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Investigation of artefacts retrieved from a shipwreck of Vasco da Gama using X-ray Computed Tomography

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***Abstract*—In 1503, two ships part of Vasco da Gamas second armada to India were lost at sea. Archaeologists followed the historical trail that led them to the wreck site in Ghubbat ar Rahib Bay off Al Hallaniyah Island, Oman. The excavation found over 2800 artefacts including a ships bell and a concretion of silver coins. In this study the use of X-ray Computed Tomography (XCT) is outlined and how its exploitation guided conservators in restoring these artefacts, leading to revealing the date on the ships bell and discovery of an ultra-rare coin: the índio or "ghost coin" of Dom Manuel I.**

I. Introduction

In 1495 King Dom Manuel I of Portugal selected Vasco da Gama to lead an expeditionary fleet of ships to find the direct sea-route to India. Gama led the epochal voyage of four ships in 1497 around Africa to reach Calicut in India. The journey took 10 months and they were the first Europeans to reach India by sea [1]. This opened an important spice trade route for the Portuguese and while costly to the lives of those who sailed with him, the commodities generated significant profit to the crown. The initial contact with the Zamorin of Calicut was unfriendly [2], leading to conflicts and ultimately a long period of open warfare along the Indian coast [3].

In response Vasco da Gama sought revenge on behalf of the King and led two squadrons of ships that departed Lisbon in early 1502. Within the smaller fleet were two ships named the *Esmeralda* and *São Pedro* commanded by two uncles of Gama; Vicente Sodré and Brás Sodré. In April 1503 the fleet anchored off the coast of the Khuriya Muriya islands, Oman, to make repairs to one of their ships. The native Omanis warned of an impending storm that risked destruction of their ships which Sodré ignored. This was a fatal mistake when the strong winds predicted by the Omanis materialised causing the loss of the *Esmeralda* and *São Pedro* and the death of both brothers and many of the Portuguese crews [4]–[8].

Recent studies of these two losses led researchers to survey Ghubbat ar Rahib Bay on Al Hallaniyah Island, Oman. The identification of the wreck site is described in Mearns et al. [9] and was initially discovered in 1998 with the finding of numerous stone shot, indicative of an early European shipwreck. Further excavations uncovered ceramics, lead shot, a copper alloy disc and a small concreted clump containing silver and gold coins. Further a vital clue in determining the age and provenance of the wreck site - a ships bell. Conservation would be key to unraveling the mystery.

XCT is a powerful tool for non-destructive evaluation of objects with the ability to digitally section and observe in full 3D. Originally it was developed as a medical tool in the 1970s [10] but there has been a significant uptake by other sectors, industrial and academic, given the wealth of information it can provide - archaeology included. It has been used in applications such as evaluating ancient ceramics [11], the sarcophagi of Egyptian mummies [12] and probably the most famous Antikythera mechanism [13]. Notable numismatic XCT studies previously performed using XCT include evaluation of a selection of the Diniacopoulos collection [14], the conservation of a marine corroded hemiobolus coin [15] and an encased pot of Roman coins [16]. Archaeological samples are often embedded in hardened debris visually obscuring fine (or all) details of the artefact, to which non-invasive internal examination by XCT is particularly suited.

In this paper, X-ray Computed Tomography (XCT) was used to evaluate key artefacts from the excavation in Oman; a ship's bell and a large coin concretion. Recovery of archaeological materials from marine environments pose a number of issues related to conservation as they are often coated in hardened debris or other deposits and corrosion crust in the case of metallic objects. Conservators are then tasked with their removal without damaging the specimen, which with limited information can be problematic or maybe even impossible. Given distinguishable material composition in the obtained samples comprising of corrosion crust, mineralised deposits and the artefact itself, XCT has enabled the extraction of qualitative and quantitative data of the excavated samples. This guided the conservators work, particularly in revealing a date on the bell, and allowed internal observation of inseparable coin concretions that exposed an ultra-rare silver coin, the índio, among the collection.

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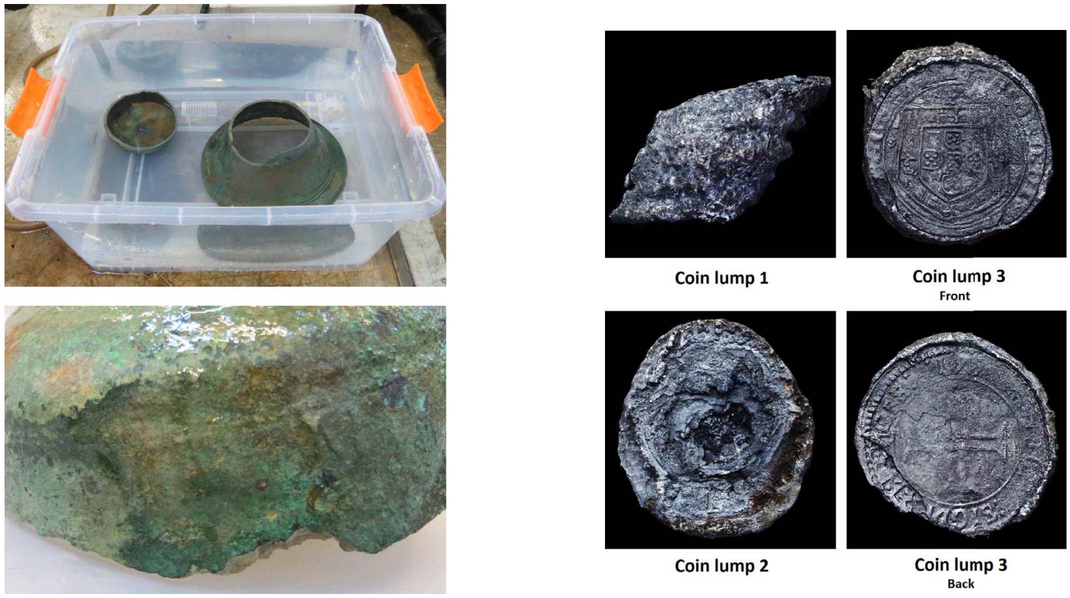


(a) (b)

Fig. 1: Artefacts recovered from the shipwreck. a) The two parts of the ship's bell recovered from the shipwreck, including a close up of the raised area on the upper part of the bell. b) Three coin lumps were also recovered, but couldn't be separated further due to fear of destruction.

Parameter	Ship's Bell	Coin lumps
Voltage (kV)	300	300
Current (μA)	215	100
Exposure (s)	4.0	2.8
Pre-filter (mm Cu)	9	2
Voxel size (mm)	0.064	0.016

TABLE I: XCT parameters for the artefacts.

II. Samples

A. *Ship's bell*

A small copper-alloy ships bell recovered from the wreck site is shown in Figure 1a). The bell was largely intact, but fractured into two parts; the upper section measuring 110 mm in diameter and the lower mouth of the bell 230 mm in diameter at its widest and 250 mm in height. The upper part of the bell is potentially one of the greatest finds of the excavation as a bell is commonly cast with the name of the ship and/or the year it was built. Figure 1a) shows the upper part of the bell where this information is most likely to be found, obscured by a thick layer of corrosion products. Conservation of the bell would involve removing these mineralised deposits to hopefully uncover any details that might help archaeologists identify the wreck. At the time of excavation a suspected 'M' was partially visible, a first clue in this identification.

B. *Coin concretions*

Also recovered were a number of silver and gold coins. While some of the gold coins (all *cruzados*) were found singly, all silver coins were found in a cemented block that also contained additional gold coins. This investigation focused on the cemented block, which was eventually separated into three clumps shown in Figure 1b); two clumps originally thought to contain 4 and 10 coins respectively, and what appeared to be two larger coins cemented together. Because the silver coins minted during King Manuels 26-year reign were better dating tools than the Manuel *cruzados*, it was essential to try and identify each individual coin. The two larger coins generated significant interest as the markings on the reverse shown in Figure 1b) were indicative of an *índio* an historically important coin of such rarity that only one other of its kind is known to exist, speculated that Manuel commissioned it specifically for trade with India [17]. For these reasons the *índio* enjoys an almost legendary status within Portuguese numismatics as the 'lost' or 'ghost' coin of Dom Manuel.

III. X-ray Computed Tomography

XCT is a non-destructive method that generates image slices of the object that together represent the 3D object. The cone-beam lab setup used in this study consists of an X-ray source and detector with the sample mounted on a rotating table between the two as shown in Figure 2. A 2D radiograph is generated by X-rays interacting with the sample in view - they are either attenuated or pass straight through the specimen which is then received by the detector. This results in a grey-scale image where darker regions indicate where there has been a greater attenuation (absorption) of X-rays, dependent on the material itself and the amount of material they pass through. Images are then taken through a full 360 degrees rotation which are then reconstructed into a series of 2D slices through a method called filtered back projection. These 2D slices provide internal observation of the object with materials

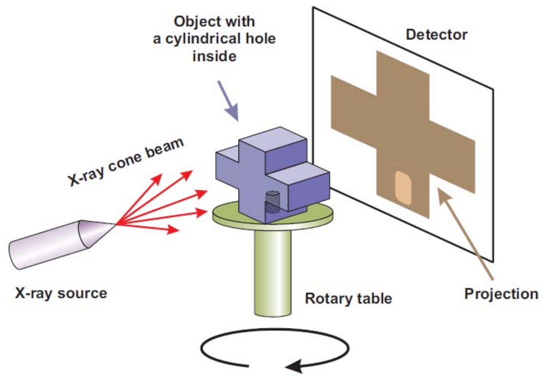


Fig. 2: Setup of XCT showing the position of the X-ray source, detector and the rotary table upon which the sample is mounted.

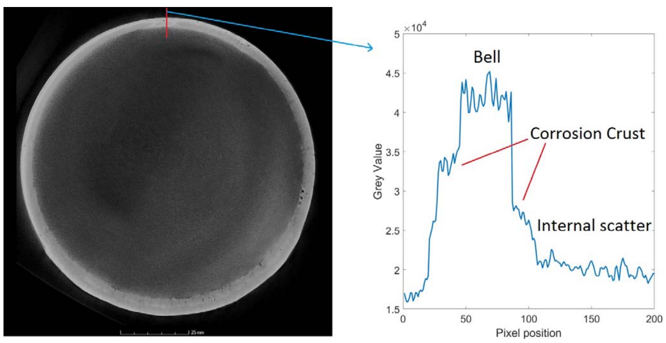


Fig. 3: Cross section of XCT scan of the ship's bell. Taking a line profile of grey-values of the edge of the bell shows the corrosion crust that was digitally removed, and indicated a threshold to represent the bell.

of different atomic numbers represented by different grey values, and when stacked together present a 3D volume.

The XCT system used in this study was the Nikon XT H 225/320 LC, utilising the higher powered 320kV head. This was needed given the metallic nature and hence high absorption of the samples considered in the study. The scan parameters are shown in Table I. The resolution achieved corresponds directly to the size of the part; the detector provides a limited field of view and the size of the part determines the maximum achievable geometric magnification. Note that a high amount of filtering has been used which is placed in front of the source during the scanning procedure. Since the specimens are highly absorbing it is required to filter the X-ray beam to remove low energy X-rays that would be easily absorbed, and further generate scatter that would lead to a reduction in image quality. All results were processed in VG Studio MAX (Volume Graphics, Germany).

IV. Results

A. Ship's bell

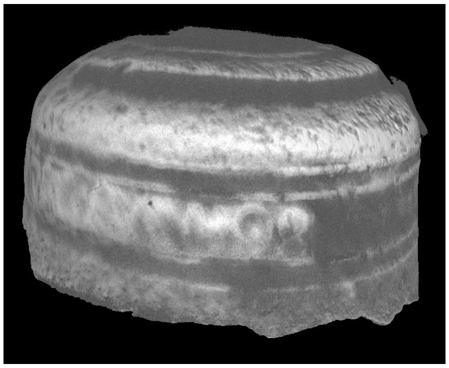
First the upper section of the ships bell was scanned, with an exemplar cross section shown in Figure 3. Here we can see the defined circular outline of the bell, but also a low intensity grey speckle pattern that surrounds the object internally and externally. This luminance is a result of a large amount of scatter owing to the thick metallic nature of the part. To evaluate this effect and inspect density composition, a line profile of the grey values along the red line is given. The pixel position denotes each individual pixel along the red line and the grey value is a representation of density of material at that pixel where higher X-ray attenuating materials have a higher grey value. Along this line there are several distinct regions; pixels 0-26 have a value of ˜16000, pixels 27-47 a value of ˜33000, pixels 48-83 a value of ˜41000, pixels 84-100 a value of ˜27000 and then averaging 21000 for the remainder. The two extremities are simply noise and scatter from the XCT setup and imaging artefacts from a metallic sample. It is the three interior sections that areas of interest. The bell itself was determined to be predominantly tin and copper in composition from previous X-ray fluorescence analysis [9], and typical mineralised deposits attenuate X-rays at a lower rate than their pure counterparts. From this it can be deduced that corroded layers around the bell will be represented by a lower grey value, providing indicative thresholds to segment the bell from the mineralised deposits and thus revealing any inscription that may remain.

To observe the object in 3D one must select a threshold such that a particular group of grey values is considered the object, and the rest is considered background. Our physical observation of the object cannot remove corrosion crust, but here we can exploit the different attenuation of the crust and the bell itself to digitally remove this layer. A threshold was selected based on the observations in Figure 3 and a 3D volume generated. The resultant model can be observed in Figure 4a) and 4b). Given the high amount of noise present in the digital reconstruction, the thresholding method is somewhat subjective but reasonable estimates can be made from the above interpretation.

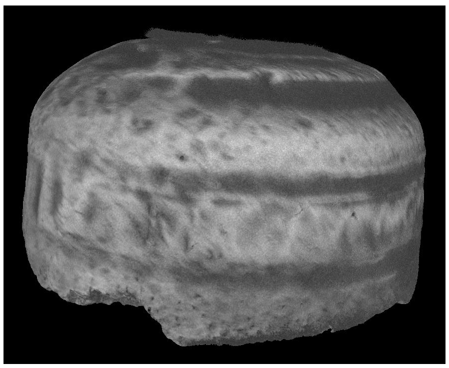
The threshold selection revealed characters that had been cast on the bell. First it was confirmed that indeed an 'M' did exist as previously thought, but most excitingly three consecutive numbers were identified; '4', '9' and '8'. These numbers are believed to date the ship to 1498, which is chronologically correct with the known history of Gamas armada leaving Lisbon in 1502. The bell also had numerous raised regions in this band but no additional characters were discernible, likely due to abrasion and severe corrosion of the casting. With this information, conservators had an outline of the location of the band of characters and were able to direct their efforts with knowledge that would otherwise be unobtainable. After removal of the crust, the fully conserved bell did indeed show the characters that had been observed with XCT as shown in Figure 4c).

B. Coin concretions

An exemplar slice of the largest coin lump can be seen in Figure 5a). After more than half a millennium of exposure to the the ocean, the coins are coated in a thick layer of miner-



(a)



(b)

(c)

Fig. 4: By selecting an indicative threshold in the digital XCT volume shown in Figure 3 several characters were revealed; a) ‘4’, ‘9’, and ‘8’. b) ‘M’. This guided conservator efforts to reveal the lettering on the physical bell with the final conserved state of the physical bell shown in c).

alised deposits and significantly distorted, displaying a wavy like structure. In each scan volume it is possible to count the number of coins within each clump; 3, 17 and 4 respectively. The clump containing four coins was the originally thought to consist solely of the suspected *índio* and real *grosso* seen in Figure 1b) denoted ‘coin lump 3’. Within each scan it is possible to traverse the stack to observe the faces and measure the diameters of each coin. The distinctive markings often contain the reigning king at the time of minting, and combined with the dimensions enabled individual identification using sources Couvreur [18], Gomes and Trigueiros [19], Vieira [20] and Gomes [21]. The analysis of the lumps can be found in

Lump	Coin #	Diameter (mm)	Reign	Coin Type
1	1	16.06	Manuel I	Meio Vintem
	2	18.24	João II	Vintem
	3	15.50	Manuel I	Meio Vintem
2	1	15.88	Manuel I	Meio Vintem
	2	16.22	Manuel I	Meio Vintem
	3	15.62	Manuel I	Meio Vintem
	4	15.37	Manuel I	Meio Vintem
	5	17.76	Manuel I	Meio Vintem
	6	15.37	Manuel I	Unknown
	7	15.34	Manuel I	Meio Vintem
	8	19.26	João II	Vintem
	9	15.72	Manuel I	Meio Vintem
	10	15.06	Manuel I	Meio Vintem
	11	15.43	Manuel I	Meio Vintem
	12	18.43	Manuel I	Vintem
	13	15.42	Manuel I	Meio Vintem
	14	15.56	Manuel I	Meio Vintem
	15	15.80	Manuel I	Meio Vintem
	16	15.72	João II	Meio Vintem
	17	15.81	Manuel I	Meio Vintem
3	1	25.08	Alfonso V	Real Grosso
	2	25.34	Alfonso V	Real Grosso
	3	15.87	Manuel I	Meio Vintem
	4	21.71	Manuel I	Indío

TABLE II: Classification of the coins from quantitative and qualitative assessment of XCT scans

Table II.

‘Coin lump 1’ was found to have three coins; two *meios vintéms* belonging to the reign of Dom Manuel I and a Joo II *vintém*. ‘Coin lump 2’ was found to have about 17 coins sandwiched together each with varying levels of detail dependent on the individual level of corrosion. The approximate figure arises as one coin appears to be an imprint on corrosion crust. Despite this, each coin revealed enough information to clearly identify all of them as either *vintéms* or *meios vintéms* from the reigns of João II or Manuel I. The reverse of a Manuel *meio vintém* has the distinctive cross of the Order of Avis shown in Figure 5b). The obverse of this coin is marked by the five escutcheons as shown in Figure 5c), and in the case of João II *vintém* the reformed royal coat of arms can partially be seen in Figure 5d). The surrounding inscription had the name of the reigning king at the time of minting which was also partially visible in most of the cases as can be observed across the three images.

A potentially interesting coin mass as pictured in Figure 1b) (‘Coin lump 3’) included the suspected *índio* and *real grosso*. The corroded crust, while minimal, obscured a number of markings that would confirm the finding. Again it was hoped that such details could be revealed using XCT. Further given its significance in Portuguese cultural history, digital records and models of the specimen are important to preserve these historical findings.

An XCT scan of the sample revealed that it was in fact a stack of four coins not two; the Manuel *índio* on the one side as suspected shown in Figure 5e), a Manuel *meios vintéms*, and two *reais grossos* shown in Figure 5f) with the obverse of one exposed on the opposite side of the clump to the *índio*. This particular *real grosso* appears to be one that was minted during the earlier reign of King Afonso V between

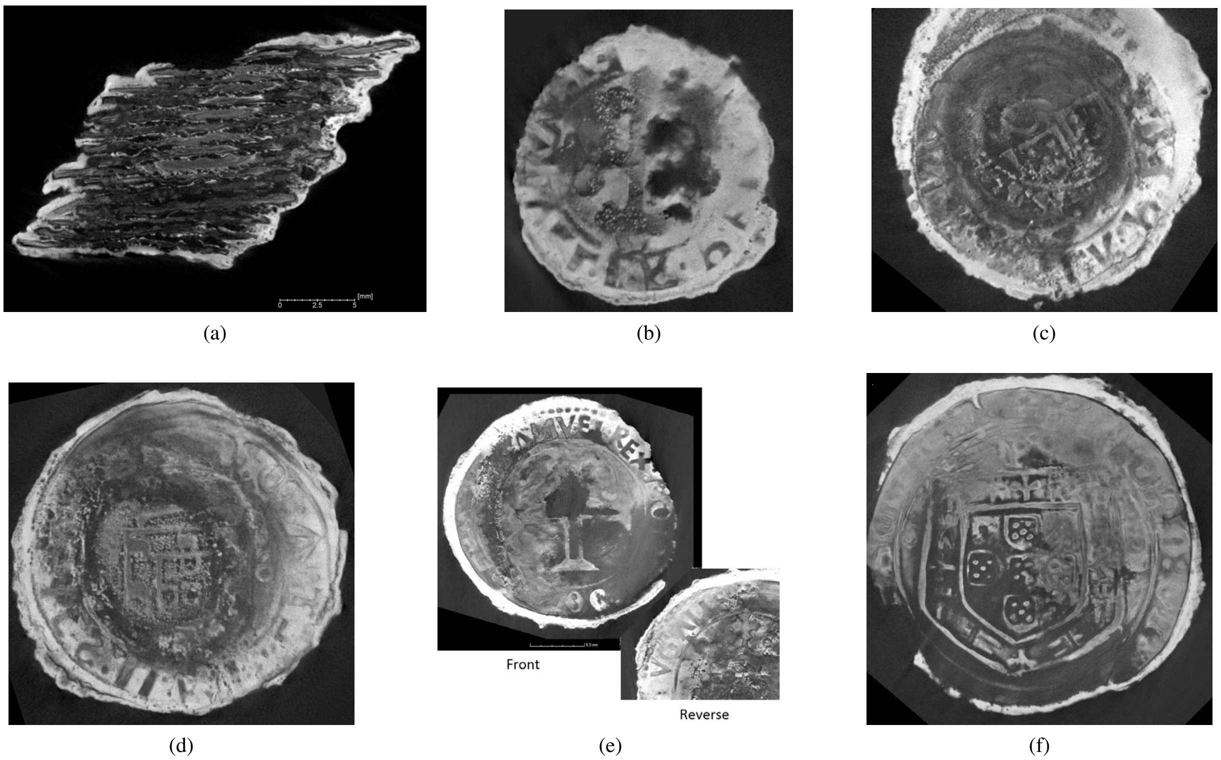


Fig. 5: XCT results from the coin concretions. a) 2D ortho slice through the largest of the coin lumps. b) The reverse of a Manuel *meio vintém* showing the distinctive cross of the Order of Avis. c) The obverse of a Manuel *meio vintém* with the five escutcheons. d) The reverse of a *vintém* of João II with the royal coat of arms. e) The reverse of the Manuel *índio*. f) the obverse of an Afonso V *real grosso*.

1475 and 1479 in the city of Oporto when the Portuguese claimed sovereignty over Castile and Leon [22]. The *índio* (the Indian) was probably minted from 1499 onwards after Gamas return to Lisbon, and seems to be where the name originates. The reverse of the coin is marked by the cross of the Military Order of Christ at the centre, one of the first Portuguese coins to do so. The gold português was minted in the same period also displaying the cross of Military Order, but the order of issue against the *índio* is unknown. The cross is clearly visible in the images surrounded by the inscription ":IN: :HOC: :SIGNO: :VINCES" meaning in this sign you will conquer. The obverse has little non corroded detail towards the centre but a faint outline of the coat of arms can be seen and a prominent cruciform finial at the top of the crown. It was possible to reconstruct the legend around the periphery with the text "+PRIMVS:EMΛNVEL·REX:PVRTVGΛLIE:". The only other example of an *índio* in existence resides within the collection of the National Historical Museum of Brazil in Rio de Janeiro, making this discovery momentous in its own right. But further still this coin is consistent in terms of size, type, style and legend with the one held at the National Historical Museum. With this degree of similarity the analysis suggests that it is possible the two coins share the same obverse die.

XCT has qualitatively shown the state of preservation of the coins. Given the extremely fragile nature of the coins and distinctly small separation between them, typically less than a millimetre at the centre, it is not possible to separate them without significant risk of damage and for this reason the conservators have decided to leave the concretion as it exists. Being able to non-destructively identify and digitally display the multitude of coins has therefore been essential for the study and identification of these important artefacts.

V. Conclusion

Archaeological excavation of the wreck site in Ghubbat ar Rahib Bay returned a large number of artefacts with the resultant study and scientific analysis identifying Vicente Sodrés Esmeralda as the probable source of this material. The historical accounts of the sinking event, which describe Brás Sodrás ship, the São Pedro, being driven ashore while the Esmeralda was lost at sea supports this probable identification. Furthermore, the date on the ships bell and the *índio* coin that was initially minted in 1499 and in production for a very limited period correlate to the correct time period. Additional numismatic evidence that corroborates the identity of the shipwreck is the absence (to date) of any coins that were issued in the period after this voyage such as the abundant silver tostões that were issued around 1504 [7] and those from any subsequent kings, namely João III (1521-1557) and Sebastião I (1557-1578). Another tentative clue is a collection of 42 large igneous shot with the inscription ‘VS’ that was also recovered, but not discussed in this paper, which might be connected with Vicente Sodré. A full description of the other recoveries to date are described in Mearns et al 2016 [9], with further archaeological analysis planned in the future.

XCT has been a central technique for archaeologists and conservators throughout this research. The initial recovery of the ships bell was met with excitement, but to properly assess this key artefact removal of the mineralised deposits and corrosion crust was required with little or no direction. A scan of the bell using XCT provided a non-destructive method to have a first look beneath the crust, revealing the characters ‘M’ and ‘498’ and their position. Their location was now visually clear for conservators to help guide the conservation and minimise damage.

The concreted clump of silver and gold coins was initially mechanically separated by applying 10% formic acid by pipette resulting in the three silver coin concretions observed in this study. Further separation was not possible given the degree to which the coins were cemented together. Internal observation of these clumps was again provided by XCT, generating 2D images of each individual coin contained within. Careful visual examination of the individual coins along with precise measurement of the coin diameters enable all 24 silver coins to be identified. The most important and rare discovery among them was the *índio* coin, confirming the initial suspicions from what could be visibly observed. This is only the second such example of Dom Manuels legendary ghost coin known to exist, and further there are indications that the coin held in Brazil is from the same reverse die. Among the recovered coins, all were from the reign of Dom Manuel or earlier Monarchs and given the limited *índio* production period 1499 - ca. 1504, this provides additional evidence to support the proposed identity of the shipwreck.

In comparison to the previously cited numismatic works utilising XCT, this study provides the highest spatial resolution of coins; Nguyen et al. [14] and Bozzini et al. [15] do not directly cite this measurement, although from the setup parameters it can be deduced that the presented work has approximately double that of the previous studies. Miles et al. [16] are working with a much larger sample size (a ceramic pot with 201 coins), again resulting in a lower spatial resolution. Despite the higher spatial resolution presented here, Miles et al. are able to provide better volume renderings of individual coins likely due to its preserved state largely consisting of soil based deposits as opposed to mineralised concretions as typically observed in excavated marine artefacts. The hemibolus coin in Nguyen et al. is more comparable given the coins coastal burial conditions, although the preserved state is still superior; the exemplar coin lump shown in Figure 5a) shows a degree of non-uniform deformation. In this study the coins were encased in severe mineral concretions in what initially appears as an unrecoverable state to conservators, but significant insight and even classification has been possible with the use of XCT.

Since this analysis a myriad of additional artefacts have been excavated from the site in late 2015, which brings the total recoveries to more than 2800. XCT is a specialist tool that generates large amounts of data that can be time-consuming to interrogate, but further application to key artefacts will seek to produce yet more conclusive evidence for identifying the wreck site as the remains of Vicente Sodrés Esmeralda.

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