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Fibrous twists and turns: early ceramic technology revealed through computed tomography

Matthew Sanger · James Thostenson · Morgan Hill · Hannah Cain

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Abstract While the emergence of pottery manufacturing is a wide-spread historical occurrence, and one that has garnered the attention of archaeologists for decades, we know very little about how these ancient vessels were created. Through the application of radiographic scanning and computed tomography this paper provides insights into the manufacturing techniques used by the earliest potters in North America. While x-rays have been used to investigate ceramic manufacturing techniques for decades, this paper provides a reassessment of radiography in light of advances in both computed tomography and reconstructive software.

1 Introduction

Archaeologists and historians have long been interested in the invention of ceramics around the world. The creation of ceramic vessels has been heralded as an important step within human history [9], yet we know relatively little about the techniques used to create these ancient objects. This paper will explore the possibilities of using radiography, including computed tomography (CT)-scanning technology, alongside new software applications, to reconstruct the particular manufacturing techniques used by ancient potters. We will determine the applicability of both traditional and three-dimensional radiographic imaging to determine ancient manufacturing techniques through an inspection of macro- and micro-structural characteristics of ceramic vessels. The benefits and drawbacks of radiographic techniques will be discussed along with suggestions for further research.

The creation of ceramic vessels requires the addition of tempering agents to the clay in order to survive the dramatic shifts in temperature associated with the firing process. Numerous tempering agents have been used by potters, including sand, shell, and grit. A less common addition, but one integral to this paper, is the use of vegetative fibers. Fiber tempering is found around the world, often in conjunction with the earliest manufacturing of ceramics in a region [5, 10, 11, 19, 26, 28]. The source of the fibers varies by region and can include bark, moss, and shredded fronds. The fibers often become carbonized and do not survive the firing process, leaving behind relatively long, thin voids within the finished vessel. Because of the dramatic difference in density between these voids and the surrounding ceramic fabric the presence, orientation, and character of the tempering agents is highly visible using radiographic technology. The visibility of tempering agents is important to this project as prior radiographic and experimental studies show that different formation techniques create characteristic internal structures within ceramic vessels. These internal structures are largely visible by looking at the directionality, regularity, shape, and boundedness of voids and temper within the finished vessel [3, 4, 16–18, 22, 24, 27, 31, 34, 35, 42]. Through experimental and ethnographic research, researchers have been able to characterize a wide range of construction techniques, including wheel throwing, paddle and anvil, and coiling and relate these manufacturing methods to characteristics visible within radiographic imaging.

The present study focuses on fiber-tempered ceramics in order to capitalize on the radiographic visibility of this tempering technique. The samples date to the Late Archaic (5000–3000 B.C.) of the American Southeast, a time period

M. Sanger (✉) · J. Thostenson · M. Hill
The American Museum of Natural History, New York, NY, USA
e-mail: sanger@amnh.org

M. Sanger · H. Cain
Columbia University, New York, NY, USA

in which ceramics were first being constructed by Native Americans in North America [39]. Prior research suggests that ceramic vessels were constructed in a variety of ways, including modeling, pinching, and coiling techniques that appear to be bounded at a sub-regional scale [6, 7, 12, 13, 15, 38, 39, 41, 43, 44]. The diversity of manufacturing techniques is unique to this time period, as after the end of the Archaic all pottery in the American Southeast appears to be constructed using coil methods [39]. It is unclear how manufacturing diversity relates to functionality, ethnicity, or changing trends through time as very little systematic research has been conducted to determine the spatial and temporal distributions of manufacturing techniques during the Late Archaic (see [3, 14] for limited attempts to determine techniques in Florida). Our first goal, therefore, is to determine whether radiography is capable of determining the general method of manufacture of the ceramics from Late Archaic sites in coastal Georgia.

Unfortunately, broadly characterizing manufacturing methods into predefined categories, such as coiling or wheel throwing, likely homogenizes the diversity of techniques found within each of these methods. While earlier studies using radiography have been successful in delineating between widely different construction methods, they are less successful in recognizing diversity within a single method. This lack of success is largely based on the limited viewpoints offered by traditional radiographic imaging. Because of an inability to interact with the radiographic data in three-dimensional space, traditional radiography offers a flat image in which data are superimposed on one another. CT-scanning technology, through which three-dimensional tomographic reconstructions of radiographic data are produced, could alleviate this drawback of traditional radiography. Our second goal, therefore, is to determine if more advanced radiographic techniques, such as CT scanning and the application of reconstructive software, will allow a more fine-grained investigation into ceramic manufacture.

2 Application of radiographic techniques

To test the applicability of radiographic imaging to determine past ceramic construction techniques, we analyzed a collection of ceramic sherds from an excavation on St. Catherines Island, Georgia (Fig. 1). This fieldwork was conducted under the auspices of the American Museum of Natural History (AMNH), the direction of Dr. David Hurst Thomas, and the assistance of the senior author of this paper (Sanger). All of the sherds were recovered from McQueen Shell Ring (9Li1648), a Late Archaic site that has been subject to archaeological investigations since 2006. McQueen Shell Ring is one of two shell rings found on St. Catherines Island [37]. Shell rings are large circular middens constructed out of marine bivalves that surround broad

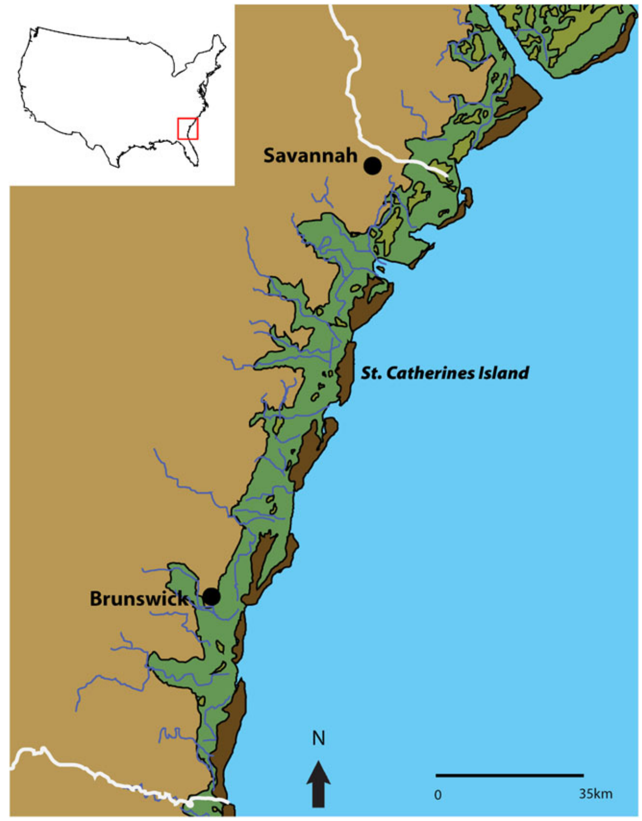

Fig. 1 Location of study area (St. Catherines Island, Georgia, USA)

shell-free plazas. Similar circular or arcuate shell middens can be found all along the Southeastern coastline and often date to the Late Archaic period [33]. Researchers at AMNH are investigating the ways in which the two rings on St. Catherines Island are related to one another, including whether they shared similar ceramic manufacturing techniques. This project is therefore designed to determine if radiographic imaging was an applicable method for a large-scale analysis of materials drawn from these two archaeological sites.

In this study, we report the application of radiographic analysis of 10 sherds. We will not detail the technology and science that power radiography because of space constraints, and instead refer the reader to several texts that discuss the physical properties of X-rays and their application for imaging cultural objects [8, 27, 30]. Our samples were first analyzed using traditional radiographic techniques in which attenuation data was captured on a two-dimensional image. These images were collected from a variety of angles in an effort to better understand the internal structure of each sherd. Two-dimensional imaging was conducted using a GE phoenix v|tome|x s240 industrial X-ray cone beam CT scanner at AMNH's Microscopy and Imaging Facility (MIF). By using real-time imaging, we were able to adjust X-ray beam and detector settings to promote visual acuity and fine-grained resolution for each sample. X-ray tube voltage ranged from 90 to 170 kV and was set according to absorption contrast seen in the real-time image of each sample. X-ray tube current, detector timing, and gain multiplication settings were set according to the dynamic range of the image histogram as well as the saturation of the detector for each independent sample. Resolution was set according to sample size to fill the detector's acceptable field of view; however, pixel sizes were kept below 40 μm to maintain fine-grained resolution.

Analysis of sherds included both real-time interaction with the sample during the imaging process as well as inspection of images after scanning was complete. Images were first inspected in raw form in an effort to determine internal structures in our samples. These raw images were then enhanced using ImageJ, an open-source Java-driven imaging program. The first step of processing the data using ImageJ was the segmentation of the image into components. Segmentation is the categorization of portions of the image based on their visual qualities. In this case, segmentation was based on the level of attenuation recorded within the image as variation along a gray scale. Segmentation was achieved through an automatic filter, which was then refined through a user interface. This categorized data was analyzed using custom macros which recorded and calculated basic spatial measurements, volumetric data, nearest-neighbor analysis, directionality, and variability within the image. The use of ImageJ greatly enhanced the analysts' ability to recognize micro- and macro-morphological traits, particularly the presence and alignment of tempering agents.

Together, these analyses provided the following data:

1. Inspection of morphological distinctions, particularly the presence and alignment of voids.
2. Spatial arrangement of ceramic fabric and tempering agents.
3. Recognition of different constituent components.
4. Quantification of constituent components, including volume, size, shape, diversity, and distribution.

The same 10 sherds were then CT scanned using the same equipment and similar settings. Real-time imaging techniques were implemented once more with slight adjustments made to promote accurate and clean tomographic data. A 0.1 mm copper filter was used for all scans to dampen the effects of beam hardening caused by low-energy X-rays. Scans were collected with sub-50-μm voxel resolution with most samples being scanned in portions to obtain this objective.

Three-dimensional CT reconstruction was done using GE phoenix datoslx 2.0 reconstruction software. Serial cross sections of the same sample but of different scans were fused together through the use of Fiji software's 3D-stitching plug-in and Volume Graphics VGStudioMax2.2's histogram calibration function to promote cross-portion homogeneity and seamlessness. Cross sections were then imported in to Volume Graphics VGStudioMax2.2 for analyses.

Through the use of VGStudioMax2.2, data was post processed to extract the empty voids where the fibrous temper had burned away. The first step in this extraction process was to digitally remove the fibrous voids from the surrounding clay matrix by using VG's Region Growing function. Due to the function's reliance towards gray values, the internal detail of negative space of the sherd was omitted during the initial region grow. To compensate and include the negative space within the newly defined volume, VG's Open/Close region function was used to fill in the negative space while maintaining surface accuracy. Once the sherd was sufficiently extracted as a region of interest (ROI) from surrounding materials, the Region Grow function was once more implemented to select the ceramic material and remove it from the ROI. This left the ROI with only negative space consisting of cracks, pockets, and fibers. From here, additional segmentation was completed on a sample by sample basis through VG's Erode/Dilate function as well as the Open/Close function until fiber acuity was optimized and various other cracks and unassociated empty pockets were removed from the model. ROIs were then colored and superimposed on the original semi-transparent ceramic sherd, which allowed greater visibility of fiber orientation and consistency (Fig. 2). The end result of this post processing was a three-dimensional model of the sherd in which the voids which once held the fibrous temper were differently colored from the surrounding ceramic fabric. This model could then be directly manipulated by a ceramic analyst, which allowed a dynamic interaction between researcher and their data.

3 Radiographic results

The two-dimensional imaging of the ceramic sherds from McQueen Shell Ring clearly show the presence, alignment, and morphology of voids left from the original fiber tempering as well as other aplastics within the sherd such as sand particles, shell fragments, and grit inclusions. In many of the scans there is an overwhelming amount of data, even when categorized using the ImageJ macros. For example, the scan of sample number 28.8/1409 (Fig. 3) shows the presence of numerous very straight, thin voids going in several different directions. The voids overlap one another to form a web of empty spaces. This scan is reflective of the larger collection in which all of the sherds showed evidence of interwoven tempering agents. As can be seen in the scan of sample number 28.6/3176 (Fig. 4), these fiber tempers often lie at strong angles from one another. Analysis performed using ImageJ macros confirmed this impression by showing that 90 % of the sherds had bimodal peaks within their void angularity. ImageJ data shows that more than 80 % of voids ran within

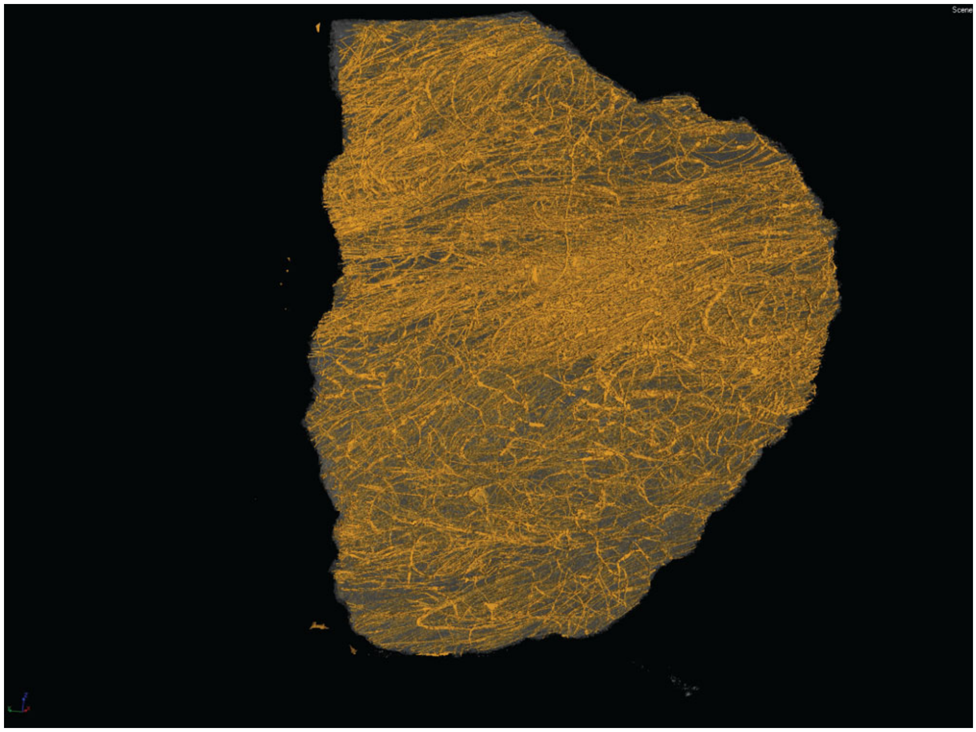

Fig. 2 Three dimensional reconstruction of fiber-tempered sherd (catalog number 28.8/1613)

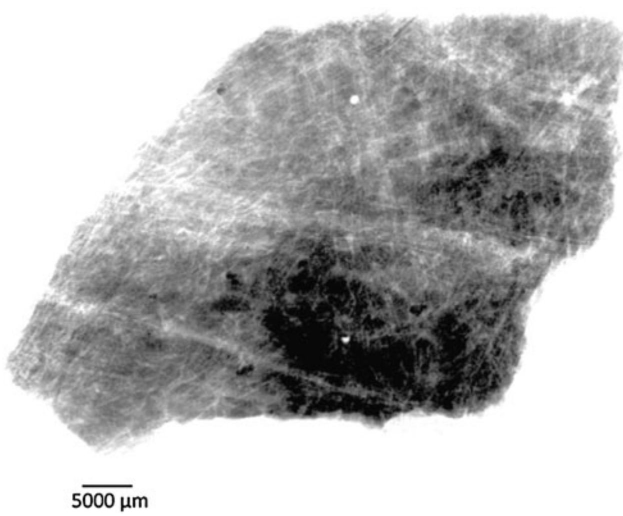

Fig. 3 Two dimensional radiographic image of sherd showing interwoven fibers (catalog number 28.8/1409)

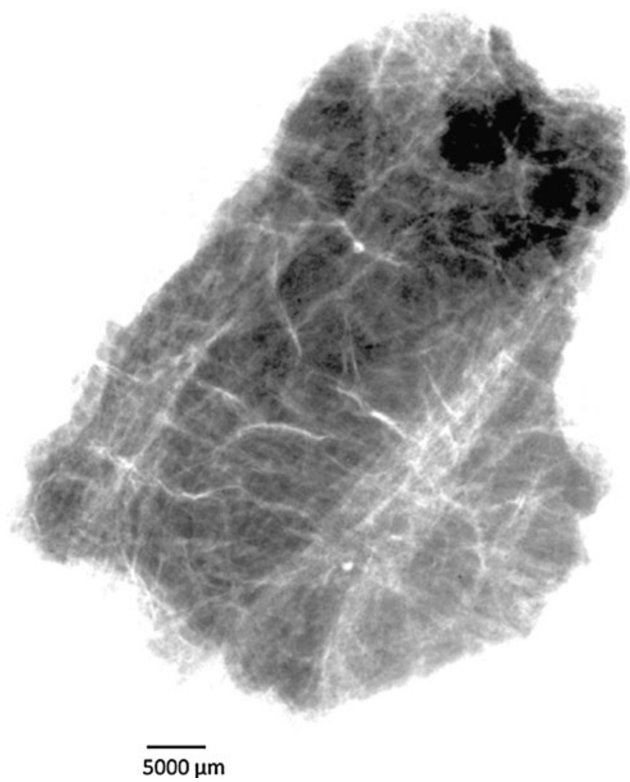

Fig. 4 Two dimensional radiographic image of sherd showing fibers at right angles (catalog number 28.6/3176)

five degrees of parallel (0 degrees) or perpendicular (90 degrees) to vessel axis (Fig. 5). The resulting pattern of voids could best be described as lattice- or cross-hatched.

The nature of this patterning is an important clue as to how these vessels were constructed. The obvious question is whether this cross hatching is an artifact of the superimposition of multiple uni-directional layers or whether the vessels were constructed out of single layers of well-mixed clays and temper. We attempted to discern the level of layering found within the sherds by scanning them edge-on with limited success (Fig. 6). Analysis of the edge-on scans produced ambiguous results largely because scanning along the long axis of the sherds compounded the amount of superimposed data.

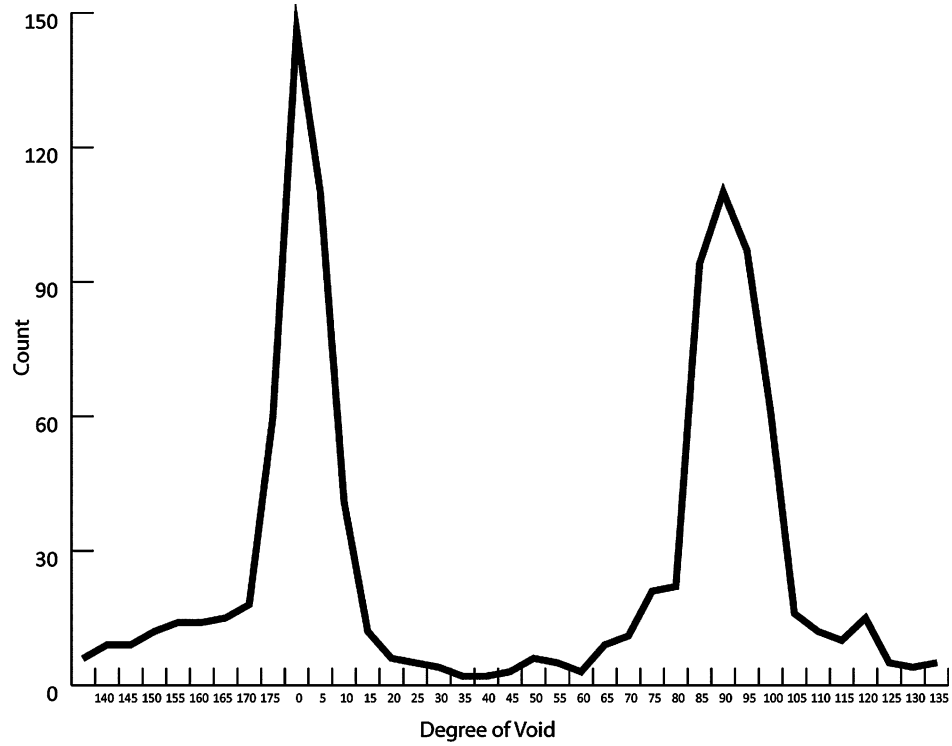

Fig. 5 Void angle occurrence within sherd (catalog number 28.6/3176)

Fig. 6 Edge-on scan of fiber-tempered sherd (catalog number 28.8/1409)

The single pot sherd that did not show a bimodal distribution of void angles was sample number 28.6/3388. Based on its morphology, this sherd was classified as a basal fragment which differs from all of the other sherds, which were recognized as being body sherds. Unlike the rest of the sherds, ImageJ analysis showed a nearly even distribution of void angles within the sherd (Fig. 7), suggesting that the voids were traveling a circular route. Even with enhancement using ImageJ, it is unclear whether this circularity was caused by voids traveling in concentric circles, or a single spiral (Fig. 8). Side scanning the sherd did not resolve this question. This sherd also contained numerous other aplastic inclusions other than fibrous voids, including large pieces of quartz grit, small shell fragments, and other unknown additions to the clay.

Three-dimensional reconstructions based on the computed tomography of our radiographic data alleviated many of the difficulties found while attempting to analyze the two-dimensional images. Following the steps outlined earlier in this paper, the three-dimensional data was transformed into dynamic models that could be manipulated along a variety of axes. By segmenting the radiographic data into components and isolating them into regions of interest (ROIs), we were able to create models in which the clay fabric was removed, leaving only the voids as positive space (Fig. 9). By turning this model, the detrimental effect of superimposition of data could be relieved and a clearer picture of the internal structure of the sherds became more accessible.

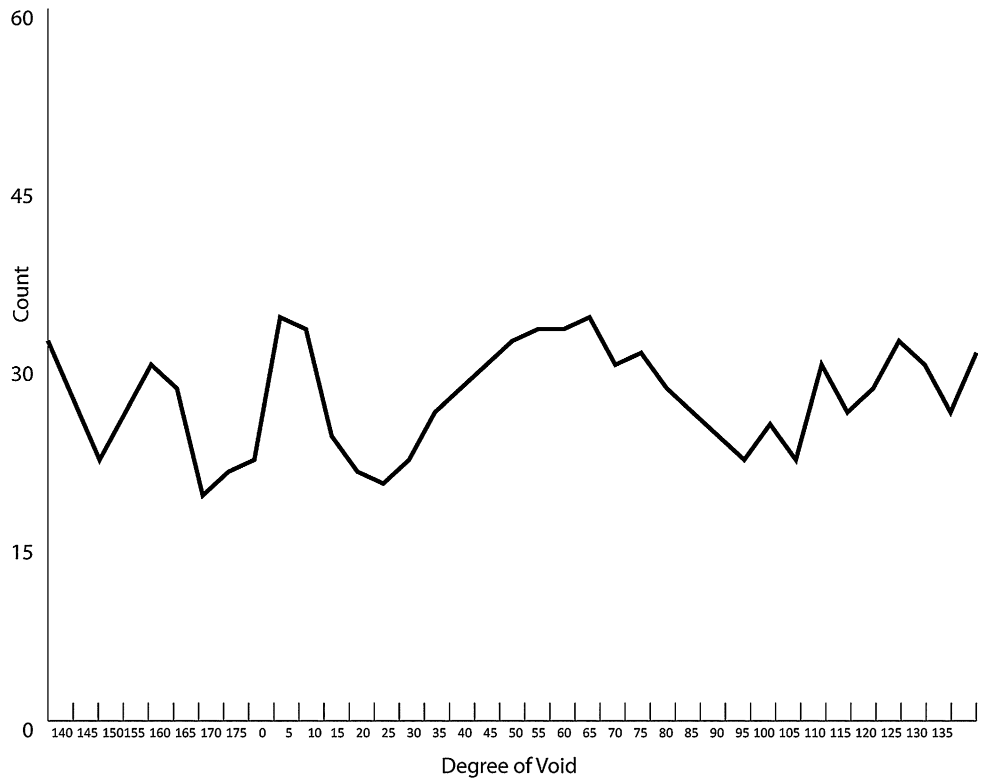

Fig. 7 Void angle occurrence within sherd (catalog number 28.6/3176)

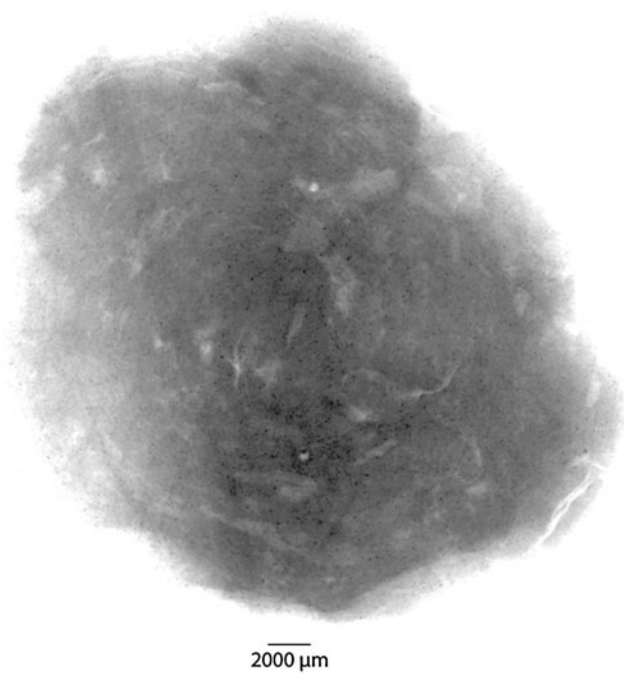

Fig. 8 Two dimensional radiographic image of sherd showing fibers in a circular pattern (catalog number 28.6/3176)

By applying this technique we were able to investigate the nature of how the fibers of almost all of the potsherds were interwoven with one another. Our three-dimensional models clearly showed that there were numerous fine layers within almost all of the sherds in our sample (Fig. 10). Rather than being constructed out of a single piece of clay that had fiber temper running in multiple directions, the sherds appear to be constructed out of multiple thin layers of clay, each of which are characterized as having fibers running in a single direction. These layers were placed on top of one another in such a way that the fibers crisscrossed one another, often at right angles.

Three-dimensional scanning also accentuated our ability to better understand the construction of the basal fragment described earlier (28.6/3388). By inspecting the three-dimensional model of this sherd, and again digitally removing the overlying matrix and focusing solely on the voids and aplastics within the object, it is clear that it was constructed in a spiral pattern (Fig. 11). The spiral generally maintains the same width from its center to the outer edges of the sherd. It appears that the sherd broke along the edge of this spiral, which could have been a natural weak point in the vessel. Analysis of the three-dimensional model also showed that this fragment was not layered like the other body fragments. Instead, its thickness was achieved with a single layer of clay.

4 Discussion of results

The goal of this project is to investigate the manner by which past people created some of the earliest pottery in North America. Through our radiographic imaging, both two- and three-dimensional methods, we have been given clues as

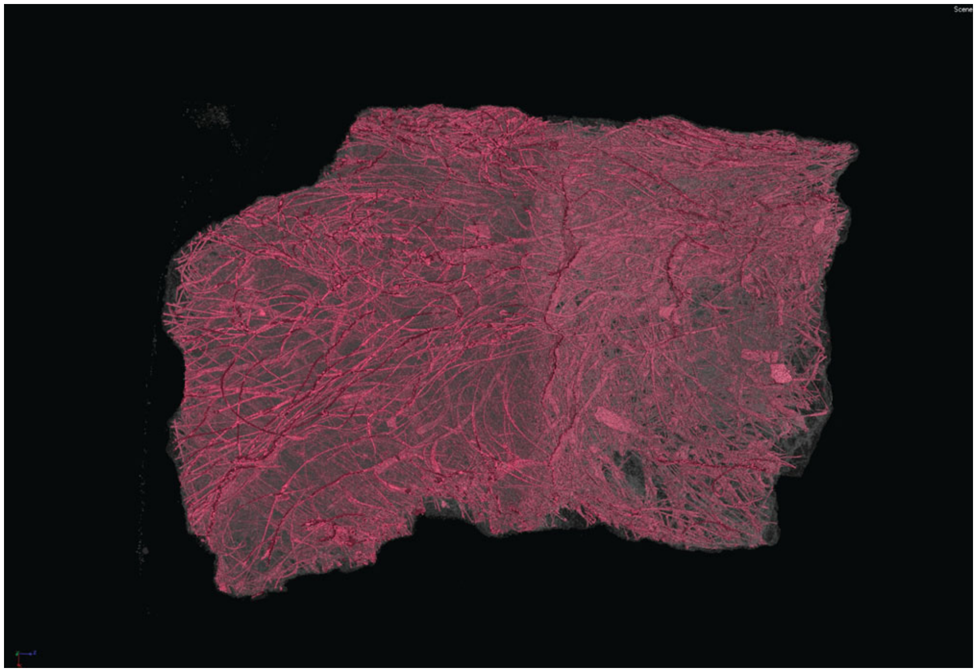

Fig. 9 Three dimensional reconstruction of fiber-tempered sherd (catalog number 28.6/3521)

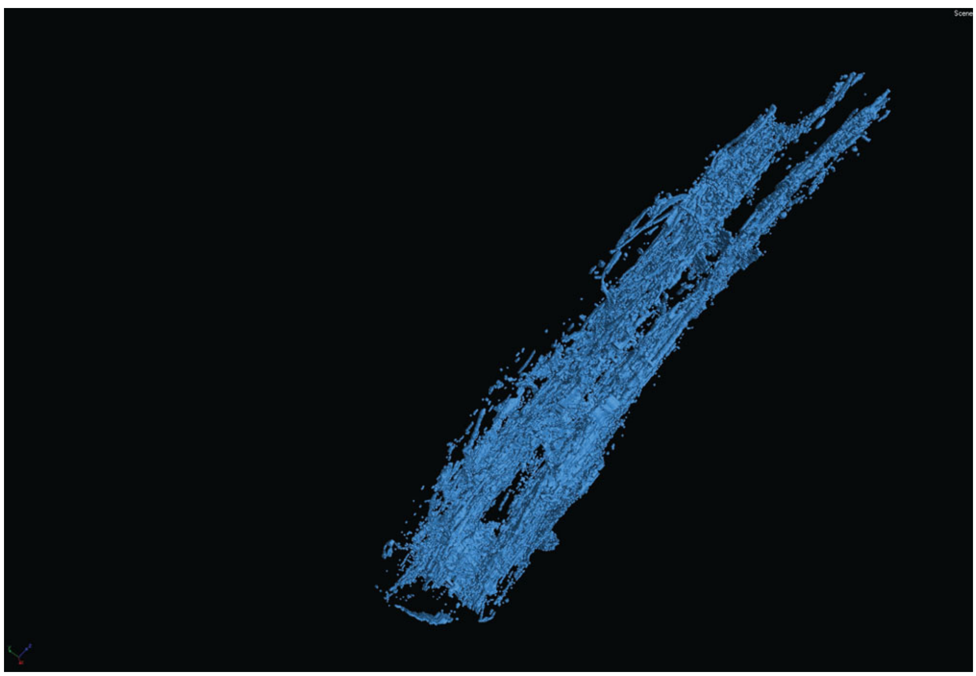

Fig. 10 Three dimensional reconstruction of fiber-tempered sherd showing layering (catalog number 28.6/3238)

to how potters built these ancient ceramic vessels. Ethnographic and historic accounts suggest that coiling was the dominant method of ceramic vessel creation at the time of contact in North America. Coiling is a method familiar to many potters around the world. Vessels are constructed by forming a solid roll of clay and temper which is then placed around the circumference of the vessel until the appropriate height is reached [35, p. 67]. Rolls can be long and spiraled around the circumference until they double over their original location, or can be built in consecutive rings. The coils are melded together through the application of pressure as well as secondary surface preparations (such as smoothing or scraping) which obliterate any visual evidence of the coiling. Experimental and ethnographic research has shown that coiling is visible in radiographic imaging [3, 16–18, 34, 35]. The forming of clay and temper into coils results in a preferred orientation of internal structures parallel to the long axis of the coil (Fig. 12). Often, the overall orientation of temper and clay fabric rotates along the central axis of the coil and can be seen as a spiral at the base of the vessel or

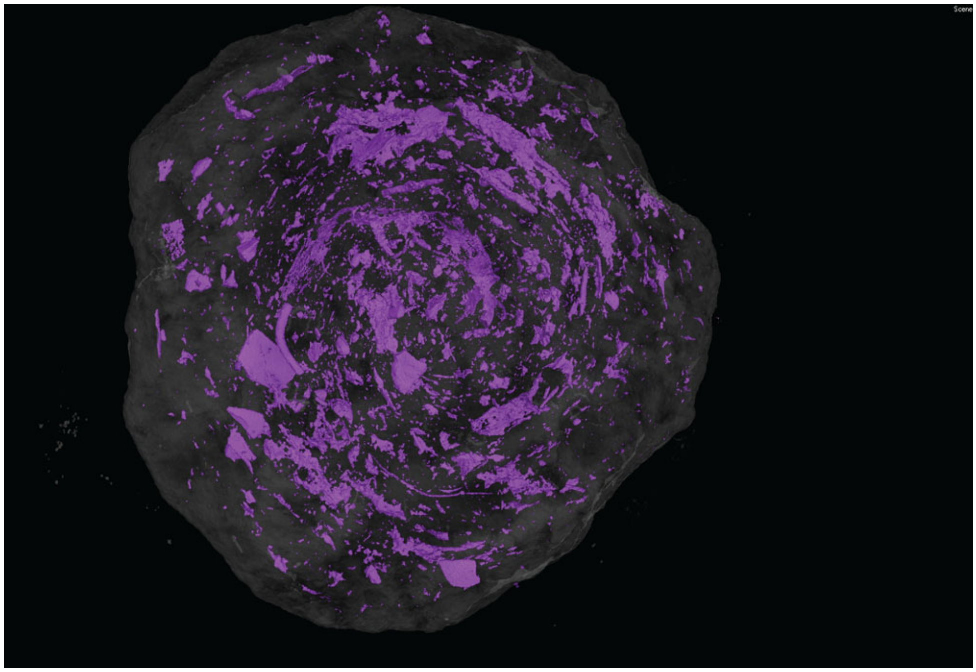

Fig. 11 Three dimensional reconstruction of fiber-tempered sherd showing coiling (catalog number 28.6/3388)

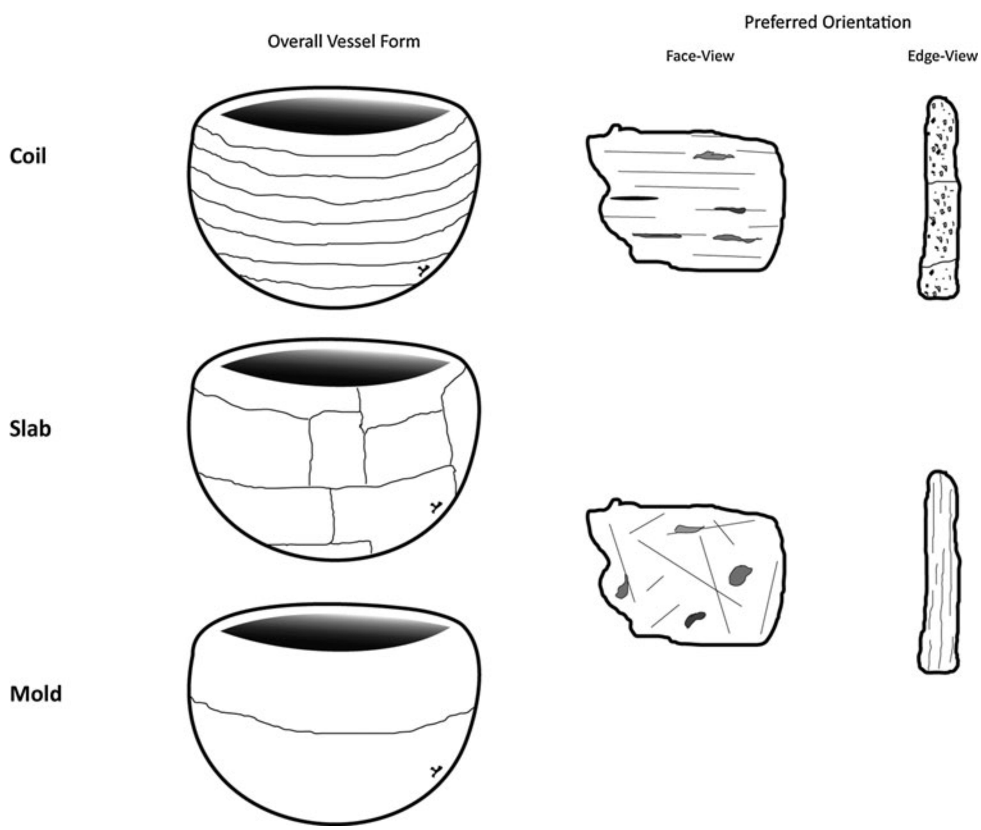

Fig. 12 Different ceramic construction techniques and expected orientation of internal structures

as a parallel pattern along the body of the vessel [35, p. 68]. Coiling also results in characteristic meld lines at the points where two coils make contact. These meld lines are often visible within radiography and follow the same patterning as the overall fabric and temper orientation.

The characteristic spiral pattern of fibers and meld lines can be found in the basal fragment described above (28.6/3388). The presence of coiling within the Late Archaic ceramic collection is surprising, as it was not thought to be used until after the Archaic period [39, 41]. While this single occurrence of coiling needs to be further verified by finding other coil-built fragments, it suggests that coiling technology was not a secondary advancement, but was present at the very beginnings of ceramic manufacture in the southeastern United States. Importantly, we have only found this coiling method in a single basal fragment. The remaining body sherds are clearly not built using coiling methods. It is therefore unclear how coiling techniques are being deployed during the Late Archaic. It is possible that this is a specialized method of creating the bases of ceramic vessels which are then built up using other techniques. Alternatively, there could be multiple methods of constructing vessels, including a relatively rare technique of coiling. Currently, our dataset is too small to offer any conclusions at this point.

While it is clear that the single basal fragment within our sample was created using a coiling technique, it is less clear how the rest of the body fragments were constructed. All of the body sherds within this study lack the parallel meld lines and fabric/temper orientation that are characteristic of coil-built ceramics. Rather, they appear to be made out of numerous thin layers of clay that are laid on top of one another to reach the desired wall thickness. The long fibrous voids run in multiple directions, often at right angles to one another. There are at least two possible methods of ceramic manufacture that would result in these findings. The first is molding, the second is slab building (Fig. 12).

Molding is a technique in which clay and aplastics are applied to an already existing form. The form can be an already existing ceramic vessel, a shape carved out of wood or stone, or any other acceptably shaped object. The clay and aplastics are often applied to this form as large sheets which are then melded together at join lines. These join lines often occur as a seam that spans the entire vessel along either its vertical or horizontal axis [35, p. 81]. Alternatively, thinner layers of clay, rather than a thick sheet, can be placed on top of one another on the mold until the desired wall thickness is reached. The fabric and aplastics within molded vehicles are most often oriented parallel to the surface and are otherwise random.

Slab building is a technique in which the potter creates a vessel by merging together flat, wide strips of clay onto one another [35, p. 72]. These strips are generally the same thickness as what the potter desires for the finished vessel, so the pieces are merged along their edges until the appropriate wall height is reached. The strips of clay can be long enough that single pieces can make up the entire radius of the vessel. Alternatively, multiple strips can be merged together at their edges to create the desired vessel width. Prior research suggests that radiographic analysis of sherds from slab-built vessels will have a preferred orientation of fabric and aplastics parallel to the surface of the vessel but otherwise random [35, p. 72]. Much of the interior structure of a slab-built vessel is dependent on how the original slabs were formed. Slabs can be single or multiple pieces of clay, flattened by hand or a cylindrical object, and cut into different shapes.

Currently, we are unable to determine whether the Late Archaic potters at McQueen Shell Ring were using slab or molding techniques to build their ceramic vessels. Both techniques could account for the layered nature of the sherds, as well as the orientation of tempering agents. The most accurate method of recognizing the presence of these two techniques is to find their characteristic methods of joining together pieces of clay. Slab building generally results in numerous small joins, while molding construction often results in a single seam. Our sample size was too small to encounter evidence of joins or meld lines, and is therefore unable to discern the difference between molding and slab building techniques. It will be necessary to both scan more sherds, as well as scan larger portions of vessels, perhaps through refitting sherds, to determine the presence of one or both of these techniques.

5 Conclusion

This paper has presented an assessment of the applicability of radiography, including the use of CT scanning and reconstruction, to determine the construction techniques used by some of the earliest potters in North America. The benefits and limitations of both two- and three-dimensional analyses were offered. Overall, we found that two-dimensional scanning offered a basic level of information in which broad-scale differences in techniques could be seen. The analysis of two-dimensional images was enhanced by using advanced imaging software and custom-built modules that performed segmentation, visualization, and measurement of visual phenomena. Even with these enhancements, fine-grained internal structures of the samples were not accessible. This was largely because of the superimposition of data and the inability to dynamically interact with the object.

The creation of a three-dimensional model based on detailed computed tomography alleviated much of these problems, allowing us greater access to otherwise obscured data. Based on the analysis of these models, we were able to better understand the ways in which these vessels were constructed. Our results are preliminary as they are drawn from a small sample size, but they suggest a complicated mixing of methods taking place at McQueen Shell Ring. Further research in which a larger sample size is analyzed needs to be carried out to better understand the ways in which these various methods were deployed by these ancient potters.

While radiographic imaging, particularly the application of three-dimensional modeling, proved useful in better understanding ancient potting techniques, it is also limited. As of yet, we are unable to discern between two major methods of ceramic manufacture; molding and slab building. We are hopeful that further experimental work coupled with the analysis of more and larger sherds, perhaps reconstructed vessels, will allow us to analytically separate these two techniques. Another potential limitation of our research is that it is limited to a single temper type, fiber, which is particularly amenable to radiographic analysis. Further research is needed to determine if other tempering agents are as amenable to analysis.

Beyond the broader goals of this project, which were to test the applicability of radiography in determining the method of construction for ancient fiber-tempered ceramics, this project has also produced an important dataset which will impact our archaeological understanding of the American Southeast. While this dataset needs to be enhanced through further research, we can now begin to discuss the particular choices made by ancient potters and relate them to the technological, functional, and social forces at play during the Late Archaic. In terms of vessel functionality, the use of vegetative fibers for tempering affects the material properties of the finished vessel. Different techniques of orienting fibers will differentially affect the permeability, fragility, and thermal character of the finished vessel. The importance of each of these characteristics depends on the planned usage and social context in which the vessel will be placed. Insights into the choices made by ancient potters may therefore offer clues to the social place of pottery within these past societies. For example, the choice by Archaic potters to construct their vessels out of alternating layers of crisscrossing fibers might suggest that these pots were planned on being used in such a way that interwoven fibers would offer an advantage over other techniques. From a structural standpoint, cross-woven fibers would likely offer a different tensile strength than offered by a unidirectional or random fiber alignment. As far as manufacturing methods were being consciously deployed in anticipation of vessel usage, radiographic analyses may offer opportunities to better understand the ways in which pottery was used in the past. This is an important research question, as archaeologists variously see early pottery as high-status serving vessels [23], storage containers [29], and tools for cooking [2]. Determining the internal structural characteristics may offer insight into this question.

While many of the choices made by potters are informed by conscious anticipation of future usage, there are other aspects of ceramic construction that are largely formed by unconscious application of habitual actions. These habitual actions are often based on apprenticeship, rote learning, and imitation of one's neighbors, which lead to habits and actions that are both deployed with little reflexivity and socially and spatially centered on a network of individuals [1, 25, 32, 36]. Methods of ceramic manufacture, particularly those that are not visible within the final product, are relatively resistant to change, particularly in comparison with changing decorative styles [20, 21]. As far as manufacturing methods were influenced less by intended function and more by the internalizing of dominant local traditions, radiographic analysis may offer an opportunity to investigate the presence, distribution, and interconnectivity of social groups within the archaeological landscape. For example, the presence of both coiling and slab/molding techniques at McQueen Shell Ring could suggest the presence of two different groups at the shell ring, each of which were using different manufacturing traditions. The level and manner to which populations were becoming regionalized yet still maintained relations with one another is an important question within the archaeology of the Late Archaic coastal Southeast [40, 45]. By tracing the variability and distribution of ceramic construction techniques across the Late Archaic landscape, archaeologists are offered another opportunity to investigate the presence and permeability of social boundaries during this period. While this project has offered an initial dataset from which we can begin to better understand the archaeological record of the Archaic Southeast, a great deal more work needs to be done before any of these questions can be addressed.

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