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Insights into manufacturing techniques of archaeological pottery: Industrial X-ray computed tomography as a tool in the examination of cultural material

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Abstract - The application of X-radiography in ceramic studies is becoming an increasingly valued method. Using the potential of industrial X-ray computed tomography (CT) for non-destructive testing as an archaeometric or archaeological method in pottery studies, especially regarding aspects such as manufacturing techniques or pottery fabrics, requires controlled data-acquisition and post-processing by scientific computing adjusted to archaeological issues. The first results of this evaluation project show that, despite the difficulties inherent in CT technology, considerable information can be extracted for pottery analysis. The application of surface morphology reconstructions and volumetric measurements based on CT data will open a new field in future non-invasive archaeology.

1. Introduction

For as long as archaeometric methods have been well established in the study of archaeological pottery, there have been many efforts to reduce their impact on the object and to look for less-destructive or non-destructive methods. X-radiography and computed tomography (CT) have played an important role within this type of non-invasive archaeology. These techniques were generally used for the visualisation of manufacturing details and to provide more accurate vessel profiles, particularly of closed shapes. The further development of the medical CT to an industrial X-ray computed tomography for non-destructive testing (NDT) established a technology that enables a much closer examination of the object due to high local resolution. Industrial CT generates a complete 3D digital model of the object with all features of its shape and its ceramic paste, which are recorded in different grey levels due to their local material density (X-ray absorption). Various, mostly medical, software programs can be used for 3D visualisations or virtual cross-sections of these objects (Fig. 1).

The successful use of the large volume of CT data for pottery analysis requires controlled data acquisition and new methods of post-processing specifically adjusted to archaeological ceramic studies (Rice 1987; Orton *et al.* 1993). This article presents preliminary results of a pilot project that demonstrates how industrial CT can be an important tool in the examination of museum objects, as well as providing an overview of the potential of its application in ceramic studies. It also offers an outlook on an integrated approach by which recent improvements in scientific computing pave the way for the use of these large data volumes for analytical purposes and help to evaluate the segmented volumetric data with surface reconstruction methods.

2. Historical review

The application of X-radiography in ceramic studies dates back to the 1930s (Berg 2008). It was used for the visualisation of manufacturing details and for the reconstruction of pottery-making techniques, but to a lesser degree also for the investigation of pottery fabrics. In the late 1980s various medical and industrial radiographic

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Figure 1. Protocorinthian Aryballos UMJ ARCH inv. 4214 (CT01184: 79 kV, 197 μA, voxel size 159 μm, Al 0.5mm), visualisation using the volume renderer developed at the VRVis Research Center, supported by ÖGI.

techniques were comprehensively reviewed and evaluated for their usefulness with regard to archaeological and anthropological case-studies (Carr 1990; Carr and Riddick 1990). Despite these, there are only a few recent ceramic projects that use X-radiography and approaches for a systematic digital radiography of archaeological pottery (Middleton 2005; Greene and Hartley 2007; Berg 2008).

Computed tomography, a three-dimensional imaging system developed in the early 1970s, has had an immense impact on medical diagnosis. Although most common in medicine, CT has also played an important role within non-invasive archaeology (Applbaum and Applbaum 2005). However, the lack of medical CT scanners available for archaeologists to use prevented investigations on a larger scale until recently. Nevertheless, a group of the Allard Pierson Museum and the Academic Medical Centre of the University of Amsterdam has shown the potential of systematically using CT in studies of Greek ceramics (Jansen and Koens 1996; Van de Put 1996; 2006; Jansen *et al.* 2001; Borgers and Brijder 2007). The technique was generally used for two purposes: to provide more accurate vessel profiles, particularly of closed shapes, and for insights into ancient pottery techniques. A very interesting aspect of the Amsterdam project was the attempt to use the variations of the grey tones of a CT scan, which are largely due to different petrographical compositions of the ceramic material, for the comparison and determination of pottery fabrics (Koens and Jansen 1999; Van Duivenvoorde 2000). Closer inspection of inner structures and the detection of inclusions and voids are greatly restricted by medical scanners due to their low resolution and contrast, which are adjusted to the investigation of *in vivo* human bodies.

In recent decades, industrial X-ray computed tomography has opened up a new field of NDT. Industrial CT has created a procedure in which the finest interior and exterior structures of mainly manufactured castings and components can be examined for the industry with high resolution and high penetration rates according to certain quality requirements. This technological progress transformed industrial CT into a method most suitable for the non-destructive investigation of archaeological objects. Some of the archaeological issues in pottery analysis benefit from experiences in industrial applications, such as defect detection of NDT (Eisele 2002). Nevertheless, industrial CT is rarely applied in the study of archaeological objects. The reason for this can be found in the cost of such an investigation, and sometimes in the lack of mobility of museum objects, because the specimens must be transported to the site where the CT scanner is located. However, the main problem until recently was the huge datasets generated. Within the research on Greek pottery, industrial CT has recently been applied to single objects, but the results have mainly been presented in terms of their visualisation capabilities, whereas their potential for further applications in material analysis has only been touched upon (Dimitrov *et al.* 2006; Friedmann and Bente 2007).

3. Method and data acquisition

Cooperation with the Austrian Foundry Research Institute (ÖGI) in Leoben made it possible to evaluate industrial CT as an archaeometric or archaeological method in pottery studies (Karl 2010). For the present study, a homogenous group of small closed vessels (maximum size about 15 cm), representing mainly Corinthian ceramic, and a sample group of ceramic fragments of different origins was selected from the archaeological collections of the Universalmuseum Joanneum in Graz (UMJ) and the Department of Archaeology at the Karl-Franzens-University Graz (KFUG) (Lehner *et al.* 1993; Karl *et al.* 2009). All objects were acquired in the 19^{th} century and have not undergone any subsequent conservation. From an archaeological point of view, the objects can be attributed confidently to well-known pottery types of the Archaic time (7^{th}–6^{th} century BC). Minimal contact with the vessels during the entire scanning procedure and carriage from the museum and back to it has proven ideal.

The objects were scanned using a Phoenix X-ray v|tome|x cone beam CT-system equipped with a 240 kV micro-focus tube with a variable focal spot size of 4 to 200 μm and a 16 bit flat panel detector (512×512 px). The maximum resolution of the scanner is 5 μm, depending on the size of the object. The material ceramic turned out to be appropriate for this type of radiography because it absorbs hardly any X-rays due to its low specific gravity that requires low energy. The requirement of low energy is very important because, in handling museum objects, the issue of preservation of integrity and the degree of non-destructiveness have to be addressed. It is well known that the objects were exposed to ionising radiation, which influences the luminescence signal (Haustein *et al.* 2003; Castaing and Zink 2004). Although dating of museum objects with unknown post-antique transformation processes by thermoluminescence (TL) often provides very inaccurate results, in the present study the effects of the added radiation dose on the TL age were investigated. By means of the analysis of different loaded series of ceramic samples, limiting values – as in medicine – were introduced in order to minimise this impact. These main limits for the Phoenix v|tome|×CT-system were defined as follows: time of scanning = 720 sec, acceleration voltage ≤ 150 kV, and tube current ≤ 300 μA. In brief, the first preliminary results of the TL analysis show that the impact of CT within these limiting values falls within an acceptable range and displaces the TL age by no more than 20% of the age of the investigated ceramic samples of ancient times (Rudolf Erlach personal communication), which is well within the accuracy range for museum objects (Dittberner 2009).

This low impact is made possible because the Phoenix v|tome|×CT-system has a fast data acquisition time of 720 sec. Within the defined limiting values for radiation, these parameters are directed to achieving the best possible image information, with high contrast and resolution. The determination of consistent parameters, even just for the one CT scanner used in this project, is a difficult undertaking, because these mainly depend on the complexity of the object (size, material density, wall-thickness, metallic applications, etc.) and on the aim of achieving the best range of optical densities. Using a 1 mm aluminium filter together with a 1 mm copper filter and a high acceleration voltage (but within the limit of 150 kV) has proven optimal for the quality of the CT data. This has reduced the softer, more easily scattered X-rays with longer wavelengths, and corrected some of the beam-hardening artefacts, which are a common phenomenon in CT technology (Eisele 2002, 6–8). The next step in CT scanning is the reconstruction process, which lasts about the same amount of time as scanning and generates a volumetric record which is represented in so-called voxels, the 3D-equivalent of a pixel, with a certain edge length – in the present study always isotropic. The 16 bit system detector has the ability to record a wide spectrum of grey values, between 0 and 65535. Finally, one record consists of 512^3 voxels and is c. 260 MB in size, which conventional PCs can easily cope with. However, there are still beam-hardening effects, like dark bands or streaks and cupping artefacts, which require further attempts at an adequate beam filtration and a better calibration correction in the reconstruction process.

4. Volumetric data

Volumetric data of CT scans have a well-known additional advantage over all other surface-based data acquisition methods, such as the 3D scanner based on structured light (DePiero and Trivedi 1996). The documentation is efficient and the scanning time is not determined by the complexity of an object. CT provides a complete 3D data set of an object and allows archaeologists to look into the body of a vessel. Inaccessible parts of objects become visible and can therefore be evaluated. Measurements can be taken at every position. In comparison to a conventional archaeological drawing, the inner profile line of an object with a narrow mouth can be accurately determined for the first time (Fig. 2).

In addition, there are also ways to use CT data for comparative analysis. The volume of the ceramic can be measured using a so-called isosurface. For this purpose, a grey level that is in between the grey levels representing the ceramic and the air is chosen. This way, all voxels with values higher than that threshold are counted as material. The iso-grey level can either be calculated automatically by software programs like VGStudio, or set manually. In addition to the dry weight of an object under defined conditions such as temperature (21–23°C) and humidity (40–50%), it also becomes possible to calculate bulk density, i.e., the density including the ceramic matrix with inter-particle voids and internal pore volume.

Various voids can be identified in the CT data and show differences in the preparation of the clay paste. One possibility involves obtaining this information about porosity from two-dimensional cross-sections and image processing (Lang *et al.* 2005). Comparable grey values for further processing have been achieved using the histogram peaks for air and ceramic. The isosurface was defined at the mean of these two peaks. The maximum grey value for the ceramic matrix has been placed symmetrically to the ceramic peak, at the same distance as to the isosurface. The next step was the reduction of the CT grey values to grey-scale images of 256 values in such a way that the lowest CT value (the isosurface) obtains the new value 255 and the highest (the densest material in the ceramic matrix) the value 0. This mapping allows an approximated evaluation of the visible voids, depending on the CT resolution (Pierret *et al.* 1996), with software programs (Adobe Photoshop, Scion Image <http://scion-image.software.informer.com>) using filtering tools for enhancing the edges, correcting the cumulative effect and reducing the number of grey values to binary images (Fig. 3).

Nevertheless, the results obtained in this first attempt with the use of standard software programs were still unsatisfactory in terms of their accuracy and the lack of a three-dimensional analysis. However, through the application of scientific computing, the ceramic volume could already be obtained with a new method of surface reconstruction, and significantly improved the accuracy of the data because of its verifiability. This surface reconstruction also enables a non-contact measurement of the capacity of the vessels, which represents important information for the standardisation of ancient pottery production (see outlook for more details).

5. Forming techniques

Much useful information about the production process can be obtained by looking into the interior of objects and into their ceramic material. Forming techniques are clearly visible in the specific texture of the ceramic matrix and in the orientation of the voids and the inclusions. A characteristically helical structure from the base to the rim (Tellenbach 2002), in the present study always in a clockwise direction, shows the rotation of the potter's

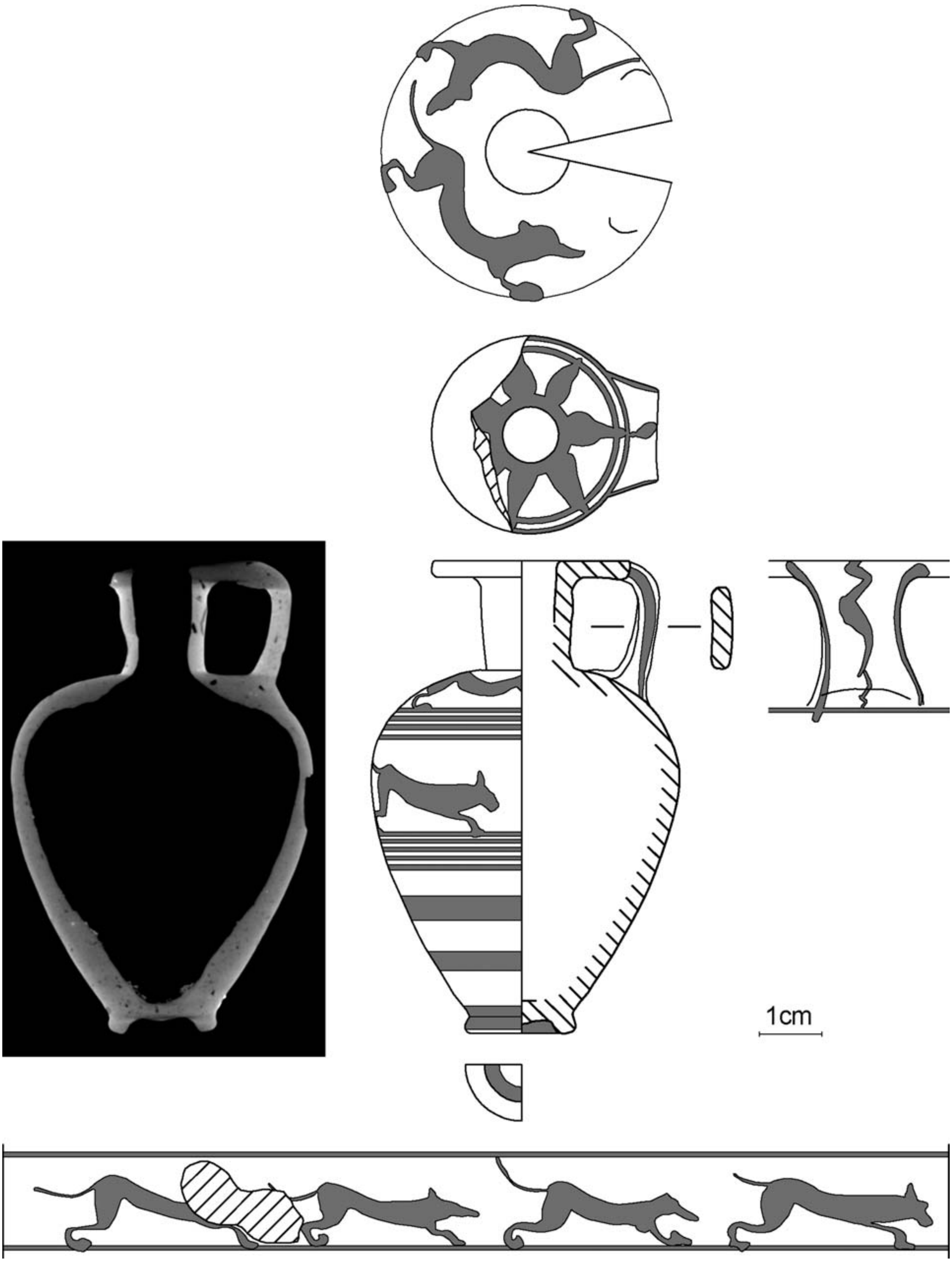

Figure 2. Protocorinthian Aryballos UMJ ARCH inv. 4214 (CT01184: see Fig. 1), conventional drawing and CT cross-section.

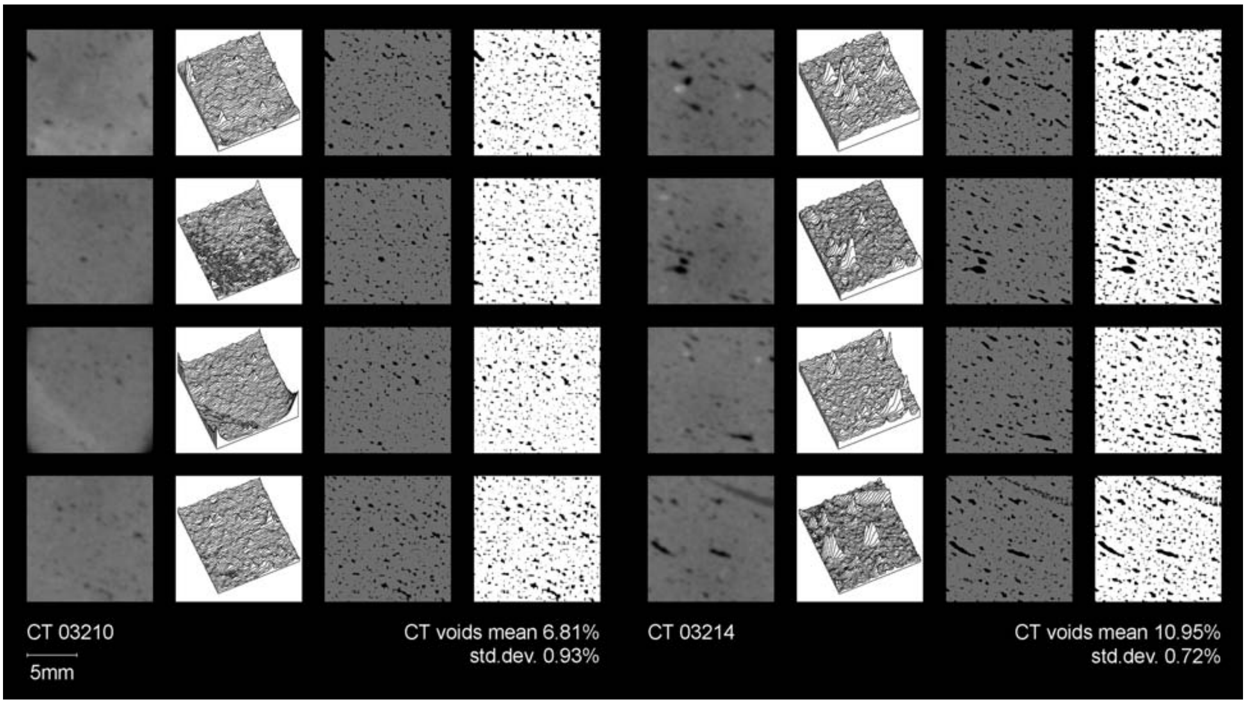

Figure 3. CT cross-sections of a Corinthian (left) and Protocorinthian (right) example (CT03210/CT03214: 150 kV, 225 μA, voxel size 184μm, Al+Cu 1.0+1.0mm) for image analysis.

wheel (anti-clockwise turning), and probably gives an indication of a right-handed potter (Schreiber 1983). Due to the high resolution of the CT, wheel-thrown vessels and those that are coiled and then wheel-shaped can be distinguished (Berg 2008). Turning marks seen inside at the bottom depending on traces left by the hand of the potter, or spiral stress lines at the shoulder running up into the neck, enables the reconstruction of the entire process of production from a lump of clay on the wheel to the finished piece (Rye 1988; Schreiber 1999). The studies show that, despite their outward similarities, vessels present differences in their construction and in the usage of additional shaping tools. CT reveals the composition of different parts, such as necks or bases, which are recognised most readily because of the alteration in the texture.

Scans of the Protocorinthian and Corinthian aryballoi indicate different manufacturing techniques of these small globular vessels with narrow mouths, which were changed over the years. They were all thrown on the wheel, but

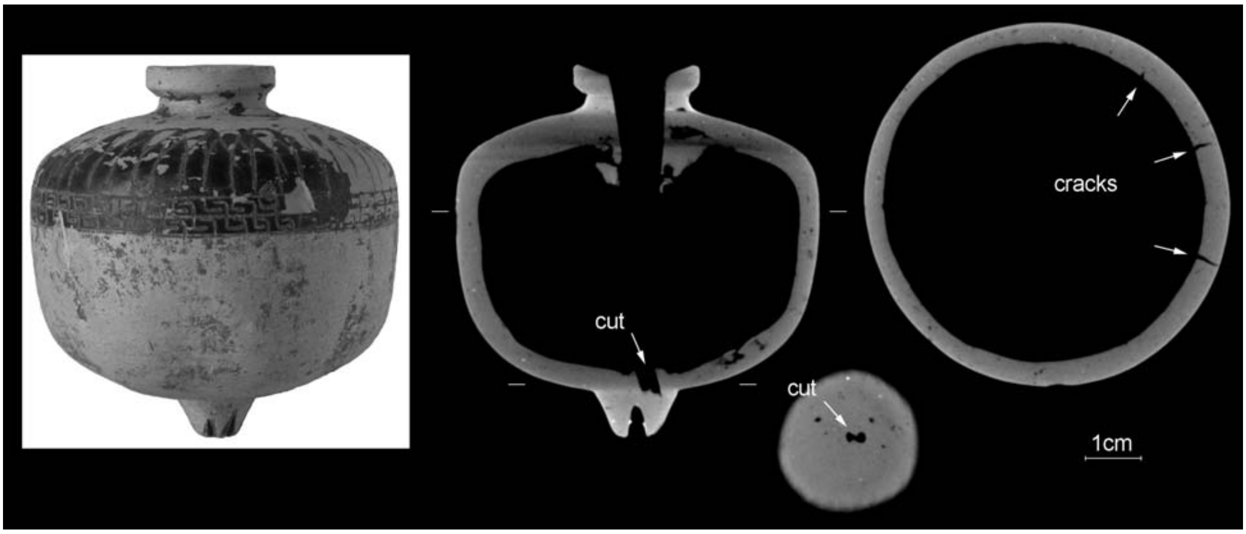

Figure 4. East-Greek pomegranate-vessel KFUG Dept. Arch. inv. G 56 (CT03047: 85 kV, 225 μA, voxel size 190 μm, Al 1.0mm), image and CT cross-sections.

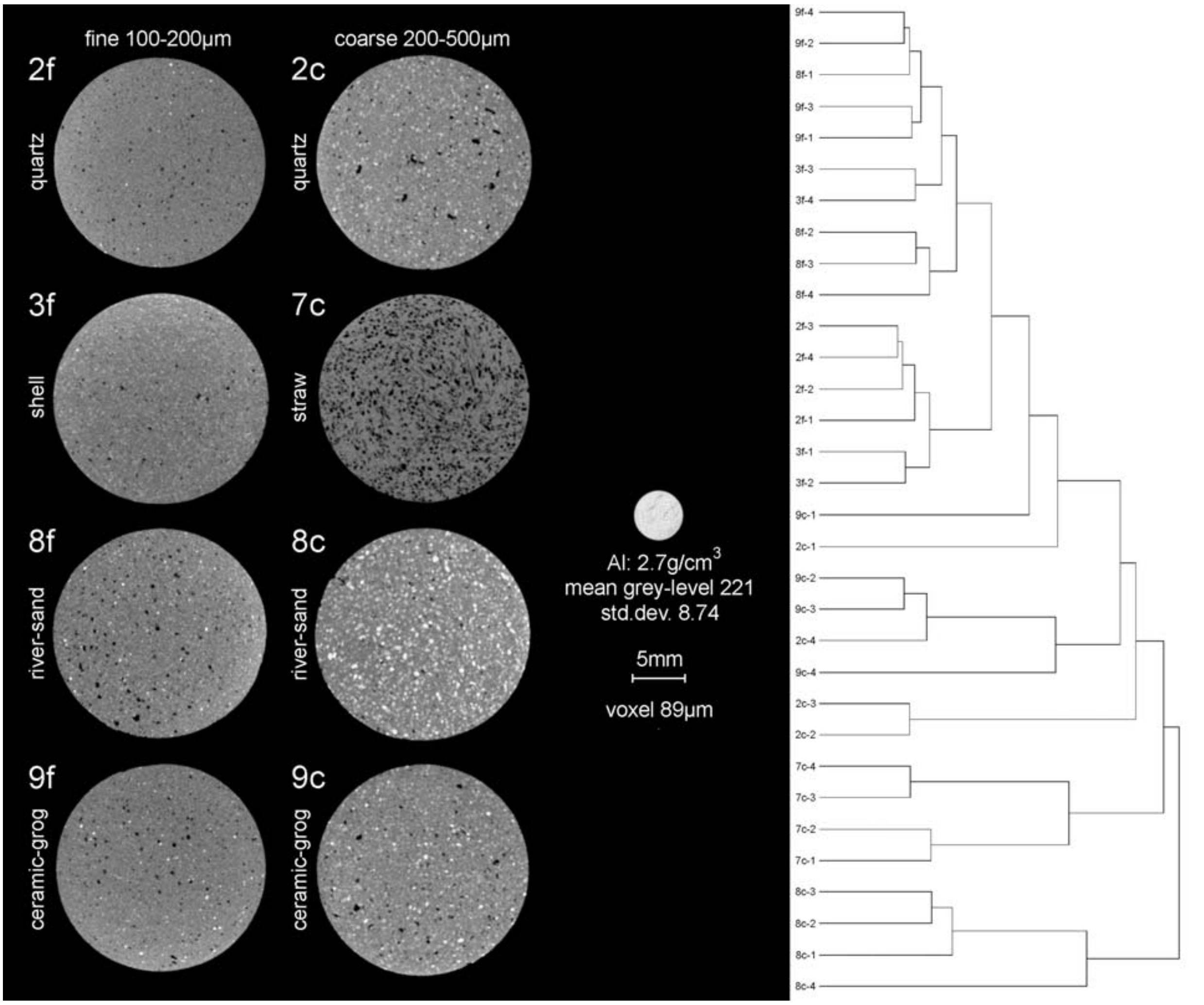

Figure 5. Test tiles 3f, 7c, 8f, 8c, 9f, and 9c (CT03071: 110 kV, 132 μA, voxel size 89 μm, Al 2.0 mm), CT cross-sections and classification dendrogram resulting from cluster analysis performed using Euclidian distance.

display differences in the making of the opening, with a very narrow neck and a wide mouth. The most difficult task in the production of these small vessels was angling the wall inward towards the centre and narrowing the opening to an inside diameter of around 5 mm. Sharp breaks and edges demonstrate the variety of potters' tools used for the manufacture of these shapes. Characteristic of the Early Corinthian aryballoi is a type of dowel that is used for this process of collaring-in and has left its mark on the break to the shoulder. The data raise a number of important questions concerning the development of this shape and the introduction of the globular aryballos. The results of each individual piece will be published in detail in a forthcoming Corpus Vasorum Antiquorum (CVA) containing the collection of Greek vessels of the Universalmuseum Joanneum in Graz.

One piece proved exemplary for the application of the CT method for the identification of forming techniques, because the results were unexpected. This is a pomegranate-shaped vessel which belongs to a well-known group of so-called East Greek plastic vases of the late 7th to 6th century BC (Ducat 1966, 142–4). The *communis opinio* is that these vessels were wheel-thrown (Boldrini 1994, 46–7). The investigation has shown the opposite; there are no turning marks at all, moreover the wall thickness varies, and the vessel was made of three separate sections joined together: the body, the mouth, and the cone end, which was originally part of the remaining sepals of the pomegranate (Fig. 4).

Due to the vertical orientation of the pores and inclusions, it is likely that this vessel was partially formed by using a one-piece mould into which the potter spread and pressed the clay wall more or less evenly with the fingers. After the formation of the body, a disc-shaped spout was appended, and, with the help of a knife-like tool, the potter opened the body wall into the interior of the vessel. Vertical cracks in the belly area were caused by physical stresses during the contraction of the wall. The possibility that perhaps all East Greek pomegranate-shaped vessels were made in moulds and could be compared to the group of Archaic terracotta figurines opens up new vistas for the archaeological understanding of this ceramic type.

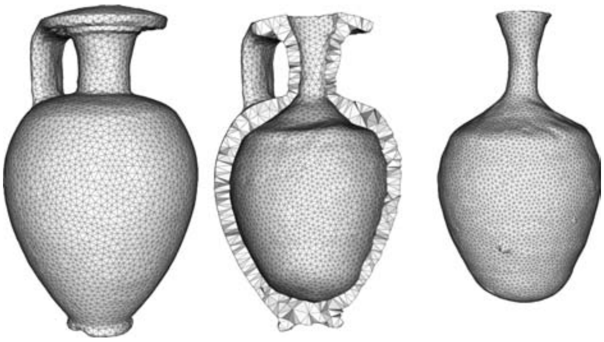

Figure 6. Aryballos UMJ ARCH Inv. 25277 (CT03145: 77 kV, 285 μA, voxel size 182 μm, Al 2.0 mm), surface reconstruction method for visualisation (left), ceramic volume (middle), and capacity (right).

6. Textural analysis

Although the emphasis has been on the different manufacturing techniques and on clarifying the hidden inner structures, the results of the present study show potential for the visual classification of pottery fabrics. A large variation of grey values is visible in the ceramic body and shows enough distinguishing criteria for such a classification. This is due to various inclusions and particles that have different radiation-absorbing rates from the ceramic matrix. CT is no substitute for petrographical investigation, but can detect these higher density particles. Perhaps the addition of reference materials with known specific gravity would enables a form of calibration (e.g., aluminium with 2.7 g/cm^3) with a view to measuring the volumetric proportion of these different particles within the vessel and using it to determine fabric groups.

The use of a series of test tiles with different tempering might help to determine the efficacy of this approach. For example, test tiles were made of modern fine levigated clay (Westerwald stoneware) with a 10% addition of one kind of tempering (quartz, shell-sand, straw, river sand, ceramic grog, etc.), each of these in two different particle sizes (100–200 μm and 200–500 μm), and fired in a modern electric kiln at a temperature of 960°C. Although some of these particles have similar specific gravity to the clay (mean 2.65 g/cm^3), for example quartz (mean 2.63 g/cm^3), they can be easily recognised because of their homogeneity as compared to that of the clay matrix, in which the inter-particle micro-voids decrease the radiodensity of the clay due to the partial volume effect (cf. Berg 2008, 1186) (Fig. 5).

Depending on the resolution, these particles could be distinguished as diagnostic features that can be analysed in terms of frequency, size, elongation, etc. by standard methods such as the optical classification of pottery fabrics normally applied at fresh breaks of ceramic sherds (Gassner 2003, 23–34; Gassner and Schaller 2009). In the further procedure, four CT cross-sections were made through each of the test tiles and grey-scale images were generated according to the procedure already described above. Each image was segmented by thresholding into the regions 0–85 (less dense, air) and 170–255 (dense), and analysed regarding area, elongation, grey-level, and major axis of these features with the use of the imaging program (UTHSCSA ImageTool <http://compdent.uthscsa.edu/dig/itdesc.html>). Analysis programs like RapidMiner (<http://rapid-i.com>) help to examine these data and to classify them into groups based on these sets of values and a similarity measure. Such an agglomerative clustering (visualised by a classification dendrogram) shows strong correlation to the initial fabrics. In spite of this two-dimensional approach, the results are encouraging and show that textural analysis using CT data is possible. Nevertheless, petrological examination by thin-sectioning of these test tiles is envisaged in order to test the reliability of this type of analysis.

7. Outlook

The reconstruction algorithm NeuRA2 (Jungblut *et al.* 2013) generates a triangular surface mesh of the scanned objects (Fig. 6). The application of a volumetric mesh generator (TetGen <http://wias-berlin.de/software/tetgen>; see Si 2008) transforms the surface mesh into a tetrahedral volumetric mesh. Summing up the volumes of each single tetrahedron yields an approximation of the volume of the scanned ceramics, and, since the mass of those objects is usually known, the bulk density of the objects can be calculated. Reconstructing the inner parts of the vessels also enables one to calculate an approximation of their capacity. However, an error estimation for the volume and capacity calculation has to be evaluated, and this will represent the objective of future research.

8. Conclusions

The above results provide considerable information regarding different manufacturing techniques and also demonstrate the possibility of using CT for textural analysis of pottery fabrics. Despite the difficulties inherent in the data acquisition and image processing, reasonably good results can be achieved by means of CT. These results indicate both a need for better grey-scale calibration as well as a reduction of the artefact-formations and beam-hardening effects. The final outcome has to be the use of the volumetric data of the CT not only for 3D visualisations, but also for textural analysis of the complete object. The application of surface reconstruction methods to the volumetric CT data is a promising approach for this type of 3D analysis. It is to be hoped that the general development of CT in industry will accommodate archaeological applicability in the future. If this occurs, studies using CT scanners will become more and more reasonable and cost-effective, the devices will be used more widely, and, as in the field of digital photography, resolution and data storage features will increase rapidly. A careful examination of the various details of manufacturing techniques relating to the reconstruction of the pottery production process, may lead to a better understanding of the ancient potter's craft.

Post scriptum

The methodological approach using industrial X-ray computed tomography for non-contact and non-invasive investigation of ancient ceramics is now comprehensively documented:

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