camera was mounted on a standard 35 mm copy stand and connected to the computer via standard SCSI cables. Two 500 watt incandescent flood lamps were used for illumination. The two lights were set up perpendicular to each other, in order to cast shadows multidirectionally and to bring out specimen relief optimally.

Photography of artifacts in the field was a relatively simple process. The camera and computer were set up in a designated area, either in the collections room or very close by to minimize the distance the fragile objects had to travel. Objects to photograph were prioritized based on their importance relative to the overall corpus of imagery, and brought to the photography area in lots. They were lined up so that they could be photographed in an assembly line style. Exposure times for the Lumina ranged from 30 seconds to 10 minutes, depending on the f-stop and lighting, with the average being 2-4 minutes. Higher f-stops were used when an object had high relief, such as the curved headplates or those objects covered with burned bone. Once an image was captured in Photoshop, it was reviewed for focus and evenness of lighting, cropped to eliminate any extra background, saved as an LZW-compressed .TIF file to the hard drive. The cropping and compressing was done solely to reduce the unwieldy size of each file, which was more than 22 MB in raw form.

For infrared image capture, we used a Cohu 4810 near-infrared camera and a Hamamatsu C1000-03 midrange infrared camera have sensing ranges of 0.7 - 1.0 microns and 1.0 - 1.8 microns, respectively. Diffuse quartz-halogen lighting operated at 3000⁰K provided specimen illumination. A Nikkor 105mm *f*4.5 IR lens was used with the near-infrared camera, and when coupled with a spectral filter, results in the imaged bandwidth of .700-1.0 microns. The camera has a 2/3-inch format frame transfer charge coupled (CCD) with an active imaging area measuring 8.8mm (horizontal) x 6.6mm (vertical).

The active imaging area is an array of 754 horizontal by 488 vertical picture elements. This results in a field-of-view of 84 mrad (horizontal) by 63 mrad (vertical) and, at a viewing distance of 28 inches, a spatial resolution of 0.1 lmm (horizontal) by 0.26 (vertical). A Nikon 24mm *f*1.4 IR lens was used with the midrange infrared camera. The camera uses a special infrared vidicon that is responsive to energy out to 1.8 microns. With an active imaging area of 12.7mm (horizontal) x 9.5mm (vertical), the camera has a field-of-view of 529 mrad (horizontal) by 398 mrad (vertical). At a specimen viewing distance of 28 inches, this camera has a spatial resolution 0.54mm (horizontal) by 0.63mm (vertical). Spectral filters used with this camera result in a wavelength sensing region of 1.0 to 1.8 microns.

Video signals from the near-infrared and midrange infrared camera/sensors are processed with a 266 MHz Pentium II PC equipped with a Meteor Frame Grabber board (Matrox Incorporated). The board produces digital output at a 640 x 480 pixel resolution and adjustable in brightness and contrast from an analog video camera signal.

The Matrox Meteor board key features include: (1) Captures NTSC/PAL/SECAM, RS-170/CCIR and standard RGB; (2) single slot PCI frame grabber; (3) real-time transfer to system or display RAM; (4) multiple video inputs (up to 4 channels); (5) high-quality video scaling unit; (6) live video-in-a-window; (7) stable synchronization; (8) support for Windows NT, Windows 95, and DOS4GW 32-bit DOS extender.

The Matrox Meteor is a high-quality color and monochrome PCI frame grabber that provides real-time image transfer to host, video-in-a-window, and support for the Matrox Imaging Library (MIL) and Matrox Inspector interactive imaging software. The use of this board and its associated image processing software allow users to develop powerful, yet cost-effective host-based machine vision, image analysis and medical imaging systems. The Matrox Meteor transfers image data in real-time to the CPU RAM for processing or the display buffer for real-time display. The Meteor is capable of up to 45 MB/sec transfers.

Other features of this frame grabber board include: (1) the incoming video stream can be tuned through software adjustable brightness, contrast, hue, and saturation; (2) excellent synchronization even when grabbing from still video cameras and VCRs in playback and pause modes; (3) high-quality live video-in-a-window display that can be scaled down to any size and positioned anywhere on the screen; and (4) the Digital Video to PCI Interface unit, which supports various data transfer formats (8-bit mono, 15-bit and 24-bit RGB).

Software used in support of the frame-grabbing board included two packages developed by Matrox, Incorporated: Inspector and the Matrox Imaging Library (MIL).

Matrox Inspector is a Windows-based software that offers interactive access to an extensive set of imaging operations. Features of this software package include: (1) complete set of imaging functions; (2) easy-to-use interactive work environment; (3)

interfaces to standard and non-standard cameras; (4) loading and saving in many file formats (5) display of color and monochrome images; (6) scaling, zooming, panning and scrolling; (7) selection and processing of non-rectangular regions of interest; (8) returning of results with sub-pixel accuracy; (9) image annotation; (10) automation of routines with powerful scripting; and (11)“Collection” for visually tracking and managing images.

MIL is a high-level ‘C’ library with commands for image processing, pattern matching, blob analysis, gauging/measurement and OCR, as well as image acquisition, transfer, and display. MIL has been designed to fully exploit the power of Intel MMX™ technology. The MIL software allows more flexibility for image processing/analysis than does the Inspector software.

Object Shape and Image Capture Methods

Two basic types of objects were photographed – flat objects and three dimensional objects. Flat objects could be photographed as is, but special attention had to be paid to the 3 dimensional objects, which included all headplates, and some celts. Headplates and celts required different approaches to imaging them. As the celts were merely tall in relation to the focal distance of the camera, it was sufficient just to increase the f-stop to between 16 and 32, thereby increasing the depth of field. The resulting digital image could then proceed immediately to the image processing stage.

Headplates required a somewhat more complicated technique. In order to best display the imagery on all objects, we needed a straight-on photograph. Since headplates were curved in at least one dimension and many times in two dimensions, accomplishing this with one photograph was not possible. To obtain a photograph of surface patterns minimally distorted by parallax error, for each headplate, multiple digital photographs were taken at different points along its curvature, perpendicular to it. The multiple photographs were then fitted together in the computer, providing a flat layout of the plate. Operationally, this was achieved by keeping the digital camera in one position and rotating the headplate approximately about its center of curvature on a styrofoam support cut to the form of the item, so as to orient the desired section of the object parallel to the focal plane of the camera. The support ensured that the plate remained a constant distance from the camera as each photograph of the series was taken, which retained the scale of the image from photograph to photograph. Photographs of a series were taken so as to ensure a few centimeters of overlap of undistorted image between them. This required an average of four photographs for each side of a headplate. Some plates required as few as two, while some required eight per side.

The multiple photographs of a series were spliced together to create a flat layout using the image scaling, rotating, skewing, and stretching capabilities of Adobe Photoshop. The overall name for this procedure of taking multiple photographs and fitting them together is *photomosaicing*.

Image Security

For image security, at the end of each day's work., all files of captured digital images were written to compact disks, zip disks, and/or tape. They were also uploaded to a remote FTP site, ensuring that the images were stored with multiple media. Once images were secured, they were removed from the hard drive for the next day's work of image capture.

Sample Size

Ultra-high resolution color digital photographs made with the above-described system and procedures were taken of 219 sides of Ohio Hopewellian copper items bearing artwork or thought to bear artwork. Of these, 122 sides were of breastplates, 22 sides were of headplates, and 75 were of celts. The items come from a diversity of sites (11) dispersed over south-central to northeast Ohio and represent a range of natural and archaeological preservation processes. In total, the items also bear the full range of kinds of inorganic and organic materials known to occur on Ohio Hopewellian copper items (see Chapters 4 and 5). The sample obtained is approximately 10% larger than that originally proposed.

Near-infrared and midrange infrared digital photographs made with the above-described system and procedures were each taken of 263 sides of the copper items, including all of the 219 sides photographed in color. The greater breadth of the infrared sample reflects the decision to photograph more than the proposed number of item-sides that do not seem to bear much or any indications of artwork, and to explore the power of IR in revealing artwork essentially not visible to the naked eye. Examples include copper surfaces that appear largely uniform in their corrosion, copper surfaces that are entirely hidden by a uniform textile wrapping or textile-pseudomorph wrapping, and intensely burned (cremated) copper surfaces.

Digital Photographic Enhancement

Preparation of Digital Photographs for Enhancement

Each of the 219 color digital images of the copper artifacts were prepared in Adobe Photoshop for image processing. Each artifact was outlined, its background was changed to a uniform 30% grey, and a rule of standard format was placed within the photograph. Excessive background had already been cropped from the images during the image capture and storage phase of the project.

Digital Photographic Enhancement

Commonly used enhancement methods include several major classes of display and mathematical routines, including color band selection, contrast stretch histogram modification, histogram equalization, spectral analysis, band-pass filtering in the spatial

and Fourier domains, boundary enhancement, and interband calculations. Different methods are designed for different tasks, such as improving image contrast, sharpening image boundaries, determining the frequencies/scales at which image intensity varies more or less, partitioning overlaid images of different scales, and removing high-frequency noise or disjunctures or low-frequency trends. Relevant overviews of how each method works are provided by Castleman (1979), Gonzalez and Winz (1977), and Carr (1987).

For this project, contrast stretch histogram modification performed in two different ways, as well as band selection, interband calculations, and hybridizing of color and infrared bands, were used to enhance color and infrared digital images.

Contrast enhancement. Black and white digital images, or a single color band within a color image or a single infrared band, typically consist of an array of pixels, each with a value that can range between a minimum of 0 and a maximum of 255. This number represents the brightness value that is assigned to a given pixel – the higher the number, the darker the brightness value. Brightness values of color or infrared bands of digital photographs commonly are limited to some segment of the 255 value range. Since the human eye is readily able to distinguish only 7 – 10 brightness values, limitation in the value range makes the band appear more uniform and lacking in contrast. To overcome this problem, a black and white band, or color or infrared band, can be altered to take advantage of the full 255 levels of brightness. A contrast stretch expands the limited range of brightness values of a black and white, color, or infrared band over the entire 255 value range of brightness values, thus making any differences between adjacent brightness values greater, and more readily apparent to the naked eye. In other words, image contrast is improved.

Color Contrast Enhancement. For this project, the contrast of each of the 219 color RGB images was improved in two ways: a total histogram stretch, in which the combined histogram of all three bands of the RGB image were stretched at the same time, and an individual color band histogram stretch, in which the histogram of each color band was stretched separately. It was desirable to do it both ways for two reasons. First, the total histogram stretch enhanced contrast but maintained the color balance of the original photograph. This was found helpful in identifying regions and various substances in the image relative to the original artifact, by color. Second, the individual band histogram stretch served to more equally balance the three colors relative to each other. This produced a sometimes dramatic and unnatural shift in the color of the image – the reason being that many of the objects are primarily green in color. The individual stretch de-emphasizes this green dominance, and allows the other bands to show through. This may reveal aspects of the object that differ in their red or blue channel signatures and that cannot be seen in an image with normal color balance.

A third contrast-changing routine – histogram equalization – proved to be seldom effective in revealing artistic representations early in the grant research period, so it was not applied to most of the digital photographs taken.

Infrared Contrast and Sharpness Enhancement. For both near-infrared and midrange-infrared digital images of all 263 item-sides photographed, contrast was improved by individual band stretches. The two infrared images of an object were not combined into two channels of a single image and stretched together as a whole. Image contrast was optimized for an infrared band when it was sharpened with the sharpening filter in Adobe Photoshop *before* stretching it. When stretching was done before sharpening, image contrast was not improved quite as much, although the differences in results between these two ordered procedures is small.

Color Band Calculations. Band calculations are essentially mathematical operations that use the numerical brightness value of each hue channel of each pixel in an image. Two selected bands from the same image (or the bands or total RGB response of two separate images) can be added, subtracted, multiplied, or otherwise operated on to create a new image. Matrices algebra applied to matrices of pixel brightness values of various bands of a photograph and/or its total RGB response is used to accomplish the operations. For example, in a Red x Blue calculation, a matrix comprised of each pixel's Red brightness value is multiplied by a matrix comprised of each pixel's Blue brightness value. For each pixel, the resulting calculated number can fall outside of the 0 – 255 brightness scale range, causing extreme values to be lumped with either 0 (solid white) or 255 (solid black). The resulting image is usually of low contrast, so it is then desirable to perform a contrast stretch on it, rescaling all pixel values between 0 and 255.

Because there are three bands in each image, and many different calculations, the potential existed in this research project for a very large number of images to be created. However, it was determined through trial-and-error observation that many potential combinations of bands and calculations were not of much value for improving the visibility of artistic compositions on the copper artifact. This determination was broken into two parts: selection of which of the three bands to use and selection of which calculations to use.

Color Band Selection. The color bands that were investigated the most for their calculations was initially based a priori on a logic that assumes the nature of formation of coloration on the objects. In general, the green band was not often used, because it was thought that the green color was mostly the result of natural copper corrosion, and that natural corrosion would mask any pigment found on the object. Conversely, it was argued that the red and blue bands would carry less information on natural corrosion and more information on any pigments that were applied to the object, consequently improving the visibility of artistic paintings on the objects. This logic turned out, by the end of the project, to be only somewhat true, because the copper objects were commonly patinated rather than painted, and some green corrosion was intentionally produced as part of artistic compositions, along with corrosion minerals of other colors.

A second factor that was considered in determining which bands to use was which bands displayed the greatest differences from each other in the spatial layout of their pixel brightness values. For example, two bands that looked very similar in layout will yield very little in new information when they are combined through band calculation,

even after a contrast stretch. Contrarily, combining two bands that looked very different in their spatial layout of pixel brightness values could yield a great deal of new information.

A quantitative assessment of the relative effectiveness of the three color bands in revealing material differences and imagery on the copper artifacts is made below in the sections authored by Jeff Barron.

Calculation Selection. For both each of the 438 digital images, the contrast of which was increased by the total histogram stretch or individual color band histogram stretch procedures described above, seven calculations using two or three color bands were selected for study: (1) R x B, (2) R x B-inverse, (3) R-inverse x B, (4) R-inverse x B-inverse, (5) B x G, (6) B-inverse x G-inverse, and (7) B - G. After calculation, the contrast of the resulting grey-scale image was then improved again with a histogram stretch. These seven calculations were selected because they usually resulted in distinct and diverse image representations that brought out different features of a given copper artifact. Band calculations that involved red and/or blue and/or their inverses were generally the most informative.

For some specimens, some calculations produced images that were largely black or largely white, even after a histogram stretch. This resulted from the aforementioned phenomenon of calculated pixel values lying outside the 0-255 range of values, and in these cases, large numbers of pixels being collapsed into the 0 or 255 category. This condition arose idiosyncratically, depending on the character of the image, and most frequently with the B - G band. This effect did not alter our impression of the general importance of all seven band calculations just enumerated.

Hybridizing Color and Infrared Digital Photographs

Hybrid color-infrared images were created by replacing the R, G, and/or B channels of a digital photograph with a near-infrared band and/or midrange-infrared band. Generally, one or two calculated color bands were also substituted for R, G, or B channels in these hybrid images, in order to bring in more color information. The various hybrid images were then explored for their relative effectiveness in making visible the artistic representations on the copper artifacts.

In order to produce color and infrared hybrid images, it was first necessary to rescale and register the color, near- infrared and midrange infrared images, which each were captured with a different camera system. The following two sections describe the rescaling and registration methods that were used.

Preprocessing

For each color digital image, RGB channels were imported into Adobe Photoshop 5.5. A standardized processing method was then followed. Most excess background on the imagery was then cropped, in order to reduce the file size as well as to facilitate the

registration process. The cropped images were then reduced in size to approximate 2400 pixels in the x-axis with the y-axis pixels being constrained in proportion to the x-axis reduction. All reduction and expansion of the imagery was done within Photoshop using its bicubic interpolation algorithm. Imagery with less than 2400 pixels were not expanded to this size but left at their smaller original size. The reduction of the imagery to 2400 pixels was determined by the necessity of reducing the much larger RGBs to a size similar to the IR images prior to registration with them, balanced against the necessity of the project to produce large high-resolution imagery. The cropped RGBs on average were approximately five times greater in size than the cropped IR images. This drastic size difference made for a difficult registration process, requiring a reduction in the size of the RGB images. . It was due to this large size variance between the two media that some size reduction was necessary in the RGBs prior to their registration with the IRs. The cropped and interpolated RGB images were then split into their three respective channels using the split channels function in PHOTOSHOP. The images then were exported to the GIS program, IDRISI 32.

The IR imagery was similarly cropped to reduce excess background, and in some cases rotated to match the RGB orientation. The IR imagery was then doubled in size using the bicubic interpolation algorithm in Photoshop. This expansion was done to reduce the size disparity between the IRs and the much larger RGB images, with the hopes that this early interpolation would make the registration process easier. Later analysis indicated that this early interpolation was not necessary and that registration would have been better or at least the same from the original cropped IR imagery. The original quality of the IR imagery was poor and with the expansion during interpolation it was degraded further. In an effort to improve the imagery and the resulting registration process an unsharpen mask filter was applied to all IR imagery. This filter was applied with a 200% increase in pixel contrast, a radius of 2 for filter width and a threshold of 0. The unsharpen mask filter improved both edge and internal boundaries. The IR imagery was then exported to the GIS program, IDRISI 32.

Registration

The preprocessed imagery was imported into IDRISI 32; a GIS developed by Clark University. The imagery was imported utilizing IDRISI's canned bitmap import module. Since the imagery had been preprocessed in Photoshop, the registration process commenced immediately after importation. The IR imagery was registered into the planar coordinate system of the RGBs. The R, B, and G channels of the color imagery had simply been split into three color channels and thus retained the same coordinates, requiring no registration.

A mapping function was required for the transformation of the IRs into the RGB's coordinate system. IDRISI supports three orders of polynomial fit: (1) linear, (2) quadratic and (3) cubic. Linear, a first order polynomial, requires a minimum of 3 registration points to create the plane necessary for transformation. Quadratic, a second order polynomial, requires 6. Cubic, a third order, requires a minimum of 10 registration points. The lowest order polynomial that provides a reasonable fit should be utilized,

since the higher the order of the polynomial the greater the distortion due to misaligned registration points. Because the majority of the images are flat or nearly flat, a simple linear transformation appeared to be the easiest as well as the best method for registering the IRs to the RGBs. In some cases a linear transformation would not suffice and a second order quadratic fit was required. This higher order transformation was necessary only in those images that possessed a substantial curvature (headplates and some celts).

The registration process in IDRISI requires the location of common points between both the base and the transformed image. These common points are recorded and entered as a correspondence file; the GIS then creates a polynomial equation to describe the spatial mapping of the transformed data. In order to evaluate a particular registration, it is necessary to locate at least double the minimum registration points required for its order fit. Since a linear transformation was chosen for the majority of the plates, a minimum of 6 points was necessary to truly evaluate the quality of the registration. The transformation process is referred to as rubber sheeting because, like a piece of rubber, the transformed image is pulled and stretched to fit to the new coordinate system. Because the transformed image can become distorted during this process by both a lack of good correspondence between registration points and a lack of registration points in certain portions of the image, a specific registration process was followed. In order to reduce the above problems, an average of 15 registration points was used for the linear transformations, with these points being separated into quadrants across the imagery. This placed at least three registration points in all four quadrants, with an additional three down the central axis of the piece. This process allowed for a reduction in the RMS (root mean square) error that would have been difficult to achieve using normal registration techniques. IDRISI calculates the allowable RMS error for each point and the total RMS error for the transformation equation, allowing for the exclusion of points that are deemed to erroneous. RMS error is an indication of the potential degree of error in ground units that the registration points may be from their actual image locale. A goal of 1.5 RMS or less was observed for the project—slightly higher than the normal acceptance range—but this was due to the poor quality and the sizable expansion of the IR images compared to the RGB images. Registration point exclusion was limited to one of the points per quadrant if possible. This allowed for a better boundary fit between the IRs and the RGBs.

Evaluation of Bands, Band Calculations, and Hybrid Band Combinations and Combination Procedures for Their Effectiveness in Revealing Artistic Compositions on Hopewell Copper Artifacts

The three color bands (R, G, B), two infrared bands (NIR, MIR), and the seven band calculations (R x B, R x B-inverse, R-inverse x B, R-inverse x B-inverse, B x G, B-inverse x G-inverse, B - G) were subjectively evaluated for their effectiveness in revealing artistic compositions on Hopewell copper artifacts. Related, quantitative assessments of the effectiveness of these bands in discriminating different kinds of surface materials found on the copper artifacts are made in the next chapter.

It would be erroneous to state that any of these bands are always helpful or unhelpful, or more or less effective than others, in revealing the artistic compositions.

The compositions vary widely in the kinds and diversity of surface materials that they bear; thus, different bands are effective in different material circumstances. However, considering the corpus of 219 copper items studied, in general, the viewer's ability to see artistic compositions in digital imagery was found to decrease from the Red to the Blue to the Green bands, and from NIR to MIR bands. Considering color band calculations, better to worse viewing conditions were found for: R x B-inverse and R-inverse x B-inverse, to B x G-inverse and B-inverse x G inverse, to R x B, to B x R-inverse and B - G. R x B images generally looked very similar to the original RGB image, and provided little new information, whereas other bands often brought out features not as visible or not visible in the RGB image. R x B-inverse usually looked very similar to B x G-inverse, with the latter usually providing somewhat less contrast. Analogously, R-inverse x B-inverse usually looked very similar to B-inverse x G-inverse, with the latter usually providing somewhat less contrast. The B - G band generally was grainy, and sometimes could not be contrast-stretched to give an image that wasn't very dark and discriminating. In general, the Red and NIR bands and these combined with other colors yielded the greatest visibility to the artistic compositions.

With IDRISI, it is possible to combine any three bands or band calculations together to produce a hybrid, false-color digital image. It is also possible to classify or group pixels with various algorithms and to map "like" and "unlike" pixels of a group in varying color palettes. Exploration of these operations for a sample of 17 artistic compositions yielded the following conclusions. (1) An artistic composition was most effectively rendered when the bands used for making a hybridized, composite image were carefully selected by examining each band individually for its relative effectiveness. No one or few band combinations were always or usually effective across artistic compositions. If only one or two bands were individually effective in revealing an artistic composition, introducing a third, suboptimal band into the composite image usually degraded the image, as expected. In other words, diversity of band information in a composite image did not necessarily guarantee better renditions of an art work. (2) One band might be effective for discriminating one feature of an artistic composition, while other bands might be effective for discriminating other features. To effectively render an entire art work in such cases required selecting bands that differed in the artistic features that they brought out. (3) Hybridized, composite images were most effective for displaying artistic works when the most discriminating band was mapped to the R channel, the next-most discriminating band to the G channel, and the least-most discriminating band the B channel. (4) The visibility of artistic compositions in composite hybrid images generally could be improved with the use of supervised or unsupervised clustering routines to classify pixels, or with manually selected palette redefinition of pixel classes defined by cluster analysis. Manually selected palette redefinition of pixels within a single band, which involves dividing the 0 - 255 brightness values along the continuum optimally in some way to bring out features of an art work, also worked well. (5) In general, unsupervised clustering provided better renderings of an artistic composition than supervised clustering when the "logical block areas" within the composition (e.g., a person's head) were spiky or grainy. (6) In general, cluster analysis of a composite image was found more effective in revealing an artistic composition than palette redefinition of a single-band image, with manually selected

boundaries between assigned colors, when “logical block areas” within the composition were spiky and grainy. When “logical block areas” were fairly homogeneous, palette redefinition of a single-band image was found more useful, and this tended to be the case for most of the art works that were examined. (7) Palette blending was found helpful in rendering heterogeneous areas of a “logical block” of an image, whereas palettes defined with crisp threshold levels were found helpful in rendering homogeneous areas of a “logical block” of an image. (8) Optimal color palettes for displaying artworks were found to be cool and neutralized blue and yellow colors. Primary colors produced too jolty an effect. (9) When the foreground image in an artistic composition was relatively well defined and not grainy, its visibility could be increased by making it into a silhouette using palette redefinition procedures with crisp threshold levels. Positive, dark-on-light silhouettes, as one would normally see in the real world, were found to be more effective than negative, light-on-dark silhouettes. Grey-scale images were found to be more effective than color images. (12) When the foreground image in an artistic composition was relatively well defined and has multiple “logical blocks” of features within it, the foreground is best rendered with a blended palette and the background with one, flat color. (13) A foreground figure can be additionally pulled out from its background by making a frame/matt around the art work that is the same color as the mid tones to darkest tones of the figure, as in picture matting theory. (14) Principal components classification of pixels was not found useful when one or two individual bands provided good definition of an art work. As might be expected, it was found more helpful when only bands of poor to moderate definition were available.

CHAPTER 8

STATISTICAL DISCRIMINATION OF KINDS OF SURFACE MATERIALS BY THEIR DIGITAL PHOTOGRAPHIC SPECTRAL SIGNATURES

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Goals of Analysis

The primary purpose of this chapter is to develop a digital photographic, quantitative model for identifying the materials used to manufacture and decorate copper Hopewell breast-plates, celts, and head-plates from the electromagnetic spectrum of the materials. These materials include cloth, leather, feathers, pigments, patinas, and various minerals. The model allows an assessment of the extent to which different materials can be distinguished from each other by their digital photographic signatures and, thus, the degree to which artistic compositions comprised of these materials are more or less resolvable by digital image processing methods of the kinds discussed in Chapter 7. The model also allows a determination of the portions of the electromagnetic spectrum (R, G, B, NIR, and/or MIR) that contribute most significantly to classification accuracy, so that processing methods of the kinds presented in Chapter 7 can be focused on the bands most productive for revealing artistic composition. In addition, the model could be used in its predictive mode to identify unknown surface materials on the many Ohio Hopewell copper artifacts that have not yet been studied chemically; this could be done without the destructive taking of material samples from the artifacts.

Artifact Sample

The artifacts evaluated in this study consist of breastplates, head plates, and celts, cold-hammered and shaped copper ore. These copper objects were subsequently patinated or painted or overlaid with various types of minerals, or organic materials, and pigments to create various symbolic and geometric designs. Ten copper artifacts were selected for development of the predictive classification model. The artifacts come from the Scioto Hopewell tradition at sites in south-central, southwestern, and northeastern Ohio, and the Erie basin. Table 8.1 summarizes the burial provenience for each artifact. While all the artifacts share certain basic formation characteristics, the specific artifacts selected for this analysis were chosen because they possess minimal damage by post-

depositional taphonomic processes, and because they providing a large number of unique materials.

Of the ten artifacts chosen for use in this analysis, seven of the artifacts are breastplates, two are celts, and one is a headplate. Images of each of the ten artifacts, as well as general descriptions of the materials that were identified by Wymer (Chapter 4) are listed in Appendix 8.1. The coordinates for the material types on each of the artifacts provide the locations for the training site selections used to build the database of spectral signatures for the various materials in order to classify them by predictive modeling.

Description of Inorganic and Organic Surface Materials

In all, 52 types of surface materials were sampled for their spectral signatures on the 11 artifacts selected for analysis (Appendix 8.2).. Some of these materials were variants of one general class of materials: for example, several kinds of malachite, and several variants of a yellow pigment admixed with malachite.

The artifacts studied here were analyzed for their mineralogy as described by Carr (2001):

“Microsamples of 11 differently colored surface materials – 10 thought to be mineral pigments and one organic binder or adhesive – were removed from 63 locations on 11 copper plaques [B-series], headplates [H-series], and celts [C-series] from four different Ohio Hopewell archaeological sites (depositional and taphonomic environments): Hopewell, Seip, Ater, and Fortney. The samples were taken from areas that are integral parts of likely human or animal images or their contrasting backgrounds, and that appear unnaturally homogenous in color (Carr 2001).

The inorganic surface materials on each artifact were identified using five different testing methods: electron microprobe analysis using energy dispersive detection, Raman microspectroscopy, x-ray diffraction, SEM microphotography, and petrological description. The materials used were found to fall into two classifications.

Of the inorganic surface materials, one group of surface materials was composed of noncopper compounds that seemed to function as pigments, and was not the result of a corrosive reaction with the copper. “Three noncopper compounds are red, yellow, white, and brown-black in color—the same colors used in other Ohio Hopewell artwork, the colors of the soils used in contrasting distributions to build some Ohio mounds and earthworks, and the colors found in much historic Woodland Native American art and ceremony” (Carr 2001). The second group of surface materials is probably the product of an intentional corrosive reaction with the copper, called patination. The copper-based compounds are red, and shades of blue from aqua to blue-green and turquoise to deeper dark blues (Carr 2001).

Both the copper and the noncopper inorganic materials, as well as the organic materials, that had their spectral signatures characterized in this analysis are listed in Table 8.2.

Univariate Statistical Analysis

The Application of Descriptive Statistics to Predictive Classification

Estimates of central tendency provide a method for identifying each material's unique spectral characteristics. The degree of overlap in the spectral distributions, as a function of their medians and dispersion directly affect the predictive classification outcome.

Discriminating Power and the Distribution of Values

Figure 8.1 shows the distribution of brightness values for all materials grouped by each of the spectral bands (one boxplot per band). The range of values recorded by a band determines its discriminating power, which is defined as the number of bands (N) raised to the power of the number of levels recorded (R), or N^R . Each 8-bit file contains a range of 2^8 (256) values, so the maximum discriminating power of a database of five spectral bands is 5^{256} . As shown in the plots, many spectral ranges do not utilize all 256 values. The actual discriminating power of the data recorded is approximately 5^{238} . While this loss of discriminating power is only slight, the results illustrate the problem posed for accurate predictive classification by the compression of multiple samples into smaller ranges. Decreases in the discriminating power of the spectral bands lead to corresponding decreases in the predictive classification accuracy of the database.

Figure 8.1 shows the distribution of the raw brightness values in each portion of the spectrum recorded. The visible bands—blue, green, and red—possess similar distributions, with slight variations in the ranges of extreme values. The near-infrared and mid-infrared comprise much smaller distributions; however, larger numbers of extreme values are also present in both these layers. The large number of outlier values could indicate errors in selection accuracy, positional error, or a heterogeneously textured material.

Measurement of Central Tendency

A fundamental issue of predictive classification concerns accurate representation of a material's spectral signature. Both the central tendency and the dispersion of a material's spectral signature are critical to its discernability.

The median value is used here to evaluate the central tendency rather than the mean, because the median is more robust outliers possess only a minimal effect on the median. The median and standard deviations of the fifty-two materials are reported in Appendix 8.3. Appendix 8.4 shows number line plots by quarters for the ranges of medians and standard deviations, respectively. Each material's median depends on its pattern and texture, and the quality of the training site selections.

Example Comparisons of Median Spectral Signatures Considering Individual Bands. The line plots in Appendix 8.4 provide an initial sense of which surface materials are more or less distinct from each other for particular bands of the spectral signatures, without considering the effect of the spectral variance of the materials. Each line plot is a primitive predictive model of the distinguishability of materials through color and infrared digital photography. For example, in the Blue band, blood-red colored cuprite (material HH) is at one extreme, with a median brightness value of 24, and white serpentine (material ZZ) is at the other extreme, with a median brightness value of 255. These two materials are very discernable in their digital photographic spectra. In contrast, dark brown hide (material FF) with a median brightness value of 89 is very similar on the Blue channel to a yellow pigment with some malachite copper corrosion admixture (material PP) with a median brightness value of 90. In the Red band, however, brown hide and yellow pigment with some malachite admixture are more distinguishable, having median brightness values of 106 and 161, respectively.

Example Comparisons of Median Spectral Signatures Considering All Five Bands. The breastplate artifact referenced as B013b provides five classes of materials. The five materials identified consist of two unrelated materials, charcoal and turquoise, and three similar materials, the outside surface of cremated, smoked bone, the outside surface of white cremated bone, and the inside surface of cremated bone.

Calculating the difference between the spectral layers (blue minus green, green minus red, red minus near-infrared, near-infrared minus mid-infrared) for each sample's median scores provides a coarse vector represent a spectral signature's unique rate of change through the measurement space. Table 8.2 identifies the rates of change for each of the materials from artifact B013b. Charcoal(A) gives change of [3, -4, 15,5], while Turquoise(G) yields [-15, -51, 27, 85]. These two rates of change show how charcoal's spectral response is smaller than the response of turquoise.

The three bone materials present more uniform responses. Bone Cremation Smoked Outside (WW) changes [23, -3, 36, 47], Bone Cremation Inside (XX) changes [38,6,76,-23], and Bone Cremation White Outside (YY) changes [28,-2,61,-13].

The 95% confidence intervals for the five materials are presented in Figure 8.2. The medians and an interval of \pm two standard deviations shows the range of potential values for each material. Two of the bone materials (XX) and (YY) possess very similar spectral signatures as shown both by similar vectors in Table 8.2 and by their close approximation in Figure 8.2. This common behavior between similar materials illustrates the consistency of the spectral signatures.

Measurement of Dispersion

A second important issue in predictive classification derives from the detrimental effects of increasing range size on the accuracy of the classifications. The primary dispersion measure calculated here was the standard deviation as an expression of the

variability of each class of materials. Large standard deviations increase the probability that two materials will exist simultaneously in a single region of the measurement space. Conversely, a material class with a small standard deviation value generates a very narrow distribution, with less likelihood of intersecting an adjacent class. The size of a material's standard deviation depends on its pattern and texture. A material with a heterogeneous, high contrast texture will possess a larger standard deviation than a homogenous material with little contrast.

The standard deviations were calculated for each class of materials for all five original spectral layers (Appendices 3, 4). Overall, the standard deviations appeared to remain consistent across the measurement space for any given class of material. The standard deviations calculated in each band for all materials are listed in Table 8.2.

The standard deviation in each band fluctuated from 9.8 to 11.8. The amount of dispersion was largest in the near-infrared and smallest in the blue band. For each spectral layer, the second quarter of each distribution contains the largest number of materials. In this quarter, discrimination accuracy will be limited, due to the occurrence of such a large numbers of materials within the quarter; many of their distributions will overlap in the measurement space. Greater amounts of overlap will produce a corresponding reduction in classifier accuracy.

Areas where different distributions overlap one another are especially critical. Overlap of multiple distributions will reduce the discriminating power of the training database for predictive application. Overlap in several bands where a single value could indicate the spectral signature for any of several overlapping distributions decreases the probability of correct assignment of an unknown to a class.

Example Comparisons of Spectral Signatures Considering both Median Spectral Response and Variance in Spectral Response. In the above example, the distributions of charcoal (A) and turquoise (G) converge in the red spectral band. When discriminating between these two materials, the red spectral layer will provide the least useful information regarding identification of unique spectral signature characteristics.

Considering all five spectral bands, the three similar materials comprised of bone all present similar behaviors in central tendency and dispersion. The other two materials, Turquoise (G) displayed in light blue, and the Charcoal (A) shown in dark blue, exhibit different responses than the bone materials. Thus, the charcoal and turquoise materials can be discriminated from the bone materials with a fair degree of accuracy due to the minimum of convergence between the distributions. The three bone materials exhibit a large degree of overlap. Because their spectral signatures are indistinct, the classification of bone into separate classes would be very inaccurate.

In sum, when the materials were mapped individually according to the median values describing their central tendencies, the intersection points between the various materials indicated where the overlap of individual sample distributions created areas of additional classification accuracy. The more important consideration in terms of classification

accuracy was that the rate of change, slope, of each different material's spectral signatures, which are unique. Although the central tendencies and dispersion provided the starting point for the classification process, the rates of change became the critical predictors that distinguished between similar materials.

Multivariate Statistical Analysis

The Application of Multivariate Statistics to Predictive Classification

Multivariate statistics compress the measurement space from a large number of variables to a smaller number of variables. This type of reduction has proven useful in other types of archaeological applications, "...because it is a way of disentangling complex patterns of variation which are not otherwise easily assimilated" (Sheenan 1998). The data matrix of dependent and independent variables provides the variance information for comparing the variation in one dependent variable with the amount of covariation in other variables. These comparisons determine the degree of association between dependent and independent variables, derive functions to estimate dependent variables, and calculate the statistical confidence of the results (Green 1976). Since the primary goal of this research concerns the predictive classification of the spectral signatures from Hopewell copper artifacts, discriminant function analysis provided the optimal the multivariate statistical method for processing the information contained in the spectral database.

Discriminant Function Analysis

Discriminant function analysis predicts potential membership in classes defined by the dependent variables through a set of classification functions. By processing an unknown sample unit-by-unit, the decision model determines potential membership based on the classification function that provides the highest classifier score at each unit. "Discriminant analysis involves deriving the linear combinations of two (or more) independent variables that will discriminate best between *a priori* defined groups. This is achieved by the statistical decision rule of maximizing the *between*-group variance relative to the within-group variance—this relationship is expressed as the ratio of the between-group to within-group variance" (Hair 1998). The application of discriminant function analysis to predictive classification was based on the following assumptions:

- 1) Distinct known classes exist within the sample;
- 2) All the cases used as training data are correctly identified;
- 3) The classes are a random sample;
- 4) Each class's attributes is normally distributed;
- 5) Similar variance/covariances matrices exist for each group;
- 6) Class a priori probabilities can be estimated;
- 7) All classes that can exist are known.

M. J. Baxter (1994) explains the primary function of discriminant function analysis saying, "Discriminant analysis starts from the presumption that a set of objects are known to belong to one of two or more groups. Two aspects are commonly distinguished – that of

discrimination, where new variables are defined that in some sense distinguish between known groups; and that of allocation or classification, where objects are assigned to existing groups on the basis of their characteristics.” The strength of the model developed from the training database determines the predictive accuracy of the discriminant function analysis.

Yet, due to the difficulty in distinguishing between outliers and other unique spectral traits in the materials, and the inherent skewness of the sample data discussed in chapter 4, the same raw data was standardized by dividing each value by the standard deviation of its respective class. Retention of complete samples is preferable since extreme values could result from either heterogeneous textures or anomalies in extracted samples.

The theoretical model for discriminant function analysis derives from Bayes’ rules of probability. Decision rules for classification require knowledge of the *a posteriori* probabilities that a pixel belongs to any of the training classes, *i*, with a feature vector *f*. Schowengerdt (1997) describes Bayes’ decision rules and the derivations used for discriminant function analysis as:

$$\begin{array}{ll} \text{Bayes:} & \text{If } D_i(f) \geq D_j(f), \text{ for all } j \dots i, \text{ assign pixel to class } i. \\ \text{Discriminant:} & D_i(f) = p(i|f)p(f) = p(f|i)p(i) \end{array}$$

Predictive discriminant analysis derives sets of linear functions based on the spectral reflectance values recorded in the training database. The data extraction technique was explained earlier in this chapter. The class that receives the highest classifier score after evaluations of all the discriminant functions becomes the most likely material for that particular unit of the measurement space. Each different class in the training database generates a unique discriminant function. The discriminant function score (D_{sc}) for a material is defined as:

$$D_{sc} = (di_1)b + (di_2)g + (di_3)r + (di_4)n + (di_5)m + \text{constant}$$

where *di* equals the discriminant function coefficient, and each coefficient is multiplied by its respective spectral layer. By definition, the discriminant function coefficients are chosen to maximize differences between groups. The sum of the means for a set of discriminant function coefficients is zero, and the standard deviation is equal to one. Each equation creates a hyperplane showing the potential class membership for each material tested. The intersections of the planes form boundaries between the classes in the band space.

The implementation of discriminant function analysis involves two stages. This first stage is significance testing. Significance testing compares variance and covariance information from the materials. Sufficient variance must exist to ensure the dependent variables can be segregated into distinct groups. The matrix of total variance/covariance is compared via a multivariate F test to the pooled within-group variance to test for significant

difference between groups. Significant difference between the means allows accurate predictive classification of materials.

The second stage of discriminant function analysis is classification. This process derives a set of classification functions from the known classes of dependent variables. These classification functions comprise the decision-making process of the predictive analysis. Each coordinate of an unknown sample is analyzed using the set of classifier functions. For each cell in the matrix, the decision for potential membership is based on the highest classifier score for that cell.

Significance Testing of Covariance & Group Means

Discriminant function analysis assumes that the covariance between the independent variables will be homogenous for all the dependent classes. Box's M tests the fifth assumption of homogenous covariance matrices. Box's M is calculated as follows.

Let $n_i = n - 1$ for the i th population

S = pooled within groups covariance matrix

S_i = covariance matrix for i th group

$$M = (\text{Sum}(n_i) * \ln|S|) - \text{Sum}(n_i * \ln|S_i|)$$

If the $p(M) < .05$ then the variances differ significantly. Therefore, a significant Box's M value is undesirable, since it requires rejecting the null hypothesis that the variance of the independent variables remain homogenous among the dependent classes. The probability of the F-statistic must be less than 0.05 to validate the assumption of homoscedasticity, homogeneity of variances. The results of the Box's M test are displayed in Table 8.5.

The results of the Box's M test shown in Table 8.5 indicate that a significant amount of differentiation exists among the covariance matrices for the classes of the dependent variable, and as a result the spectral signatures in the training database do not appear to follow the assumption of homoscedasticity. When analyzing large samples, even small deviations from homogeneity will be found significant by the Box's M calculation.

Calculation of the log of the determinant matrix for each of the dependent classes allows the degree of individual dependent class covariance to be evaluated. In Table 8.6, the rank column identifies the number of independent variables. In each of the 52 classes, the number of independent variables remains constant at five—the five spectral bands. The pooled within-groups log determinant is -2.5331. Classes that deviate broadly from this value possess larger amounts of covariance. The largest log value is the bone cremation smoked outside (WW); thus, this material's possess variance least likely to conform to the homogeneity assumption. The two other bone materials exhibit similar behavior, possessing log determinants more than twice the size of the pooled value. The clay, yellow, malachite, and hide materials also have values more than twice the average value. When the log determinants are ranked by value, twelve of the values are less than the pooled value, and forty of the materials are greater than the pooled value.

To determine if the groups' means were unique, Wilks' Lambda test, also called the maximum likelihood criterion, was employed as a significance test. According to Hair (1998), Wilks' Lambda ranges from minus one to plus one. Results closer to zero indicate high potential for discrimination between groups, whereas values closer to one indicate group means that are identical. The Wilks' Lambda statistic can be converted to an F-statistic, allowing the calculation of significance. Low significance for the F-statistic indicates strong difference in the group means.

As shown in Table 8.7, each Lambda statistics results in very low values. The small Lambda values indicate that strong differences exist between means of different materials in the data set, and this conclusion is additionally supported by the low significance values of the Chi-square-statistic. The strong differences between the fifty-two materials analyzed seem to support the assumption for unique central tendencies, and the existence of heterogeneous means that are required for discriminant classification functions to accurately represent the dependent variables.

The significance tests automatically determine the optimum combination of variables in order to maximize discrimination between groups. Orthogonal functions that remain independent of one another are used; thus, each function contributes unique information to predictive classification. The successive functions are determined by a canonical correlation analysis.

Used primarily as a descriptive measure, the canonical correlation shows the strength of agreement between the discriminant scores and the transformed layers. The canonical correlation measures the proportion of the total variability explained by the differences between groups. Each function defined using the canonical correlation incorporates the largest remaining amount of the unexplained variance. Thus, each subsequent function will account for less variance in the measurement space than the preceding function.

The eigenvalues were calculated as the between-groups sum of squares divided by the within-groups sum of squares. The largest eigenvalue indicates the maximum dispersion for the first function as an eigenvector direction. Each subsequent function's eigenvalue is accompanied by a corresponding eigenvector. The square root of the eigenvalue determines the length of the eigenvector; thus dimensions with very small eigenvalues encompass only small amounts of the original variance, and do not account for any significant amount of dispersion between classes of materials.

The five raw spectral bands, or layers, comprised the independent variables. The materials where more than one sample was extracted during the training process were pooled into a single class, and as a result, the fifty-two materials were condensed into thirty-seven classes. The eigenvalues, cumulative percentage of variance, and the canonical correlations for the analysis are listed in Table 8.8.

As Table 8.8 shows, the first four functions possess a cumulative percentage of 99.3, and lowest canonical correlation with the original data layers was .806. These results

indicate a fairly strong agreement between the original and transformed measurement space. Additionally, even functions with relatively low eigenvalues possess strong canonical correlations between layers and the discriminant scores. The strong correlations from the first four functions indicate that these functions strongly represent the relationships of the data in the spectral layers. The fifth function correlates less strongly to the original variables, but the contribution of this function to predictive classification is minimal since it accounts for less than one percent of the variance inherent in the measurement space.

Both the standardized coefficients and the structure matrix express the contribution of each spectral layer to the classification process. Larger coefficients indicate greater influence on discrimination by a particular layer. In the structure matrix, Pearson's product moment correlation quantifies the degree of the relationship between two variables. Correlation coefficients measure the degree of agreement between two sets of scores. The coefficients range from minus one to plus one. A zero coefficient indicates no agreement, while a coefficient of one or negative one represents full agreement. A greater agreement between scores corresponds to a greater accuracy of the predictions (Kline 1994). The structure matrix in Table 8.9 shows the within-group correlations for each predictor variable in the canonical function. The strength of correlations was used to determine which spectral layers provided the most or least influence on a particular function. The strongest correlation for each layer is marked with an asterisk. By comparing the results of each column, the contribution each layer made to a particular function was evaluated.

As shown in the results from the structure matrix in Table 8.9, for function 4, the layers green, blue, red, and nir correlate more strongly with this function than any of the other, making it represent the visible color portion of the spectrum. Function 2 possesses the strongest absolute correlation with the mid-infrared layer, and also the strongest correlation among the entire group of materials. Functions 1, 3, and 5 possess no absolute correlations with any particular spectral bands, yet certain spectral layers--green, near-infrared, and near-infrared, respectively--still possess stronger relationships to these functions than any of the other layers.

Interpretation of Eigenvalues and Structure Matrix

The combination of the eigenvalues and the results of structure matrix allow the contribution of each spectral layer to the variance represented by each function to be calculated. Function 1 accounts for 72% of the variability in the brightness levels of the bands for all 52 materials. It most strongly and almost solely reflects the green band.

Function 2 expresses 21% of the variability in brightness levels – a still important contribution. It strongly and almost solely expresses midrange-infrared variation in brightness levels.

Function 3 represents only 3.4% of the total variance in brightness levels. It is correlated to moderate degrees to the near-infrared and red bands, and secondarily to the green band.

Function 4 expresses only 3.0% of the total variance of the brightness levels. It reflects all three visible bands (R, G, B) as well as the near-infrared band moderately strongly.

Function 5 accounts for .73% of the variability in brightness levels. It, again, correlates with a wide range of spectral bands (near-infrared, blue, red, and midrange infrared), but to only a moderate to weakly moderate degree. This residual dimension is not especially significant to the distinguishing of artistic compositions.

It is significant that the red and near-infrared bands correlated both substantially (> .37) with three of the five discriminant functions, whereas other bands correlated substantially with only two discriminant functions. This indicates the important contribution made by the adjacent red and near-infrared bands to the total brightness variation of the materials, and the great significance of these reddish bands to discerning the artistic imagery. This conclusion was also reached through the qualitative studies presented in Chapter 7.

Euclidean Distance as a Measure of Similarity

Euclidean geometry provides an effective method for comparison of spectral traits for the various classes of materials. The Euclidean distance coefficient is one of the most commonly implemented measures used to create an $n \times n$ matrix of distances between n objects (Sheenan 1998). Each of the five data layers was derived from an 8-bit image, and as a result, each layers possesses a possible range of 256 (2^8) values. The uniformity of the ranges in each data layer allows each one the potential to contribute equally to the distance measure. Combining the multiple spectral layers into a five dimensional measurement space creates a matrix where distances between materials are assessed using Euclidean distance transformations. By calculating the straight-line distance between pairs of materials in the five dimensions of the measurement space, the proximity of the various classes of materials was evaluated. Based on the Pythagorean Theorem, the Euclidean distance between two data points is calculated by computing the square root of the sum of the squares of the differences between corresponding values for the various pairs of materials (Sheenan 1998). The Euclidean distance is defined as follows:

$$D = \text{Sqrt} [(X_r - Y_r)^2 + (X_g - Y_g)^2 + (X_b - Y_b)^2 + (X_n - Y_n)^2 + (X_m - Y_m)^2]$$

The X and Y values used in the equation were the median values for each pair of materials where X is material 1 and Y is material 2, and the r, g, b, m subscripts are the set of spectral layers. The result of this set of calculations is a 52×52 matrix of distance values that indicate the straight line separation for all combinations of materials. Each row in the matrix represents a specific material and the columns of the matrix also contain the array of all materials. In this way, the pair-wise distance combinations are presented for the entire sample set. As the Euclidean distance value, D , decreases, the accuracy of classification between pair of materials shows a corresponding reduction. Similarly, increasing distance values, D , result in more accurate of classification between the pairs of materials. The entire matrix of Euclidean distances ($52 \times 52 = 2074$) is presented in Appendix 8.5.

The lowest distance values in the matrix indicate materials where correct predictive classification would be problematic. Logically most of the comparisons with low Euclidean distance values are materials that possess similar physical or chemical properties, or where multiple samples of the same material are included in the training database. Additionally, since the matrix is 52 materials by 52 materials, each material was compared with itself. If two materials are identical, they possess no dissimilarity; thus, these Euclidean distances are always zero, indicating no separation between materials.

The lowest two percent (40 of 2,704) of the comparisons between different materials is listed in Table 8.10. As shown in the table below, the materials with the lowest scores are multiple samples of the same class of material or materials that are of a single, general kind and that possess similar physical and chemical properties. Similarities in color accounted for a significant portion of the minimal distances, since the three spectral layers that equate to a material's color would account for sixty percent of the information used to calculate the Euclidean distance coefficient. However, the infrared layers still contribute a portion of the information regarding the separation of materials; consequently, criteria other than color also influence the separability results.

Out of the twenty comparisons representing the materials with the least likelihood for successful classification, ten of the comparisons are between same materials or materials with only subtle variations in color and chemistry.

In order to ascertain if the transformed measurement space is a more effective classifier than the untransformed raw data, the lowest two percent of the raw Euclidean distances from the separability index were compared with their corresponding distance in the transformed measurement space. Both types of distance scores were converted to standardized units using z-scores, and the two values were then compared to determine if the transformed layers provided an increased amount of separability. The results of these comparisons are shown in Table 8.11.

The transformed measurement space improves the results of the standardized Euclidean distance scores. By maximizing the amount of variance represented in each successive function, the canonical discriminant functions optimize the separability of the materials in the transformed measurement space. The increased separation between the distributions of materials reduces the degree of overlap between similar materials and consequently improves the predictive accuracy of the classifiers.

Discriminant Transformation Functions and Classification Scores

The discriminant functions convert the raw spectral data from the original measurement space to the optimized transformation space for all points in the distribution. The functions consist of five coefficients, one per spectral layer, and a numeric constant. "The traditional approach to interpreting discriminant functions involves examining the sign and magnitude of the standardized discriminant weight (sometimes referred to as a discriminant coefficient) assigned to each variable in computing the discriminant functions. Independent variables with relatively larger weights will contribute more of the discriminating function's power than do variables with smaller weights" (Hair 1998). The classification results from a set of discriminant functions that assign class membership based

on the contributions of the independent variables. Each different type of material in the training database generates a unique discriminant function based on its own within-group mean and variance. The transformation functions are listed in Appendix 8.6.

By calculating a classifier score for the entire set of derived transformation functions at each position in the training database, each location was evaluated for potential membership in all classes of materials. Tabulating the results of the classification scores for the known versus predicted materials indicates the classes of materials where incorrect identifications were most probable. Each function was processed individually; the spectral bands were multiplied by a material's function coefficients, and the five products of these multiplications were summed with the constant value. The function that generated the highest return value, called a classification score, indicates the most probable group membership.

Discriminant Function Classification and Accuracy Assessment

Classification accuracy is a critical feature of predictive analysis. Without accuracy greater than chance, the outcome of a random distribution, there is no justification for the application of the discriminant functions to additional data sets. The correct classes of the values were known *a priori* to the classification by the functions, and the probability of correct classification by random assignment would be less than three percent ($1/52 = 0.019$). Assessment of function accuracy involves determining the number of incorrect versus correct responses. If each cell along the diagonal of the matrix were the total number of classifications for a given material and all other cells in the matrix were zero, the accuracy would be one hundred percent. However, most discriminant functions did not classify all the values in the data matrix with perfect accuracy; thus a lower the value on the diagonal indicated a reduction in the accuracy of a classifier function.

The tabulated classification matrix of materials predicted by the discriminant functions is listed in Appendix 8.7. Each value in the dataset was classified using the discriminant functions in order to determine the most likely class membership. In order to evaluate these classifications, a 52 x 52 matrix of the materials was constructed, where each row represents the training site data for a material, and the columns represent the predicted material based on the highest classification score from the set of discriminant functions. The diagonal of the matrix indicates the number of values that were trained from and predicted to the same group (correct classification). The overall percentage of correct classification using this set of discriminant functions to predict materials was 82.1 percent.

Certain cells in Appendix 8.7 are highlighted based on the results of the discriminant function classification using the thirty-seven pooled materials. The highlighted cells represent the classification accuracy of the discriminant functions. Cells highlighted in grey possess a classification accuracy of greater than fifty percent. The red cells represent thirty to fifty percent classification accuracy for the discriminant functions. These classifications are most problematic since they represent either poor classification accuracy, if it is a material's comparison with itself, or they are comparisons between materials between materials that result in large amounts of misclassification.

Yellow shaded cells represent between one and fifteen percent correct classification. On the diagonal that would include a significant amount of misclassification of a material, but in other cells representing inter-material comparisons, less than fifteen percent error in classification could yield acceptable results for predictive analysis. Non-shaded cells indicate percentages of classification less than one percent, and misclassification error in the minimum range would possess the least amount of influence on the accuracy of the predictive model.

The purpose of accuracy assessment is to determine how efficiently the discriminant functions represent the sample data. While the overall percent of correct classification is useful for determining the predictive strength of the entire set of classification functions, calculating the classifier accuracy for the individual functions is necessary in order to determine how well the individual functions were able to predict specific materials.

These classification accuracy results seem to indicate that the potential copper precipitate materials that were discussed earlier, such as malachite and psuedomalachite, will be problematic for predictive analysis, due to the inability of the function modeling to properly predict the correct material. The majority of the non-copper precipitates that were believed to be intentionally applied appear to possess enough diversity and unique attributes in their distribution to allow successful classification.

The materials extracted from the training sites on artifact B013b provided a good example of how the discriminant functions classified both correctly and incorrectly. As discussed earlier, this artifact provided three types of related bone materials, and two other non-similar materials, turquoise and charcoal. Examining how these five materials were classified by the discriminant functions showed the strengths and weaknesses of the functions for predictive classification. As shown in Table 8.13, the five materials were classified into sixteen different classes of materials by the discriminant functions. However, the majority of the erroneous classifications involved minute portions of the data, typically less than one percent of the total sample of a material.

The sample of charcoal was assigned to fourteen different categories in the matrix. The amount of the charcoal sample classified correctly was 77 percent, an amount slightly lower than the overall accuracy of the classification functions. Examination of the categories showed that most of the erroneous classifications were less than two percent of the total, and were generally materials that shared properties such as organic content, color, or texture with charcoal sample.

The largest erroneous classification of charcoal occurred with the azurite lighter and azurite darker discriminant functions. Over sixteen percent of the charcoal sample was erroneously classified to these two functions. Whether the incorrect classifications of the charcoal sample were the result of incorrect selections during the training site extraction or resulted from the carbonate component of the azurite new samples of charcoal would have had to have been required to be extracted and tested with the discriminant functions to see if the new samples exhibited a similar distribution among the predictive functions. As

expected, the three classes of bone materials showed a significant amount of inter-group classification error. The greatest amount of error was in the material designated bone cremation smoked outside, which had a correct classification rate of only 57 percent. This material became distributed among twelve different functions, mostly in amounts less than two percent; however, twelve percent of the materials was classified erroneously as organic hide. Thirty-seven percent of this material was attributed to the other two classes of bone material.

The other outer bone material, bone cremation white outside, had a correct classification rate of seventy-one percent. The remaining twenty-nine percent of this material was attributed to both of the other bone materials by the discriminant classifiers. The erroneous classification of these groups was most likely due to the large degree of overlap between the spectral signatures as shown previously in Appendix 8.3. Correct discrimination among the three similar materials was reduced due the large amount of shared measurement space, and similarities among their unique spectral signatures.

The third type of bone material, bone cremation inside, possessed the greatest classifier accuracy of any of the bone groups. Eight-six percent of this material was classified correctly. Approximately twelve percent was incorrectly determined to be the other two classes of bone material, while the remaining two percent was attributed to the yellow light material erroneously. As shown in Appendix 8.3, the higher accuracy of classification for this material was most likely the result of its spectral signature being more divergent from the other two bone signatures.

Of the five materials from artifact B013b, turquoise presented the optimum classification results. The turquoise classifier function was able to categorize ninety-nine percent of the sample data correctly. The remaining one percent was divided between two other blue materials. Referring to the spectral signature listed in Appendix 8.3, the strong results for the turquoise classifier resulted from a combination of its unique distribution in the measurement space, and the strong influence of its unique hue since the color component contributed the most variance in the transformation functions.

Relationship between Separability of Materials and Classifier Error

By determining the amount of classification error among the materials that were determined to be the least separable in Table 8.10, the effects of the degree of separability on classification accuracy can be explored. As shown in Table 8.12, the separability between the materials was not equivalent to the amount of erroneous classification completed by the particular discriminating function. Additionally, the relationships between materials of a pair were not reciprocal, meaning that the same distance between the samples, A-G, would result in a different distance than G-A.

The distance separating malachite pine green from olive medium dark was approximately 2.67 units, and nearly seven percent of the malachite was categorized as the olive material. However, less than .10% of the olive material was mistakenly classified as the malachite. These differences in the classifier accuracy resulted from the differences in

the amount of overlap between the distributions for the materials. Thus, it would seem a greater portion of the malachite pine green overlapped into distribution space of the olive material, and that the olive material had a smaller amount of shared measurement space with the Malachite Pine Green.

Additionally, the amount of separation between the materials did not necessarily indicate the degree of classification error. The separation between organic hide dark and olive light-medium was 2.69, and the incorrect classification ratio between the materials was 0 to 1.94. There was a smaller amount of separation between malachite pine green and olive light-medium. Yet, this separation of 2.4 still provided better classification results than the larger separation value, since the classification error ratio for these two materials was 0.235 to 0.457. Although the majority of the materials followed the trend of decreasing separability creating large amounts of classification error, there were enough exceptions to this trend to indicate that the separability index provided an effective tool for preliminary analysis of predictive classification, but it was inefficient at indicating the degree of classification error that could be expected.

Figure 8.3 compares the distributions of materials in three layers of the measurement space using both the raw reflectance values and the optimized transformation of the original values. The upper scatterplot, showing the raw reflectance, possess much broader overlapping distributions for the materials. The lower scatterplot displays the distribution of the materials in the optimized measurement space, and the dispersion of the materials, and the resulting overlap between adjacent materials has been reduced.

This figure shows the relationship between overlap of samples and the separability between the materials. olive medium(U), olive light medium (W), and olive light monocot (Z) possess a large amount of shared measurement space in the raw reflectance values; however, in the transformed layers, the materials exhibit more compact distributions and the separability between the materials increases. The transformation functions alter the distribution of the pine green malachite material (P) changes more drastically than the other materials.

In the upper scatterplot for the raw data, the malachite possesses a skewed distribution, but in the transformed measurement space, the malachite shows a more normal distribution of values, although the large amount of space between the values for this material still creates problems with classification. This reduced classification accuracy is evident in both the discriminant function classification results in Appendix 8.7 and the results from the Euclidean distance comparisons shown in Appendix 8.5.

Case Studies of Copper Artifacts

The derived discriminant classification functions were applied to assess potential membership in classes on both small sections of artifacts and on complete artifacts (Appendices 8.8 and 8.9). The number of spectral signatures processed at one time was limited to less than fifteen by the GIS software.

Breastplate B013b. Artifact B013b's Turquoise sample was the first artifact sample tested for new materials not previously identified. The results of the predictive classification are shown for a 4x4 cm area of the artifact in Figure 8.4. During preliminary signature development, five spectral signatures were extracted from the sample. These materials were charcoal (A), turquoise (G), bone cremation smoked outside (WW), bone cremation inside, (XX), and bone smoked cremation outside (YY). The materials tested for possible inclusion include azurite darker (D), blue dark slate light (F), malachite pine green (M), pseudomalachite (S), olive medium (U), and yellow light (TT); none of this second set of materials was sampled from this artifact. The upper-right portion of Figure 8.4 shows the original RGB image of the sample area. Below this image is the legend showing the symbols, material named, number of cells classified, and the percentage of area classified. The large image on the left show the results of the predictive classification.

The Azurite Darker material disperses throughout the range of the sample area, typically along the margins of the charcoal, turquoise, malachite pine green materials. The blue dark slate light and turquoise samples were highly intermingled in the predictive classification. Malachite pine green was identified in nearly twenty-five percent of the sample area. Additionally, most of the cells assigned to this material were not previously identified during the extraction process. Charcoal was also identified in areas of the images where it was not indicated during the extraction process. The Olive Medium material showed concentrations within the charcoal material and along the perimeter of the bone and turquoise materials.

The bone materials possessed problematic classifications. The bone cremation smoked outside, and bone cremation inside were successfully identified within the regions where the original spectral signatures were extracted. However, the bone cremation white inside material was not identified anywhere in the sample area, even though this was the signature's origin artifact. This seems to indicate that the similarity and amount of overlap in the spectral signatures prevented the classification scores from correctly discerning the correct material types (see Figure 8-2).

Breastplate B031a. Application of the predictive discriminant functions to this object are shown in Appendices 8.8 and 8.9. The gum (B) material was extracted only from artifact B031a Gum1. The extractions from this artifact are shown in Figure 8.5. During the classification process, this material was classified in nearly twenty-five percent of the sample area. Charcoal (A) was identified in less than two percent of the sample area. The sample area identified as charcoal was a cohesive unit, and appears to result from a graphite or black pen used to encode a catalog number on the artifact.

The gum (B) material is concentrated at the upper portion of the image, along the margins of the materials classified as chrysocolla medium (J) and olive medium (W) materials. Chrysocolla medium (J) and olive medium (W) occurred predominately in the central portion of the sample area. Several cohesive areas of olive medium (W) and serpentine white (ZZ) are found throughout the image.

Feather light medium (AA), a spectral signature extracted from another artifact, was predicted on nearly thirty-two percent of the sample area. Thus, it could be inferred that the gum (B) material was used to affix the feather light medium material to the artifact. Copper (LL) was the only material was not identified on any areas of the artifact, and the blue light (H) material was predicted in less than a fifteenth of a percent of the sample area. This would seem to indicate these were anomalous classification due to variation in the spectral data from other materials.

Celt C013a. Artifact C013a Cuprite, shown in Figure 8.6, provides very clear classification results for certain materials. Gum (B) occurs outside the artifact perimeter within the image area, and the results are definitely erroneous classifications. Chrysocolla medium (J) is located on the outer edge of the artifact, where intersects with both the clay med. brown (MM) and clay light and medium brown (OO).

Gum (B), olive light monocot (AA), and copper (LL) occur only minimally in the sample area. Cuprite dark pink (II) and cuprite light pink (JJ) are found in no portion of the image, although cuprite blood red is classified over almost sixty-eight percent of the image. Unlike the bone materials contained in Figure 8.4, the copper materials possess sufficient spectral separability to be successfully discerned. When the RGB image is compared with the predictive classification, the left portion of the RGB image appears very heterogeneous and would be composed of several different cuprites. However, the predictive classification image shows the classification as a single discrete unit, even when several types of cuprite were included in the predictive classification.

Summary and Conclusion of the Discriminant Function Analysis

The Model. Discriminant function analysis allows the predictive classification of materials based on scoring materials into their most probable categories. In order to maximize the classification accuracy, the dataset comprised of 52 materials and 5 spectral bands was transformed using a logarithmic function. The model for discriminant function analysis is based on Bayesian decision rules. Building the model involved determining the uniqueness of the groups of independent variables, calculating eigenvalues and eigenvectors to determine the amount of variance represented by each transformed function, and interpreting the structure matrix in order to determine how the original independent variables are represented by the transformed functions. The model's Function 1, which accounts for 72% of the variability in brightness levels of the bands for all 52 materials, most strongly reflected the green band. Function 2, which accounted for a still substantial 21% of the variability in brightness levels, was comprised primarily of midrange-infrared variation. Functions 3, which contributed only 3.4% of the total variance, represented the red and near-infrared bands. Functions 4 and 5, which accounted for much less of the variance in brightness levels and are largely inconsequential, were correlated with four or more bands each. The red band was correlated substantially with four the five discriminant functions, documenting its importance to the spectral distinctions among materials.

The transformation functions used by the discriminant analysis tended to optimize the separability among materials, as was demonstrated with the list of the least separable materials identified through the use of the Euclidean distances. However, as the results of the user and producer confusion matrix showed, several of the materials that were most problematic for discrimination were materials that possessed larger amounts of separability. In this portion of the analysis, the severity of the overlap of the distribution spaces for the materials played a much more critical role in successful prediction than did the distance separating their central tendencies.

Future Studies with the Method of Discriminant Function Analysis. While the results of classification using the visible and infrared portion of the spectrum provided satisfactory results for basic predictions, increasing the portion of the spectrum sampled would allow identification of a larger portion of the spectral curve of a material. This would increase the chances of recording the portion of the spectrum where a material generates a unique spectral response, which would allow it to be accurately identified.

The predictive model would also benefit from the inclusion of a larger number of benchmark samples. Increasing the types of materials that can be identified by the discriminant model would allow the predictive functions to more closely estimate a material's correct identity.

Summary of Contributions of the Studies to Identifying Artistic Compositions with the Image Enhancement Methods Presented in Chapter 7.

Ten sides of Hopewellian copper artifacts, including seven sides of breastplates, two sides of celts, and one side of a headplate, were characterized for the color (R, G, B) and infrared (NIR, MIR) electromagnetic spectral responses of 52 materials found on them. Both univariate and multivariate analyses show that most of these materials can be discriminated from each other by one or more of the five spectral bands, and that artistic compositions made with these materials should be discernable with digital photographic enhancement methods discussed in Chapter 7.

Specifically, the single spectral band line plots in Appendix 8.4 show which materials are separated more or less from each other for each of the five spectral bands, i.e., univariately. The Euclidean distance matrix in Appendix 8.5 documents which materials are separated more or less from each other considering all five spectral bands simultaneously, i.e., multivariately with equal weighting of all five bands. The classification matrix in Appendix 8.7, which resulted from the discriminant function analysis, records which materials are discriminable from each other more or less considering all five spectral bands simultaneously and optimizing for differences among materials, i.e., multivariately and with weighting of the five bands according to the degree to which they help to discriminate among materials. All materials could be discriminated from each other with correct identifications between 89.9% and 100%, and most materials with more than 95% accuracy (Table 8.12).

Statistically, a Box M test shows that, taken as a set, the covariance matrices of the materials are significantly different from each other. Wilks' Lambda, and the Chi-square statistic derived from it, indicate that, taken together, the materials exhibit strong differences among themselves in their means.

The pairs of materials that are most likely to be confused for each other and that theoretically could interfere with the recognition of artistic compositions – 20 of 2,704 pairs – are shown in Table 8.10, based on simply the Euclidean distances between the materials. Most of these problematic cases pertain to materials that are slight variations of a more general class of materials, such as malachites of somewhat different color, or lighter and darker azurites. A few of the cases are more serious, because they represent distinct general classes of materials: (1) organic hide and light to medium olive green variant of malachite; (2) gum and a pine green variant of malachite; and (3) a dark variant of azurite and a pine green variant of malachite.

Of the five spectral bands that were used to characterize the 52 kinds of materials, two were found most essential in distinguishing among them through the discriminant function analysis: the green and the midrange-infrared band. These two bands dominated discriminant Functions 1 and 2, respectively, which together account for 92% of the brightness variability of the 52 material samples that distinguished them. The red and near-infrared bands were also found important, in that each correlated with and contributed significantly to a large number of discriminant functions—three of the five derived functions. The blue band was found to offer the least discriminating power among samples, and would be expected to be least helpful in general in distinguishing artistic imagery on the copper artifacts. Of course, it would be very helpful in the case of those (minority) artifacts where imagery was produced by creating a blue azurite patina (e.g. breastplate B050).

This quantitative finding differs somewhat from the a priori and qualitative assessments of band significance reported in Chapter 7. There, it is reported that we initially *assumed* a priori that green would be least important to the definition of artistic images because it would represent natural corrosion rather than pigments of other colors. Even when we understood that the images were produced primarily through copper patination, we weighted the green band less important than the red and blue bands. The significance of the red band to the definition of artistic images was recognized qualitatively in Chapter 7 and supported quantitatively here. The qualitative assessment made in Chapter 7 did not consider the midrange-infrared and near-infrared bands. The importance attributed to the blue band in defining of the artistic imagery differs in the qualitative and quantitative analyses; the qualitative study gave the blue channel more weight.

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Insert Tables 8.1 - 8.14, Figures 8.1 - 8.6, and Appendices 8.1 - 8.9 here.

CHAPTER 9

SUMMARY OF PROJECT RESULTS

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This project had three broad goal. First was to identify the nature of the surface materials that are found on Hopewell copper artifacts and that possibly were used in the process of creating works of art on the artifacts. Second was to identify the artistic technical processes, themselves. Third was to develop a systematic, integrated set of digital photographic techniques for effectively recovering, enhancing, and displaying the works of art.

Through the work of a team of eleven researchers, who specialize in the areas of archaeology, remote sensor systems, digital image photography and enhancement, applied metallurgy, mineralogy, petrography, paleoethnobotany, and prehistoric textile analysis, each of these three goals were achieved. The following specific accomplishments and professional contributions were made with NCPTT funding.

(1) *Preservation.* A large number of Hopewellian copper artifacts were preserved for the artistic imagery rendered on them and the surface materials found on them through the taking of ultra-high resolution, color, near-infrared, and midrange-infrared digital photographs of them.

(a) *Color Digital photographs.* Ultra-high resolution (3360 x 2253 pixel) color digital photographs were taken of 219 sides of Ohio Hopewellian copper items bearing artwork or thought to bear artwork. Of these, 122 sides were of breastplates, 22 sides were of headplates, and 75 were of celts. The items come from a diversity of sites (11) dispersed over south-central to northeast Ohio and represent a range of natural and archaeological formation and preservation processes. In total, the items also bear the full range of kinds of inorganic and organic materials known to occur on Ohio Hopewellian copper items. The sample of items photographed is approximately 10% larger than that proposed.

(b) *Infrared photographs.* Near-infrared (.715 - 1.1 microns) and mid-range infrared (1.0 - 1.8 microns) digital photographs were both taken of 263 sides of the copper items, including all of the 219 sides photographed in color. The greater breadth of the infrared sample reflects the decision to photograph more than the proposed number of item-sides that do not seem to bear much or any indications of artwork, and to explore the power of IR in revealing artwork essentially not visible to the naked eye. Examples include copper surfaces that appear largely uniform in their corrosion, copper surfaces that are entirely hidden by a uniform textile wrapping or textile-pseudomorph wrapping, and intensely burned (cremated) copper surfaces. The sample of items photographed is approximately 30% larger than that proposed.

(2) Identification and Mapping of Inorganic Materials. The mineralogy of inorganic surface materials was identified, described, and mapped exhaustively for 19 sides of 11 copper breastplates, 5 celts, and 3 headplates, and in more focused regions for an additional 25 sides of 21 breastplates, 2 celts, and 2 headplates. A wide range of copper corrosion minerals and other relatively fine-grained minerals were observed, including: cuprite, malachite, azurite, chrysocolla, turquoise, hematite, and hydroxyapatite (bone, calcined). Some minerals had multiple, distinct kinds of morphological variants. Other materials found on the artifacts include soil, mica, mother-of-pearl, calcite or aragonite, a powdered bone and calcite pigment, a powdered talc/serpentine applique, and ash. In all, 21 distinct kinds of surface materials were observed. Identifications of these substances were made by 10X and 30X binocular microscopy, as well as by reference to areas of copper artifacts known by previous chemical and physical determinations to bear these materials.

Only one item-side (B031A) was found unequivocally to evidence painting as the means by which art works were created on the copper artifacts. A yellow pigment probably comprised of bone and carbonate (identified by chemical assays done prior to the NCPTT research) was evidenced by six macroscopic and microscopic characteristics: its homogeneous, very fine grain; its lack of chemical interaction with the underlying copper substrate, causing it to flake off; its unnatural flat top surface; shrinkage cracks within it; possible drying lines within it; and its limit to a well-defined area with sharp boundaries. The item also bears a white serpentine or talc substance that was applied as a powder rather than a pigment in a liquid vehicle, within well constrained lines. Three other items – B052A, B053A, and C023A – had a yellow material that is chemically similar to that on B031A and that probably was the same paint, but its nature as a paint could not be confirmed by its visual properties. C023 also bore hematite powder that was well bounded and that was probably applied, either as a paint or powder.

Copper minerals (corrosion) were the minerals found most commonly on the artifacts. Malachite was most common, followed by azurite. Materials that occurred on most artifacts and that occupied a moderate to a large portion of the area of each include stalactite-form malachite, cauliform malachite, malachite grown through an organic material forming a pseudomorph, malachite grown after cuprite, stalactite-form azurite, iridescent cuprite, and cuprite in situ.

Art works on the items that did not bear paints or powdered pigments were most probably created by patination. Several observations support this conclusion. First, almost all the inorganic materials within areas thought to represent artistic compositions are copper corrosion products with natural patterns of growth. Second, no evidence was found for particular kinds of corrosion having grown unintentionally under particular kinds of paints, nor was corrosion growing through paints observed. Third, soil that adhered to the objects seldom had corrosion growing into it. This suggests that the corrosion developed *prior to* burial of the objects in the ground. In contrast, in experiments made by Pimentel and Carr reported above, soils that served as vehicles for applying acids to copper plates to produce patinas had corrosion that grew through them and that made them difficult to remove from the patinas. Fourth, half of the copper items surveyed for organic remains on them had

textiles, and additional items had other absorptive materials on their surfaces. Patinas may have developed naturally under such materials if they had been applied to the copper artifacts as decorative cutout images—cutouts are a well-developed form of Hopewell art—or if they had been applied with acids to the artifacts in order to intentionally produce patinas of those shapes on the artifacts. Fifth, 32% (n = 6) of the 19 item-sides thoroughly examined had corrosion with a mesa-like growth habit, suggesting their formation underneath a growth-limiting boundary, such as organic cut-out shapes that were applied for decoration and unintentionally produced patinas, or that were applied soaked with acid in order to intentionally produce patinas. Sixth, several artifacts exhibited “drying lines” or “meniscus lines” that would have developed around the edges of acid or water-soaked organic cut outs. Seventh, no sharp boundaries were found between corrosion minerals of different kinds, suggesting that corrosion was not gathered as a pigment, mixed with a liquid vehicle, and painted on the artifacts. Where boundaries did occur, they were more diffuse and related to meniscus effects. Eighth, one item – B050 – bore an apparently complex artistic composition and had an equally complex mineralogy, with 9 distinct kinds of surface materials that were spatially distributed to form the art work. Several other items had 7 or 8 distinct kinds of inorganic surface materials, supporting their artistic rather than natural origin – one would expect only one or a few kinds of corrosion to develop naturally on an artifact of limited size. Ninth, no significant differences were found in the kind of corrosion products that occurred on opposite sides of an item, which might have been the case if the corrosion were natural and different moisture and other corrosive conditions existed above and below the item in the ground.

In general, the three different classes of artifacts – breastplates, celts, and headplates – had similar ranges of minerals on them. However, certain exceptions possibly point to different kinds of artistic patination having been intentionally produced on different kinds of artifacts used in different social and ritual contexts. Azurite was absent from the celts examined, but occurred on two-thirds of the headplates and one-third of the breastplates studied. Cauliform malachite occurred twice as frequently on breastplates and celts (two-thirds of them) than on headplates (one-third of them). Malachite bubbles (perhaps from the burning of patinated items when they were decommissioned) occurred on two-thirds of the celts examined but on none of the headplates and breastplates studied. Malachite pseudomorphs of organic materials were found slightly more often on breastplates than on celts and headplates.

No inorganic surface materials beyond burnt bone significantly correlated with items bearing cremated remains. This suggests that art works made by different processes were not distinguished from one another in their ritual form of decommissioning.

(3) Identification and Mapping of Organic Materials. The organic surface materials on the entirety of both sides of 77 copper artifacts, including 59 breastplates, 14 celts, and 4 headplates, totalling 154 sides, and from seven sites, were identified with stereobinocular microscope from 7 - 30X and then mapped, for comparison to their color and infrared photographic responses. The sample is about 30% larger than that proposed, which was made possible by the team paleoethnobotanist contributing extra effort without cost to the grant.

Eleven general categories of organic materials were identified on the artifacts: textiles composed of the yarns from Group 1 fibers (herbaceous plants such as Indian hemp or milkweed, for example), leather/hide, feathers, fur, bark, carbonized wood, uncarbonized seeds, bast, monocot stems, cut-up plant stems, a plant-fiber plaster of a kind, and unknown organics. Textiles, leather, and wood charcoal were the organic materials most commonly observed, with up to 40 or 45% of the surveyed copper objects from a site having them. Feathers and bark were about half as common, and fur about a third as common. Organic materials turned out to be much more common on the copper artifacts than had originally been thought, which can be related in part to some of them likely having been used in the process of making art works on copper, by collage or patination, as described below.

Two copper artifacts and possibly a third were found to have traces of paints on their textiles: red and olive green in one case (B034), and red in one or two others (B044, B079). The olive green pigment may have been an example of a paint made from gathered copper corrosion; green paint is known to have been applied to other, free examples of textiles.

Different kinds of copper artifacts vary in the kinds of surface organic materials that they bear. Breastplates had organic materials of all kinds more often than celts. Breastplates were especially favored with textiles, twice as commonly as celts. Different sites varied in the kinds of organic materials that commonly occurred on their copper artifacts. Seip had greater percentages of copper artifacts with Group 1 plant textiles, bark, and wood charcoal. The Hopewell site had greater percentages of copper artifacts with leather/hide and monocotyledon leaf fragments. Edwin Harness mound had greater percentages of artifacts with feathers. These differences in the materials found on the artifacts by artifact type and by site probably reflect, respectively, first the different ritual functions and social contexts of use of the different artifact types and the somewhat different manners in which they consequently were decorated, stored, and/or decommissioned, and second, the different rituals of decoration, storage, and decommissioning practiced by different, neighboring Hopewellian communities. Differences in the frequency and means of copper patination among artifact types and among communities is one possibility.

Most sides of most breastplates bear a diversity of organic materials, rather than only one kind. Of 60 breastplates examined in detail or scanned, 52 (86.7%) had two or more distinct kinds of materials. This pattern is in line with the observation that organic materials appear to have been arranged on copper items as collages, to produce artistic compositions.

In all, a broad range of explanations can be offered for the observed occurrences and spatial distributions of organic materials on the surfaces of Hopewellian copper artifacts. These possibilities, which are not mutually exclusive, include: (a) cutouts of textile, hide, fur, and/or feathers that were directly and intentionally applied to the artifacts to form collages; (b) cutouts of the same materials soaked with mild acids and applied to the copper artifacts to produce patinas in those shapes; (c) textiles, hide, fur, feathers, and/or plant masses that were spread over a copper artifact and then removed in places by sanding or carving them away to produce positive or negative images; (d) small flowers, seeds, cut up

stems, pearls, shell beads, or cremation remains that were intentionally placed on the objects during decommissioning rituals, forming imagery or not; (e) feathers that were arranged in various directions over the entire surface of an item to create an artistic composition; (f) textiles, hide, fur, feathers, and/or plant masses that were layered on top of a copper artifact during a decommissioning ritual, but not with the intent of creating imagery; (g) textiles, hide, textiles with feathers possibly attached, and hide with feathers possibly attached, which were used to wrap copper artifacts with patinas for decommissioning and burial, followed by the differential preservation of the materials in locations of different patinas; (h) textiles, hide, fur, and feathers that were components of clothing and against which copper artifacts with patina were laid during burial, followed by the differential preservation of the materials in locations of different patinas; (i) textiles, hide, or textiles with attached fur or feathers that were used to wrap plain copper artifacts without patina images; (k) textiles, hide, fur, and feathers that were parts of clothing and against which copper artifacts without patinas were laid during burial; (l) large expanses of hide or fur that were placed over copper artifacts and painted; and (m) any of the above processes combined with differential preservation or erosion in the ground or during cleaning. Of these multiple ways in which organic materials may have come to be present and preserved on Hopewellian copper artifacts, none was common in the sense of pertaining to the majority of the 154 artifact sides examined.

(4) *Identification and Mapping of Textiles and Cordage.* The textiles and cordage on 132 sides of 66 copper breastplates, celts, and headplates were identified for the structural properties of their yarns and/or weaves with a 7X stereozoomscope and mapped for their locations on the items. This sample is smaller than that proposed, by 68 item-sides, because a good percentage of textiles and cordage on items in the Ohio Historical Society collections had been converted to pseudomorphs comprised of corrosion. This condition prevented firm structural observations. In addition, the textile identification process turned out to be more time consuming than originally planned.

Textile constructions were limited to four kinds: oblique interlacing, spaced 2-strand twining, alternate pair twining, and spaced alternate pair twining. Textiles were found on breastplates and celts with approximately equal commonality (approximately half the artifacts of each type examined) and not at all on headplates in the Ohio Historical Society. (One headplate at the Ross County Historical Society had much cordage on both sides.) Most copper artifact sides with fabrics present on them (48 of 68; 71%) had fabrics on less than 50% of their area. Very rarely did fabrics cover 80% of the area of a side. One-third of the 66 artifacts had textiles on both sides, one-third on only one side, and one-third had no textiles.

Textiles could, in the abstract, have come to occur on the copper artifacts in several ways: (a) by the artifacts being wrapped in a cloth or placed in a bag; (b) by the artifacts having lain against clothing or shrouds worn by the deceased; (c) by textiles having been cut out into shapes that were applied to the artifacts to decorate them; and (d) by textile cutouts having been soaked in weak acid and applied to the artifacts to create mineral images through copper patination. The idea of artifacts wrapped in bags is not relevant to most of the copper artifacts examined because most do not have textiles on both sides of them. The

same is true for the idea of the artifacts having lain against clothing. In addition, neither of these ideas is supported by the small area of a copper artifact that textiles typically cover. The latter fact provides greater support for the idea that the textiles were cutouts applied to the artifacts for decorations or to create copper patinas in their shape.

(5) *Quantitative Modeling of Corrosion Processes.* Ten Pourbaix thermodynamic quantitative models of corrosion development were created. The models allowed an evaluation of whether the several to many mineral species of copper corrosion found on single copper breastplates, celts, and headplates likely developed naturally after burial in soil or, instead, were copper patinas that were induced intentionally by Hopewellian artists to create artistic compositions. The models show that only one compound will be chemically stable at a given pH and electrical potential, and that thus it is unlikely that more than one copper corrosion compound or at most two will form on a given copper artifact naturally. If chemical environmental conditions and equilibria change over time, the previously formed corrosion will become unstable and a new corrosion will form in its place. Reasonable explanations of the diverse copper corrosion minerals found on the copper artifacts, from a chemical corrosion perspective, include painting with corrosion pigments or patination. Examination of the surface materials on the artifacts showed that painting seldom occurred, leaving intentional patination as a logical explanation.

(6) *Examination of Breakage Patterns of Copper Artifacts for Intentional, Standardized Means of Decommissioning Them from Their Ritual and Social Uses.* In the course of detecting imagery on the copper breastplates, it was noticed that some broken ones ($n = 49$) were similar in shape to the images of animal and human heads applied to such plates by patination, painting, and/or collage. Many of the breaks occur at odd angles that do not appear natural. It was hypothesized that these breastplates were decommissioned by purposefully breaking them into specific, culturally-preferred forms. This practice had already been witnessed by C. Carr in other media, including fabrics, stone bifaces, and shell artifacts.

To explore this possibility, a sample of 20 of the 49 plates was selected for further study, including 16 breastplates and four headplates. The edges of each selected item were examined by microscope at 10 - 20X to determine whether the broken edges had as much corrosion development as the unbroken edges, or whether they appeared to be fresh breaks (made at the time of excavation or thereafter). The kinds and amounts of corrosion on the broken edges were also compared to the kinds and amounts on copper plates that had been mechanically or electrolytically cleaned of corrosion during their early curation. The latter served as a baseline for defining “recent” corrosion, i.e., that which might develop between the time of excavation of the artifact and the present.

The microscopic examination showed that most of the broken edges of the 20 plates were well-covered with cuprite and/or malachite and were very old, with the strong likelihood that they corroded in the soil and were produced prior to burial. It is concluded that breastplates and headplates were sometimes decommissioned by breaking them into specific animal and human head shapes that were culturally important.

(7) Innovations in Image Capture Methodology.

(a) Photomosaicing. Curved objects, including copper breastplates that were curved in length and usually width, as well as a few large celts with curved tops and sometimes bottoms, posed special photographic problems. The goal of creating a flat layout of each object with minimal distortion from parallax error could not be achieved with one photograph. To create a flat layout, multiple digital photographs were taken at different points along the objects curvature, perpendicular to it. Operationally, this was achieved for headplates by keeping the digital in one position and rotating the headplate about its approximate center of curvature on a styrofoam support so that each photographed section was oriented parallel to the plane of focus of the camera. Celts, having less curvature, were repositioned more subtly between photographs. The photographs of the series for each artifact were then spliced together to form a single, flat layout using Adobe Photoshop's image scaling, rotating, skewing, and stretching routines – a procedure from satellite imaging called photomosaicing.

(b) Lighting. Photography light stands commonly orient two lights at 180° from each other and 45° from the object plane. This tends to remove shadows on an object that are produced by its surface texture. To the contrary, we wished to document the relief of the surfaces of artifacts photographically because surface texture is an important diagnostic characteristic of the organic and inorganic materials on the artifacts and, thus, critical to the definition of art works comprised of these materials. To include information on material relief in the digital photographs taken, without shadows from relief overwhelming the photograph and the recording of material color, we oriented both lights at 45° from the object plane, as usual, but oriented the two lights at 135° from each other: 90° from the length of the object on its “west side” and 45° from the length of the object on its “east side.” This lighting orientation produced shadows from relief features that were oriented in essentially any direction on the object. The orientation of the lights 45° from the object plane ensured that much of the color of the object was also visible and not obscured in shadow.

(8) Qualitative Evaluation of Digital Photographic Spectra and Digital Enhancement Procedures for Discriminating among Surface Materials and Discerning Artworks.

(a) Color Image Processing. Each of the 219 color digital images of the copper artifacts was prepared in Adobe Photoshop for image processing by changing its background to a uniform grey, and adding a rule of standard format. Contrast enhancements of two kinds were made for each photograph: a total histogram stretch, in which the histogram of all three bands of the RGB image were stretched at the same time, and an individual color band histogram stretch, in which the histogram of each band was stretched separately. The first contrast enhancement maintained the normal color balance of the image, which usually emphasized the green and/or blue channels, whereas the second contrast enhancement gave more equal balance to all three channels and de-emphasized the green and/or blue channels compared to normal. Both kinds of contrast enhancements considerably improved the visibility of art works on the artifacts. A third routine, histogram

equalization, seldom proved effective in this regard, and was not pursued for the entire set of photographs.

Seven kinds of calculations of only two of the three color bands (R x B, R x B-inverse, R-inverse x B, R-inverse x B-inverse, B x G, B-inverse x G-inverse, and B - G) were made for both of the two kinds of contrast enhancements just discussed. These band calculations, of the many possible, were the ones found most effective on a trial-and-error basis in distinguishing and clarifying features in the art works. All seven of the bands were found important, in that different bands were helpful in distinguishing different kinds of organic and inorganic materials and, thus, different features within the art works.

(b) *Infrared Image Processing.* Each of the 263 near-infrared photographs and each of the 263 mid-range infrared photographs were enhanced in their contrast by a simple histogram stretch, using Adobe Photoshop. The images were sharpened with a sharpening filter before contrast stretching them. This order of the two operations was found to give images of slightly better contrast than the reverse.

The near-infrared and midrange infrared photographs both clarified the definition of art works on the copper artifacts, but different bands were more or less effective for different artifacts, apparently depending on the materials comprising their art works. In general, the near-infrared photographs corresponded more closely to the visible light, RGB photographs in the images that they revealed than did the midrange-infrared photographs, as was expected. The midrange-infrared photographs thus provided more information independent of the visible light bands than did the near-infrared photographs – a finding substantiated by the discriminant function analysis made of all five visible and infrared bands (see below).

(c) *Hybrid Color and Infrared Images.* Hybrid, color-infrared images were created in the GIS program, IDRISI, by replacing the R, G, and/or B channels of a photograph with a near-infrared band, a midrange-infrared band, and/or a calculated color band or occasionally a calculated color and infrared band. Hybridizing the digital photographic bands required that the three visible bands be reduced in their resolution closer to the resolution of the infrared bands, and that the three visible bands and the two infrared bands be resized and registered in relation to each other. These image modifications were necessary because the color, near-infrared, and midrange infrared images were captured with different sensor systems. Registration was accomplished in IDRISI, usually with a linear, rubber-sheeting transformation anchored in 15 points of correspondence among images. Occasionally, a quadratic transformation was required.

(d) *Evaluation of Bands, Band Calculations, and Hybrid Band Combinations and Combination Procedures for the Effectiveness in Revealing Artistic Compositions.* In general, the ease with which artistic compositions on the artifacts could be defined decreased from the Red to the Blue to the Green bands, and from the near-infrared to the midrange-infrared bands. Band calculations ranged in their effectiveness from high to low as follows: R x B-inverse and R-inverse x B-inverse, to B x G-inverse and B-inverse x G inverse, to R x B, to B x R-inverse and B - G. In general, R x B images looked very similar to the original RGB image and provided little new information, whereas other bands often

brought out features not as visible or not visible in the RGB image. R x B-inverse usually looked very similar to B x G-inverse but often provided somewhat better image contrast. Likewise, R-inverse x B-inverse usually looked very similar to B-inverse x G-inverse and commonly produced better image contrast. The B - G band generally was grainy, and sometimes could not be contrast-stretched to give an image that wasn't very dark and discriminating. The Red and NIR bands and combinations of these bands with other colors gave the artistic composition their greatest visibility.

Working with hybrid, color-infrared images allowed the exploration of the effectiveness of a number of operations in revealing the artistic compositions. First, no one or few bands or band combinations were always or usually effective in improving the clarity of the art works. For each different artifact, different bands were found optimal and were selected for use. Using information from all five bands was not found to be a good, general strategy, because this approach muddled the clarified information in some bands with the grosser information in others. Second, the same art work was often best explored with multiple combinations of bands; different features of a composition were brought out by different bands, presumably depending on the materials of which they were comprised. Third, it was found essential for effective display of the art works to place the most discriminating band in the R channel, the next most discriminating band in the G channel, and the third most discriminating band in the B channel. Third, unsupervised clustering gave clearer renditions of artistic compositions than did supervised clustering when logical units within a composition were internally heterogeneous or spiky. Fourth, cluster analysis helped to define artistic compositions better than palette boundary redefinition of a single-band image when logical units within a composition were internally heterogeneous and spiky. Palette boundary redefinition was found preferable when logical units were internally homogeneous. Fifth, palette blending was found better at rendering artistic compositions when their logical units were internally heterogeneous, whereas a palette defined with crisp boundaries among colors was found to better at defining compositions with internally homogeneous logical units. Sixth, cool and neutralized blue and yellow colors were found optimal color palettes for displaying images and for avoiding eye-jarring color contrasts. Seventh, principle components classification of pixels using multiple color and/or infrared bands was not found as helpful in clarifying artistic imagery as was cluster analysis or palette redefinition, when one or a few bands providing good definition of the art could be found initially. Principle components analysis was more helpful in clarifying art works when only bands with poor to moderate image definition were available.

(9) *Developing a Quantitative Model for Identifying Surface Materials and Discerning Artworks.* The color and infrared electromagnetic spectral differences among 52 kinds of surface materials that are found on Hopewellian copper artifacts and that often comprised elements of their artistic compositions were characterized and modeled digital photographically and statistically. The materials include cloth, leather, feathers, pigments, patinas, and various minerals. The spectral bands examined encompassed red, green, blue, near-infrared, and midrange infrared. Digital photographs of ten copper artifacts provided the samples of the materials and the source of the spectral bands. The goal of this work was to build a quantitative model that allows an assessment of two things: (a) the degree to which the various materials can be distinguished from each other by their color and infrared

spectra and, thus, the artistic compositions on the artifacts can be clarified photographically, and (b) the particular portions of the electromagnetic spectrum that are most useful for making such discriminations.

The degree to which materials can be distinguished from each other photographically was estimated univariately and multivariately. First, simple, single spectral band line plots were made of the spectral responses of the 52 materials for each of the five spectral bands. These plots show which materials are more or less alike in the R, G, B, NIR, and MIR responses. Second, the Euclidean distances between all pairs of the 52 materials were calculated, based on their “distances” from each other on the R, G, B, NIR, and MIR bands. The matrix documents which materials are more or less alike in the multispectral responses. The relationships among materials in the matrix could be summarized approximately by a multidimensional scaling plot or cluster diagram, although this was not done. Third, a canonical discriminant function statistical model based on all 52 materials and all five spectral bands was built. The model is very successful, in that it is capable of identifying all materials and discriminating them each other 89.9% to 100% of the time, that is, for 89.9% to 100% of the spectrally sampled pixels of a material. A Box M statistical test, Wilks Lambda, and the Chi-square statistic all indicate strong differences among the spectral responses of the materials and their distinguishability. The least well discriminated materials were primarily slight color or textural variants of a given general class of materials, such as malachites of somewhat different color or lighter and darker azurites. Three more serious misidentifications made occasionally by the model include: (a) organic hide and a light to medium olive green variant of malachite; (b) gum and a pine green variant of malachite; and (c) a dark variant of azurite and a pine green variant of malachite. Overall the results of the discriminant function analysis suggest that most features of artistic composition comprised of any of the 52 materials should be discernable with color and infrared digital photographic methods.

Of the five spectral bands used to build the discriminant function model, two were found most helpful in distinguishing among the 52 kinds of materials: green and midrange-infrared. These two bands dominated the first two discriminant functions, which together accounted for 92% of the brightness variability of the materials that distinguished them. The red and near-infrared bands were also found to be important to distinguishing among materials. These two bands correlated with and contributed significantly to three of the five derived discriminant functions – more functions than any other spectral bands correlated with. The blue band was found to have the least discriminating power. These generalizations about the utility of particular bands, of course, are based on all 52 materials simultaneously. A given pair of materials might be most distinguished by the blue band: for example, light and blue azurite patinas, or azurite and malachite. The need to tailor digital photographic enhancement procedures to the particular artifact rather than a large set of artifacts in general must be emphasized.

(10) Reconstruction of Hopewellian Artistic Methods for Creating Images on Copper. The mineralogical and chemical analyses of the copper artifacts, supported by the inventory of organic materials on them, have led to a reworking of our team’s understanding of how imagery was made on the copper objects. At the time of writing of the grant proposal, it was thought likely that spatial patterning in both the copper and noncopper

minerals was the result of painting with copper and noncopper pigments in some organic vehicle. The research team has, indeed, confirmed through microscopic examination that a few artifacts clearly have deposits of ground pigment particles on them – hematite, serpentine, and hydroxyapatite. Azurite and other copper corrosion minerals may also have been painted onto copper very occasionally. However, it appears that the great majority of images comprised of copper corrosion minerals were probably produced by patination, either intentional or incidental in nature.

Specifically, we suggest that some artifacts probably bear patinas that were produced intentionally by techniques common in copper artwork today. These techniques include (1) painting corrosive solutions in the form of images or parts of images directly on the copper artifacts, perhaps with the application of heat to accelerate the corrosion process before the maker's eyes; (2) applying shaped cutouts of various organic materials (e.g., textiles, hide) to the copper artifacts and soaking the cutouts with corrosive solutions to produce patina images under the cutouts; and (3) applying naturally particulate or ground organic materials (e.g., seeds coats, ground up wood or other plant material) in a pattern on the copper artifacts and soaking the covered area with corrosive solutions to produce patina images under the covered area. The likely production of some patinas by these particular methods was brought to our attention by a master copper worker (David Pimentel, Professor and Chair of the Jewelry and Metals Department, School of Art, Arizona State University).

It is also possible that some of the patinas were incidentally produced. They may be a byproduct of the intentional application of decorative organic cutouts onto the copper surfaces, followed by natural patina development under the organic cutouts or paints, unintended for the eye. The organic cutouts or paints then may have deteriorated, delaminated, and been lost, or been removed during excavation and/or museum curation.

The empirical observations that lead us currently to suggest patination development as a mechanism by which the images were produced and/or preserved are the following. (1) Most instances of copper corrosion minerals in image-bearing areas of the artifacts have natural mineral growth patterns, or natural growth patterns modified somewhat by the occurrence at one time of growth-restricting surface materials of some kind (organic materials?) over the corrosion. (2) Despite the natural growth patterns of the corrosion minerals in particular locals, there are three features of the corrosion surfaces that are clearly unnatural, cannot be explained by fully natural corrosion processes as we understand them, but can be explained by the intentional or incidental patination processes described above. These features are: (a) the occurrence of relatively sharp linear and curvilinear boundaries between areas of different corrosion minerals; (b) the homogeneity of the corrosion minerals within those bounded areas; and (c) the great diversity of kinds of corrosion minerals present on some single artifacts, despite their restricted size, compared to what normally would occur on a single piece of float copper in nature. (3) Organic surface materials on the artifacts were found to have affected the kinds of corrosion minerals that developed on them. (4) Organic materials of one kind or another occur on the copper artifacts in much higher frequency than previously thought, perhaps as high as 80% of the specimens. (5) Examples have been found of textiles that were cut into recognizable, repeated shapes, and pasted/laid on the copper artifacts. (6) Examples exist of free-standing Ohio Hopewellian

fabrics that were used for mortuary canopies and/or shrouds and that were decommissioned by cutting them into shapes of the same kinds found on the copper artifacts, at sites where the copper artifacts also occurred.

To test the hypothesis that intentionally or incidentally made copper patina images were produced on Hopewellian copper artifacts, Pimentel and Carr made 42 test copper plates with 15 test patches each, documenting various combinations of salts, acids, and acid absorbant materials. All the materials are easily found in nature and were accessible to Hopewell Native Americans. The salts include table salt, crushed gypsum, crushed shell, and bone meal, as sources of corrosive chloride, sulfate, and carbonate, and phosphate ions, as well as crushed copper corrosion as seed crystals. For acids, pure red grape juice, apple juice, citric acid, cranberry juice, apple vinegar, white vinegar, urine, and three strengths of tannic acid as found in acorns we used. For the absorbant materials, we used hide, textiles, and feathers, which were found on the Hopewellian copper artifacts. In two weeks at room temperature, the test plates developed thick patinas of cuprite, malachite, chrysocolla, turquoise, and azurite – the minerals that predominate on Hopewellian copper artifacts. Corrosion impressions of feathers and textiles, which occur commonly on the artifacts, were also produced. Finally, a cuprite patina image of a bird-man creature, as found commonly on Hopewellian copper artifacts, was reproduced by cutting out its silhouette in textile, moistening it with a salt-acid mixture, covering it, and letting it stand for two weeks. The cuprite grew from the substrate naturally, but had crisp edges not usually found in natural corrosion, as in the case of the artistic compositions on Hopewellian copper artifacts.

(11) Tangible Products

(a) Final Report.

This detailed, final report to the NCPTT has also been sent to and archived in the Ohio Historical Society, Columbus, OH.

(b) Publications and Professional Presentations Made.

Carr, Christopher, A. Lydecker, D. Pride, S. Hoffman, J. Colwell, & J. Mitchell

2000 Digital Photographic Preservation of Artworks on Ohio Hopewell Copper Artifacts. Paper presented at the annual meeting of the Society for American Archaeology, Philadelphia, April.

Wimberly, Virginia

2001 Preserved Textiles on Ohio Hopewell Copper Artifacts: Clues for Artifact Relationships. Paper presented at the annual meeting of the Society for American Archaeology, New Orleans, April.

Wymer, DeeAnne

2001 Organic Preservation on Ohio Hopewell Copper Artifacts: New Insights into Middle Woodland Ritual. Paper presented at the annual meeting of the Society for American Archaeology, New Orleans, April.

Wymer, DeeAnne

- 2001 Organic Preservation on Prehistoric Copper Artifacts of the Ohio Hopewell. Paper presented at the annual meetings of the American Anthropological Association, 100th anniversary, Washington, D.C., November.

Barron, Jeffrey W., and Christopher Carr

- 2002 Hopewell Mortuary Artifact Analysis using Spectral Indices & Discriminant Analysis. Poster presented at the Mid-West GIS Conference, Kansas City, MO., April.

Carr, Christopher, Andrew D. W. Lydecker, Edward Kopala, Jeffrey S. Nicoll, Jeffery A. Colwell, Steven M. Hoffman, John Mitchell, Ann Yates, David Pimentel, Duane Simpson, and Jeffrey Barron

- 2002 Technical Studies of Artworks on Ohio Hopewell Copper Artifacts. Paper presented at the annual Midwestern Archaeological Conference, Columbus, OH, October 3.

Wymer, Dee Anne

- 2002 The Value of Archival Collections: Organic Preservation on Hopewell Copper Artifacts. Paper presented at the annual Midwestern Archaeological Conference, Columbus, OH, October 3.

Wimberly, Virginia

- 2002 Hopewell Fabrics: Evidence from Copper Artifacts. Paper presented at the annual Midwestern Archaeological Conference, Columbus, OH, October 3.

Barron, Jeffrey W., and Christopher Carr

- 2002 Hopewell Mortuary Artifact Analysis Using Spectral Indices and Discriminant Analysis. Paper presented at the annual meeting of the American Anthropological Association, New Orleans, November

Bernardini, Welsey, and Christopher Carr

- 2005 Hopewellian Copper Celts from Eastern North America: Their Social and Symbolic Significance. In *Gathering Hopewell: Society, Ritual, and Ritual Interaction*, ed. by C. Carr and D. Troy Case, pp. 624-647; esp. pp. 626-631. Kluwer Academic Press, New York.

Wimberley, Virginia

- 2005 Preserved Textiles on Hopewell Copper. In *Perishable Material Culture in the Northeast*, ed. by Penelope Ballard Drooker, pp. 69-85. University of the State of New York, The State Education Department, Albany, NY.

Wymer, DeeAnne

- 2005 Organic Preservation on Prehistoric Copper Artifacts. In *Perishable Material Culture in the Northeast*, ed. by Penelope Ballard Drooker, pp. 69-85.

University of the State of New York, The State Education Department, Albany, NY.

(c) Masters' Thesis

Barron, Jeffrey W.

2005 A Determination of Hopewell Mortuary Artifact Composition Using GIS Modeling, Spectral Indices, and Discriminant Analysis. Unpublished Masters' thesis. Department of Anthropology, University of Arkansas, Fayetteville, AR. January.

(d) Archiving of Project Images and Notes.

Compact disks of each of the 219 raw color images, 263 raw near-infrared images, 263 raw mid-range infrared images, and many hundreds of trial enhanced color images and enhanced hybrid color and infrared images have been made and archived at Arizona State University. The laboratory notes and maps produced by the mineralogist, plant and animal materials specialist, and textile specialist, who are members of this NCPTT research team, have been duplicated and archived with the Ohio Historical Center, Columbus.

(e) Media Announcements.

In late summer, 2000, the project was announced to the press and a full page Sunday cover story was published in the Columbus Dispatch, Columbus, OH. An interview about the project, for release to local and national presses at its closure, has been given to the Arizona State University Press Media Office.