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ANDEAN PRE-HISPANIC POTTERY FORMING 3D ANALYSIS: A PILOT STUDY FROM QUEBRADA DE HUMAHUACA (ARGENTINA) USING DIGITAL METHODS

ANÁLISIS 3D DE LA FABRICACIÓN DE CERÁMICA PREHISPÁNICA ANDINA: UN CASO PILOTO DE LA QUEBRADA DE HUMAHUACA (ARGENTINA) USANDO MÉTODOS DIGITALES

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Highlights:

- Morphological Residue Model (MRM) analysis and Virtual Reflectance Transformation Imaging (V-RTI) visualisation are useful methods to study pottery forming techniques.
- This paper provides information on late pre-Hispanic pottery forming methods of Humahuaca Black-on-Red vessels.
- Digital photogrammetry, MRM and V-RTI techniques provide evidence of the presence of paddling as a forming technique in the North of Argentina, particularly in Quebrada de Humahuaca.

Abstract:

Digitization, three-dimensional (3D) documentation and visualization of archaeological materials are processes in increasing development that are used for enhancing heritage. These tools have multiple uses for the analysis and research of archaeological objects, although their use in pottery forming techniques studies is less explored. In this paper, diverse digital methods are analysed in the study of pottery forming macro-traces, using the 3D model of an archaeological vessel from South-Central Andes. This case is proposed as a pilot study, aiming to reveal the digital techniques' potential for understanding pottery forming techniques. The particular case dealt with corresponds to a globular pot of the Humahuaca Black-on-Red style, recovered at the *Pucara de Volcán* archaeological site, in Quebrada de Humahuaca (Jujuy, Argentina). Initial studies of macro-traces on the pot suggested the use of paddling as the forming technique. To contrast this hypothesis, the workflow applied included the generation of a 3D model by close-range photogrammetry; the author also analysed the resulting point cloud and mesh using Morphological Residue Model (MRM) and Virtual Reflectance Transformation Imaging visualization (V-RTI). This was possible thanks to various open-source software packages, such as AliceVision Meshroom and CloudCompare. These methods increased the micro-topography visibility of the pot surface. As a result, the presence of sub-circular depressions in the body of the pot -similar to percussion cupules-, horizontal pressure lines in the collar, and micro-pull-outs in the maximal diameter of the pot were described. These macro-traces were interpreted as corresponding to the paddling technique used for the elaboration of the pot body —a technique not previously identified in pre-Hispanic traditional pottery manufacturing in the north of Argentina—, and of coiling for manufacturing the collar. The digital methods explored have great potential in the study of pottery forming techniques, although their scope depends on the accuracy of the 3D model analysed.

Keywords: morphological residue model (MRM); virtual reflectance transformation imaging (V-RTI); visualization; 3D; archaeological pottery; forming techniques

Resumen:

La digitalización, documentación y visualización tridimensional (3D) de materiales arqueológicos son procesos en creciente desarrollo que se utilizan para la puesta en valor del patrimonio. Estas herramientas tienen múltiples usos para el análisis y la investigación de objetos arqueológicos, aunque su uso en el estudio de las técnicas de manufactura cerámica está menos explorado. En este trabajo se exploran diversos métodos digitales en el estudio de las macro-trazas de manufactura cerámica, utilizando el modelo 3D de una vasija arqueológica de los Andes Centro-Sur. Este caso se propone como un estudio piloto, con el objetivo de revelar el potencial de las técnicas digitales para la comprensión de las técnicas de manufactura cerámica. El caso particular analizado corresponde a una vasija globular del estilo Humahuaca Negro sobre Rojo recuperada en el sitio arqueológico Pucara de Volcán en la Quebrada de Humahuaca (Jujuy, Argentina). Los estudios iniciales de las macro-trazas en la vasija sugirieron el uso del paleteado como técnica de manufactura. El flujo de trabajo utilizado para contrastar esta hipótesis incluyó la generación de un modelo 3D mediante fotogrametría de objeto cercano, y el análisis de la nube de puntos y la malla resultantes mediante el Modelo Morfológico de Residuos (MRM) y la visualización de imágenes por transformación de reflectancia virtual (V-RTI) utilizando diversos

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paquetes de software de código abierto, como AliceVision Meshroom y CloudCompare. Estos métodos aumentaron la visibilidad de la microtopografía de la superficie de la olla. Como resultado, se describió la presencia de depresiones sub-circulares en el cuerpo de la vasija -similares a cúpulas de percusión-, líneas de presión horizontales en el cuello y micro-extracciones de pasta en el diámetro máximo de la vasija. Estas macro-trazas fueron interpretados como correspondientes al uso del paleteado para la elaboración del cuerpo de la vasija -técnica no identificada previamente en la manufactura alfarera tradicional prehispánica del norte de Argentina-, y de colombinos para la fabricación del cuello. Los métodos digitales explorados tienen un gran potencial en el estudio de las técnicas de manufactura cerámica, aunque su alcance depende de la precisión del modelo 3D analizado.

Palabras clave: modelo de residuo morfológico (MRM); imágenes por transformación de reflectancia virtual (V-RTI); visualización; 3D; cerámica arqueológica; técnicas de manufactura

1. Introduction

Pottery, as one of the most widespread productive activities of the past (Skibo and Feinman, 1999), provides access to different aspects of people's lives. Thus, the study of ceramic vessels, far from being an end in itself, is a tool to answer various archaeological questions. The use of new technologies for the study of pottery vessels allows working on different scales of observation. In particular, the use of 3D models offers the possibility of evaluating the surfaces of the vessels, as well as aspects related to their symmetry and volume (Rodríguez González, Carbonell Pastor & Casals, 2019; Ferrari & Giligny, 2020).

3D documentation of archaeological remains is an increasingly developing activity, and the resources at hand are continuously growing. The analysis of 3D models of archaeological materials has an important potential in research that is in constant development (interesting results were produced by Georgiou, Armostis, Hermon, Christophorou & Vassallo, 2014; Fazio & Lo Brutto 2020; Ferrari & Giligny, 2020; Sequenzia, Fatuzzo & Oliveri, 2021; and Fernández-Tudela, Zambrano, Lagóstena & Bethencourt, 2022).

In this opportunity, a pilot study of pottery forming techniques is presented using digital methods on 3D models. This study had the purpose of assessing the scope and limitations of digital methods in the study of ceramic forming macro-traces. The methods in question include Morphological Residue Model (from now on MRM) analysis (Correia Santos, Pires & Sousa, 2014; Pires, Fonte, Sousa, Correia Santos & Gonçalves-Seco, 2014) and Virtual Reflectance Transformation Imaging (from now on V-RTI) visualization (Cultural Heritage Imaging, 2008; Ferrari & Giligny, 2020). These two methods had been used in different types of archaeological records, such as terrain studies, rock art, and engravings on plaquettes, coins, or architectural features, among others. Their use for the study of forming macro-traces is still underdeveloped. MRM and V-RTI were introduced after the traditional study of macro-traces of a globular pot recovered in the Pucara de Volcán archaeological site (northern Argentina) in order to evaluate their ability to provide further evidence regarding forming techniques.

The manufacture of a ceramic vessel involves a sequence of technological behaviours. This process includes different stages; from the selection and preparation of raw materials to the manufacturing of the vessels, their firing, and post-firing treatments. Throughout the manufacturing sequence, culturally significant features that reflect shared practices in a group of potters can be identified. These practices are embedded within cultural traditions in a particular landscape.

Despite the importance and amount of archaeological pottery in the Andean area, traditional manufacturing techniques are still little known. The accelerated disappearance of communities of practices centred on pottery production in the Andes, especially in the North of Argentina (Cremonte, 1995; Scaro, Couso & Cremonte, 2021), highlights the importance of understanding traditional ways of doing pottery and their links with communities of practice and identities throughout the Andes, using different strategies of analysis. Ethnographic and ethnoarchaeological studies have been carried out since the 1980s, in parallel to the study of archaeological materials -the latter generally focused on petrographic aspects of ceramic fabrics. The study of forming surface markings, both in macroscopic observations and in digital models provides valuable information to understand past pottery practices.

2. Forming techniques and ceramic studies

Ceramics is part of the material dimension of practice, embedded in a process by which objects and humans constitute each other (Miller, 2005). An integral ceramic analysis, considering stylistic, technological, and functional aspects, is relevant to understanding the social, symbolic, and ideological dimensions within the daily practices of the groups that made and consumed ceramic vessels.

Pottery, as the technical result of an operational chain (*chaîne opératoire*), depends on a series of choices made by the potter in the different stages of production of a vessel (Lemonnier, 1992). As such, a way of making that materializes certain cultural patterns is established, insofar as the vessel's attributes are recurrent. The manufacture of a ceramic vessel involves a sequence of technological behaviours. Throughout the forming sequence, culturally significant features that reflect practices shared by potters can be identified. These behaviours will depend on environmental availability and on cultural traditions, which imprint their identity on the ceramic universe for a given place and time. Technological manufacturing traditions imply the presence of a tradition of shared information among the populations of the same region or several regions (Cremonte, 1995).

Technological traditions are shaped by technical choices, integrated into the operational chain (Lemonnier, 1986), and related to the "know-how" (Lemonnier, 1992). From this perspective, the operational chain (‘*chaîne opératoire*’) allows the reconstruction of the technological choices within a group of potters, which are part of ceramic technological traditions. The process of fabricating ceramic vessels requires a technical practice that is acquired through a learning process carried out within a social group (Arnold, 1985; Roux, 2015, 2019).

The study of the operational chain is centred on the interpretation of the sequence of physical operations which transform raw materials into objects. Such interpretation is based on the study of the recurrent pieces of evidence left by the physical and chemical changes produced during the process of an object fabrication (García Rossello & Calvo Trias, 2013).

The recurrent nature of the technical choices made by potters highlights the importance of analysing manufacturing traditions as a tool for accessing the ways of making pottery and the production contexts in which they would have developed. Exploring manufacturing techniques through the study of surface markings gives an insight into technical aspects and technical gestures of the potters of the past in the forming stages of manufacture (Rye, 1981; García Rossello & Calvo Trias, 2013; Livingstone-Smith, 2001; Roux, 2016; Santacreu, 2017). The study of surface markings includes the macroscopic and mesoscopic observation of pottery vessels, describing their surface topography, variations in texture and wall thickness, the morphology of breaks, the orientation of the clay matrix, and the presence and nature of voids and temper (Ferrari & Giligny, 2020). The systematic description and interpretation of these elements provide evidence to reconstruct the *chaîne opértoire.* As Thér (2020) points out, pottery forming methods are most commonly described and classified according to qualitative categories.

3. Ceramic tradition in a sector of the South-Central Andes

Previous work in the north of Argentina, particularly in Jujuy Province, provides interesting information regarding forming techniques of pottery vessels in this area of South-Central Andes. As it was aforementioned, pottery communities are rapidly disappearing, and nowadays most ceramic culinary equipment is being replaced by metal, plastic, and glass utensils, pans, and pots (Scaro & Musaubach, 2021).

Ethnoarchaeological studies conducted in the last thirty years (Cremonte, 1989, 1989-90, 1990, 1995, 1996; Menacho, 2000; López, 2014; Scaro et al., 2021) have provided valuable information regarding traditional knowledge for the manufacturing of pottery vessels, its changes and continuities. In most of the mentioned cases, a mixed technique that includes coiling and modelling has been identified. Generally, the base and lower body of the vessels are modelled from a lump of clay, hollowed by pinching using the hands to generate a bowl. Coils are attached to this bowl to elaborate the upper body, neck, and rim. Each part is dried before adding new coils, resulting in four or five stages for the forming of a small pot. Finishing techniques include the shaving of the surfaces with a metal instrument (a knife blade) to level its thickness, and the use of a cloth dipped in clay. Once finished, the vessel is left to dry in the sun for about two hours.

Previous analyses in the archaeological record (López, 2014; Scaro & Calomino, 2019) had revealed the presence of a forming method similar to the one described above for ethnographic contexts: a base modelled by pinching to which coils are attached to lifting the body and neck of the vessel. Finishing treatments including the smoothing of the surface by hand and with stone polishers were also recorded. The study of archaeological vessels revealed the presence of other forming techniques, not identified in current contexts in the region. They include the use of coils for the elaboration of the base and the body of the vessel and the possible presence of paddling discussed in this paper. The presence of these techniques in the archaeological record marks the loss of the diversity of pottery-making practices in current groups in north-western Argentina.

Regarding paddling, it is a forming method still used in the Central Andean area (Druc, 2011; Lara, 2018), where large wooden paddles are used to form restricted vessels from a lump of clay, using a large stone as an anvil. This technique has not been registered in north-western Argentina. López (2014) has proposed the presence of paddling with pebbles as a technique for smoothing the surfaces in archaeological vessels from Quebrada de Humahuaca, although it is another technique, used in different moments of the operational chain.

4. Materials and methods

4.1. Characteristics of a vessel from Quebrada de Humahuaca

A ceramic vessel from the archaeological settlement Pucara de Volcán was selected since it is a complete vessel in a good state of preservation. Pucara de Volcán (Gatto, 1946; Suetta, 1969; Garay de Fumagalli, 1998; Cremonte & Scaro, 2010; Scaro, 2020) is located in the south-central sector of Quebrada de Humahuaca (Fig. 1), in north-western Argentina, a part of the South-Central Andean region. The site was occupied between the 13th and 16th centuries, and it was an important Inca node after the annexation of the region to the Inca Empire ca. 15th century.

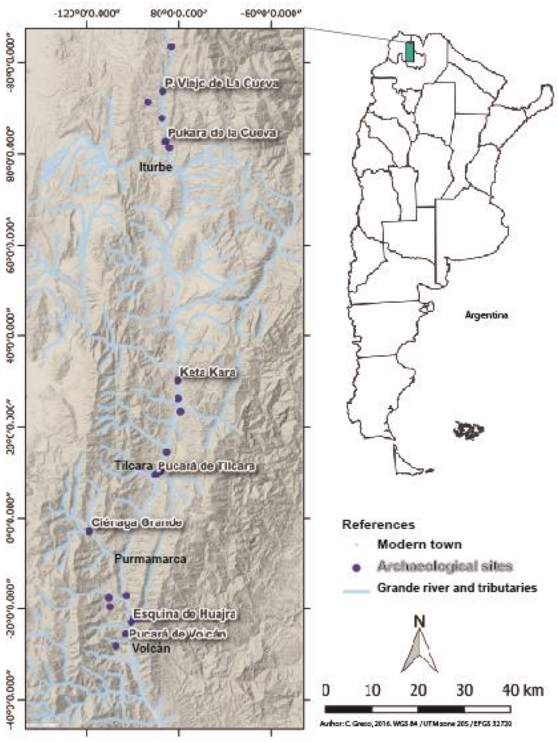


Figure 1: Map of the Quebrada de Humahuaca, with the location of the main archaeological sites of the region.

Pucara de Volcán settlement includes a residential area, a segregated cemetery, dwellings located on a hillside to the north of the main residential area, and retaining walls. The entire site covers over seven hectares. The architecture of the settlement is homogeneous, with rectangular enclosures with rounded corners, double walls filled with pebbles, and beaten mud, which in some cases have mortar. Despite the dense occupation of the central residential area, there are empty spaces that would have been used as communal areas or plazas. There is a series of circulation routes that run through the settlement, including an axial road that divides the site longitudinally into two halves. Secondary roads run through the entire settlement, delimiting housing units.

The funerary structures of Pucara de Volcán are circular, built with double walls and covered with slabs, some of them are located in the living area, close to the walls of the courtyards. As already mentioned, a large number of burials appear, segregated from the main residential area, in the so-called Necropolis located on a smaller terrace separated from Pucara de Volcán by a drainage furrow. Another burial area is located at the western end of Volcán, forming part of the so-called 'plaza-mound-cemetery complex'.

The plaza corresponds to the largest open space at Volcán —approximately 2400 m^2— associated with an artificial mound that would have contained a tomb on its summit (looted before the first systematic excavations were carried out at the site). The axial road and a 'plaza-mound-cemetery complex' were identified as part of the remodelling carried out at Pucara de Volcán by the Inca imperial administration.

The selected vessel was recovered in 1940 by Gatto (1946), on a second expedition to the region sponsored by the Argentinian Museum of Natural Sciences, and is currently deposited in the Ethnographic Museum 'Juan B. Ambrosetti' (Faculty of Philosophy and Letters, University of Buenos Aires). The vessel (Figure 2), identified with the number M.E. 40-220, corresponds to a globular pot with a short neck and everted rim with a rounded lip, identified as part of the local Humahuaca Black-on-Red style (Nielsen, 2007; Scaro, 2019). Although there are no radiocarbon dates or clear contextual relationships, recent studies at the settlement (Garay de Fumagalli, 1998; Cremonte & Scaro, 2010; Scaro, 2020) have allowed to chronologically place this vessel in the last centuries of the pre-Hispanic occupation of the Quebrada de Humahuaca, between the 13th and 16th centuries.

The Humahuaca Black-on-Red style stands out for its wide dispersion in the Quebrada de Humahuaca and its high incidence in the archaeological record. For this reason, several researchers have suggested that this emblematic style would have been linked to the consolidation of new identities and political territories that would have emerged around the 12th century (Cremonte, 2006; Nielsen, 2007; Runcio, 2009). This style continued to be used after the Inca conquest when Humahuaca-Inca pottery also emerged, a ceramic made according to local traditions but imitating the shapes and designs of Inca pottery.

An initial macroscopic study of the vessel revealed the presence of circular depressions in the external surface that provides a very irregular aspect to the vessel. The inner surface is very regular, without depressions, and it presents stretching marks for restricting the globular vessel and elaborating the minimum diameter. The everted collar and rim were formed with two coils.

Initially, the possibility of modelling the complete vessel was considered; the depressions identified were regarded as the product of digital pressures (Scaro & Calomino, 2019). The identification of modelling as a forming technique for the Humahuaca Black-on-Red pot responded at the time to the absence of ethnographic and/or archaeological evidence of the use of paddling in Quebrada de Humahuaca or adjacent areas of Jujuy province. Further analysis and comparisons with evidence from other Andean regions allowed proposing the use of paddling as a forming technique for the body of the pot, combined with the use of coils for the elaboration of the collar and rim. This proposal was tested with virtual analyses on a 3D model.

Figure 2: Analysed Humahuaca Black-on-Red globular pot (M.E.40-220).

4.2. Digital methods

A combination of digital procedures was used for the study of pottery macro-traces, including photogrammetry, MRM, and V-RTI.

A 3D model was created with close-range photogrammetry (Santamaría Peña & Sánz Méndez, 2011; Murray, McDonald & Kimpton, 2016), using a fixed model acquisition mode with a Nokia D5300 Camera, generating 103 photos of the vessel (Table 1). A Structure for Motion Technique (SfM) was used to elaborate a high quality 3D model (Fuentes-Porto, García-Ávila & Marrero-Salas, 2021). The model was generated with the open-source software AliceVision Meshroom v. 2019.2.0 (Griwodz et al., 2021) (Fig. 3) and subsequently edited in Blender v. 2.92.0 to scale it and to remove loose mesh fragments (Fig. 4). The final model contains 828576 vertices and 1,657122 faces (Table 2). An optimized version of this model is available on Sketchfab (https://sketchfab.com/3d-models/olla-humahuaca-e6f8c63c19724d17994f0537df3503bd).

Table 1: Protocols for photogrammetric acquisition.

M.E. 40-220

Camera Model	Nikon D5300
Aperture (F)	f/3.3
Exposure Time	1/30s
ISO	250
Lens	45mm
Illumination	2 neutral LED lamps
Acquisition Mode	Fixed object
Photogrammetry Software	Meshroom v2019.2.0

Table 2: Results of the photogrammetric processing.

M.E. 40-220

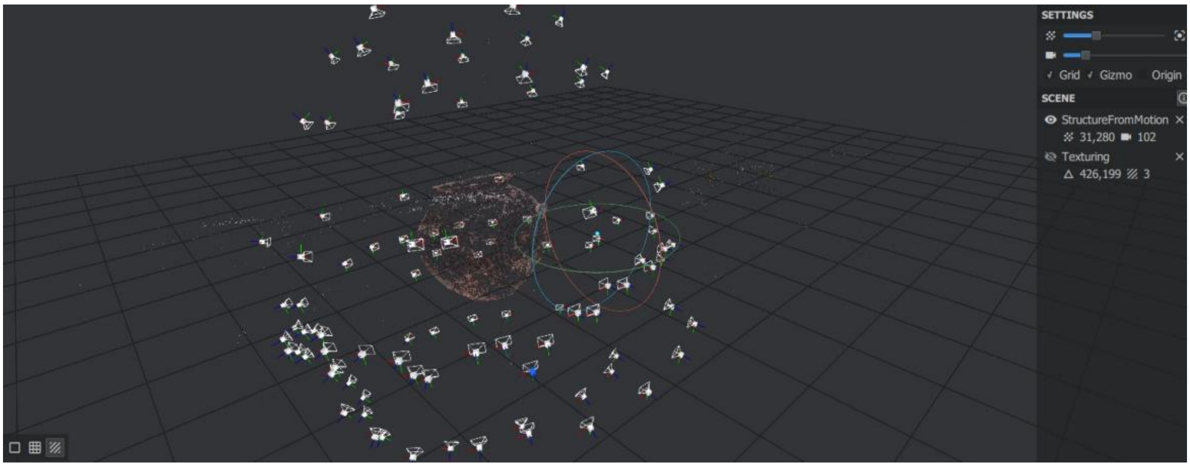
Number of input images	103
Number of camera calibrated	102
Number of landmarks	31,280
Residual RMSE	0.82125
Vertices	828,576
Faces	1,657,122

The model was then analysed using MRM and V-RTI, using the open-source software CloudCompare v. 2.11.3-Anoia. These methods are currently been used in the study of 3D models of archaeological materials, mainly in the field of LiDAR, rock art, and engravings on diverse elements, among others. They are part of what has been identified as “3D visualisation methods” (Torregrosa-Fuentes, Spairani Berrio, Huesca Tortosa, Cuevas González & Torregrosa Fuentes, 2018), used directly on 3D models and point clouds, along with others, such as Algebraic Point Set Surfaces (Guennebaud & Gross, 2007). Another interesting group of methods for the study of 3D models includes Geographic Information System (GIS) visualisation techniques. These methods entail the generation of a Digital Elevation Model (DEM) from the point cloud obtained by photogrammetry, and the subsequent use of GIS tools such as hillshade, sky-view factor, slope shade, and LRM (Torregrosa-Fuentes et al., 2018). The use of GIS visualisation techniques on DEM has provided promising results analysing engravings on small artefacts, highlighting micro-topographies of the surface (Carrero-Pazos, Vázquez-Martínez, & Vilas-Estévez, 2016; Torregrosa-Fuentes et al., 2018).

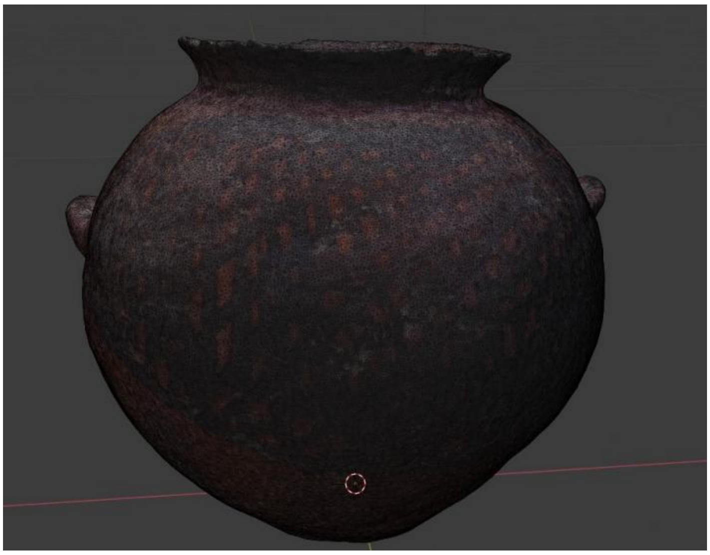
Numerous software packages are available for the different methods mentioned above, allowing a variety of results to be obtained. In the proposed case, visualisation techniques that work on the point clouds and meshes generated from photogrammetry were preferred, using open-source software throughout the process. The use of MRM and RTI have provided interesting results in surface analysis at different scales and problems (Correia Santos et al., 2014; Pires, Fonte, Sousa, Correia Santos & Gonçalves-Seco, 2014; Mytum & Peterson, 2018), although they have not been used in the study of pottery forming macro-traces. Extending ceramic studies to include different digital methodologies will make it possible to compare the relevance of the results of different methods, as well as increase the accuracy of the results.

Regarding the analyses carried out on the obtained model, the MRM analysis (Correia Santos et al., 2014; Pires et al., 2014; Pires, Martínez & Elorza Arana, 2015) proposes the existence of multiple scales of relief perceptible from different observation distances in an object. It is possible to detect subtle irregularities by segmenting the morphology at different scales. Methodologically, MRM analysis involves the use of a high-resolution 3D model and the generation of a decimated mesh from the original model, which is then smoothed with a Laplacian filter. The smoothed mesh and the original mesh are compared to observe the morphological differences generated, called "morphological residue". As pointed out by Pires et al. (2014), this method allows the creation of a clear and contrasted visual perception of morphological anomalies in most types of surfaces, revealing irregularities that are invisible to the human eye. The smoothing and mesh comparison processes can be performed with CloudCompare software, generating a colour-coded image projected of the 3D model.

RTI captures the shape and colour of the surface of an object and allows it to be interactively re-illuminated (Earl et al., 2011). This visualization reveals information about the surface that is not observable to the naked eye (Cultural Heritage Imaging, 2008). By projecting light from different directions, following a sphere or semi-sphere around the object, a series of images of the same object with varying illumination and shadows are produced. From this, a mathematical model of the surface is generated, which allows the image to be interactively re-illuminated for examination. Acquiring the images for RTI requires a lengthy process with a series of light sticks that are rotated in a controlled manner as the photographs are being taken (Cultural Heritage Imaging, 2013). However, CloudCompare software allows RTI visualization to be performed virtually from a 3D model, using the graphic card to calculate the illumination of a point cloud or mesh, based on the algorithm developed by Tarini, Cignone & Scopigno (2003).



(a)



(b)

Figure 3: Photogrammetry results for M.E. 40-220 vessel: (a) Photogrammetric orientation step showing the point cloud and the spatial attitude of the cameras in Meshroom; and (b) Photorealistic 3D model.

Figure 4: 3D model of the Humahuaca Black-on-Red globular pot (M.E.40-220). CloudCompare Sun-light on.

5. Results

In this section, the results of MRM and V-RTI methods are presented, considering the workflow followed for each one of them. As it was mentioned above, describing and interpreting pottery forming macro-traces is related to qualitative categories, constructed from ethnographic and experimental sources. In this case, the evidence obtained from the macroscopic study of the vessel, as well as the results of the MRM and V-RTI analyses were interpreted following the guidelines presented by Roux (2016), and García Rosello & Calvo Trias (2013). The basis for automatic trace detection and classification does not currently exist.

5.1. MRM Analysis

The 3D model of the ceramic vessel was processed on CloudCompare, calculating the Normals of the model to improve the visualization of its geometry. Next, the point densification of the mesh was increased (Fig. 4), generating a new point cloud with 1000320 points. A decimated mesh was reconstructed from the newly generated point cloud with the Poisson Surface Reconstruction algorithm (Fig. 5).

To perform the MRM analysis it is necessary to compare the original mesh with the new decimated mesh, calculating the distance between both of them. The result (Figure 6) shows some first details that may be linked to forming surface markings. The presence of horizontal markings in the collar of the vessel may correspond to pressure lines due to the superimposition of two coils to manufacture the collar and rim of the pot. In the centre of the body, there is a mark that may be related to interdigital pressures or percussion cupules for the forming of the vessel.

The decimated mesh was smoothed using a Laplacian algorithm (Fig. 7), with a factor of 0.200 and 20 iterations, increasing the details of sub-circular surface markings around the body of the vessel in a continuous rhythm. The characteristics of these patterns resemble percussion cupules, a diagnostic feature of the percussion technique. These cupules correspond to the marks of an instrument used to form and thin the clay mass by hammering, and these marks may be associated with irregular overthickness related to moving the paste by percussion blows (Roux, 2016). The percussion forming technique implies that the surface of the ceramic vessel is pressed with an instrument through short and continuous blows (Garcia Roselló & Calvo Trías, 2013). As the authors point out, the state of the clay (fresh or in hard leather) and the expertise of the potter will determine the visibility of the marks in the finished vessel.

The decimated mesh also increased the visibility of depressions around the semi-circular handles. This type of pattern has been associated to the pressure of a secondary element on the vessel wall (Garcia Roselló & Calvo Trías, 2013). Thus, the handles might have been press-fitted to the vessel after it was formed.

A new smoothed decimated mesh was generated with 40 iterations and a factor of 0.400. In this new mesh, sub-circular markings visibility throughout the body of the pot was increased (Figure 8). A difference in the percussion cupules pattern was observed between the upper and lower body of the pot at the handles height. The upper body shows less marked percussion cupules than the lower body. This difference was interpreted as the result of two production moments of the pot: a first one in which the base and lower body were manufactured, and a second one in which the upper body was produced on the lower body top.

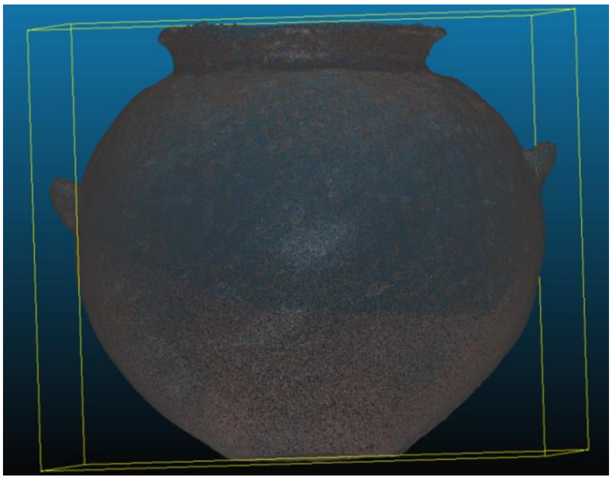


Figure 4 : Result of the increased point densification.

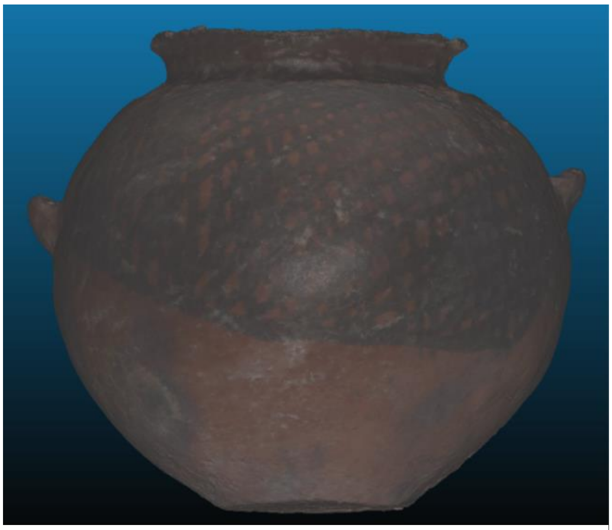


Figure 5 : Decimated mesh generated by the Poisson Surface Reconstruction algorithm.

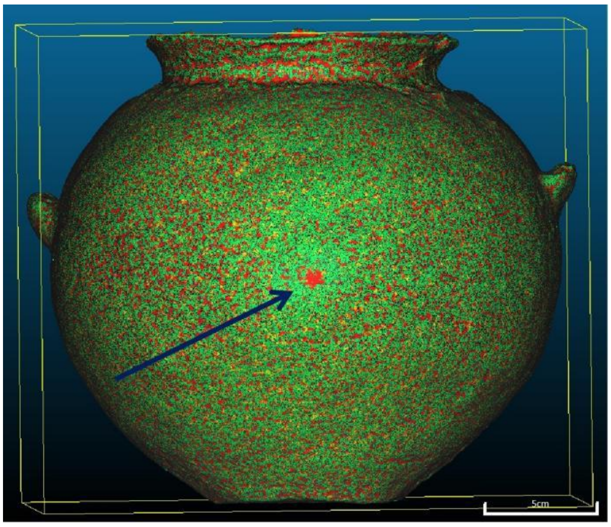


Figure 6: Distance calculation between the original mesh (in green) and the decimated mesh (in shades of red to yellow).

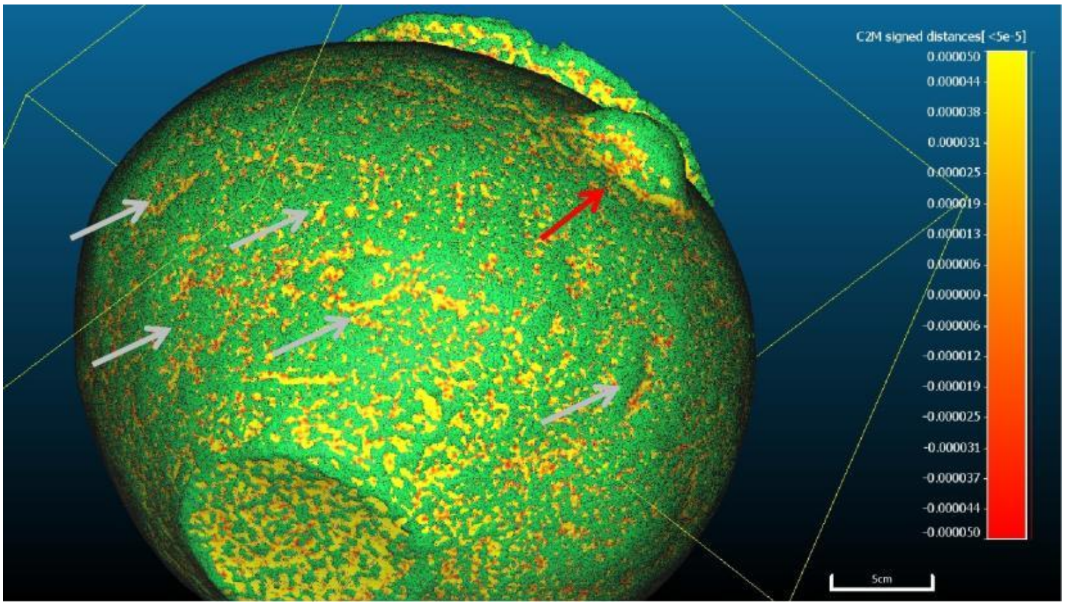


Figure 7 : Comparison of the original mesh (in green) with the smoothed mesh (20 Iterations, Factor of 0.200). Grey arrows: sub-circular depressions. Red arrows: pressure-sticking indentations.

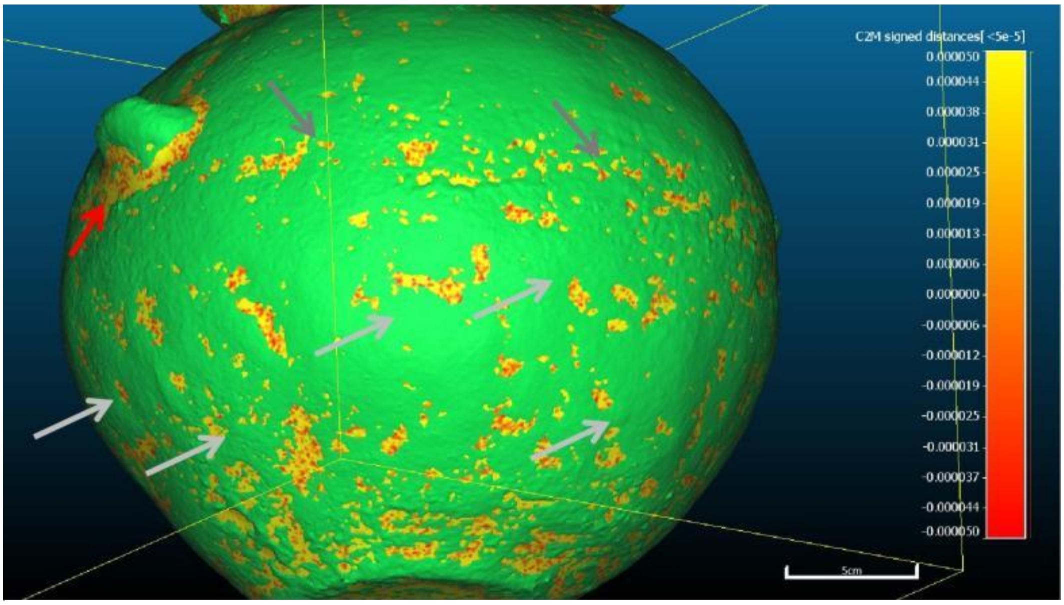
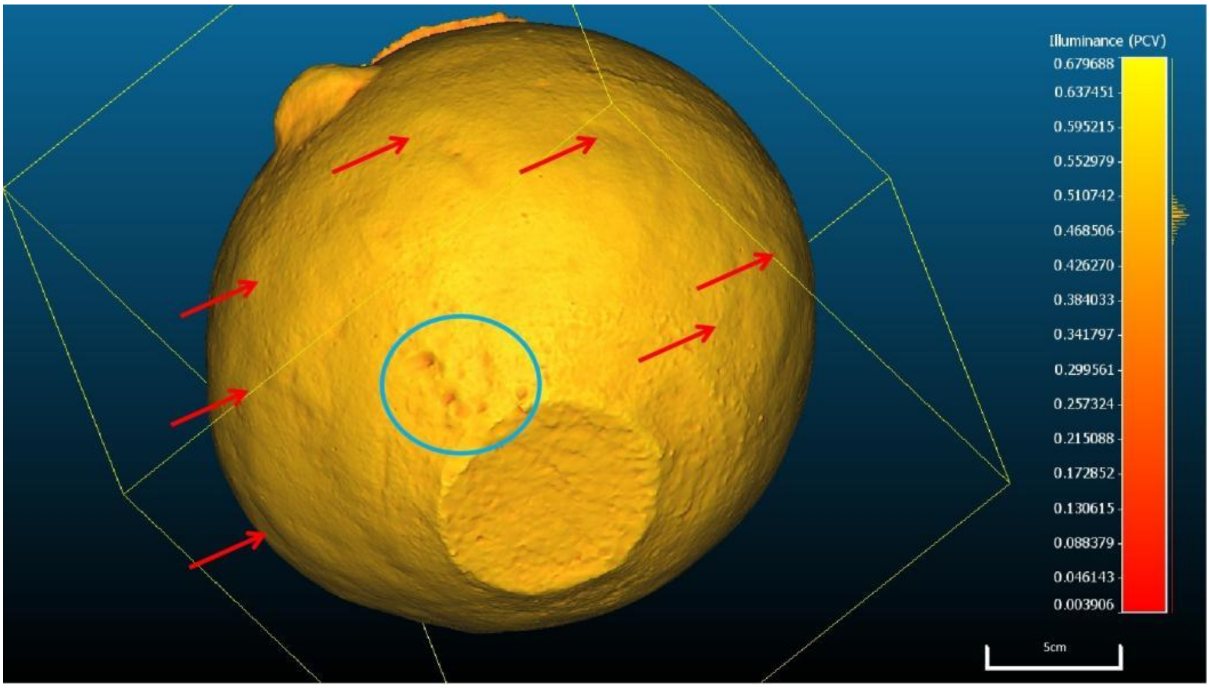


Figure 8 : Comparison of the original mesh (in green) with the smoothed mesh (40 Iterations, Factor of 0.400). Grey arrows: sub-circular depressions. Red arrows: pressure-sticking indentations. Light blue arrows: the boundary between the lower and upper body, indicating two instances of manufacture.

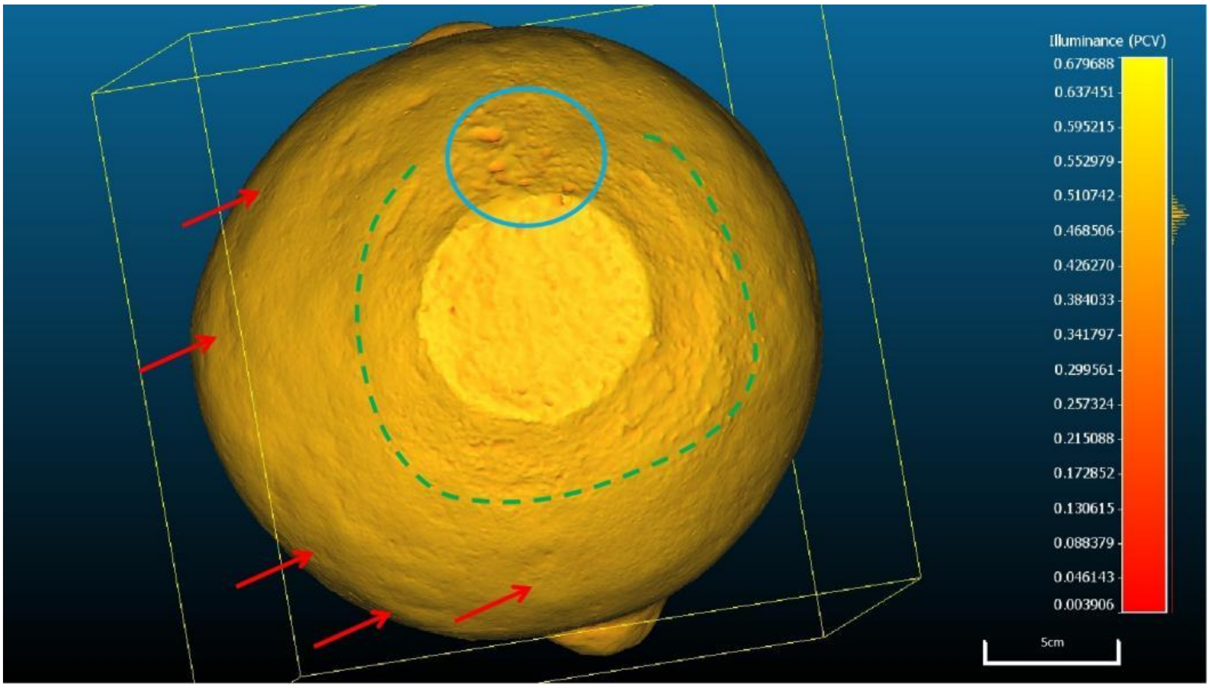
5.2. Virtual RTI visualisation

The virtual RTI Visualisation was conducted by CloudCompare; this software calculates the illumination of a point cloud or mesh, as if the light was coming from a theoretical sphere around the object, using the graphic card to achieve it. This visualisation revealed a semi-circular marking presence, corresponding to those observed with the MRM analysis, especially in the lower body of the vessel (Figure 9a). Deep and small circular depressions were visible in the lower body, which may respond to manufacturing flaws or perhaps to use-alteration traces; and also the presence of abrasions in the base and lower body areas (Figure 9b). This latter may respond to use-alteration traces generated by the contact of the pot with a surface which caused the partial loss of clay. The presence of oxidation marks and soot on the surface of the vessel (Figure 10) above the aforementioned attrition may indicate that the vessel was placed on a hard surface over the fire. The percussion cupules on the upper body are also visible, as well as the overlap markings between the upper and lower body (Figure 11).

Changing the colour tones of the V-RTI Visualisation from red-yellow to blue-yellow-red, revealed irregularities in the vessel maximum diameter area, which were not discovered by the initial study of the vessel or by the MRM analysis (Figure 12). These irregularities have been identified as micro-pull-outs, generated when part of the material was pulled out leaving irregularities and micro-cracks (Roux, 2016). This type of trace appears in leather-consistency pastes after percussion blows, such as those used in paddling.



(a)



(b)

Figure 9 : After V-RTI: (a) Visualisation of the lower body of the globular pot. Red arrows: sub-circular depressions on the lower body. Light blue circle: deep circular depressions. ; (b) Visualisation of the base and lower body of the globular pot. Red arrows: sub-circular depressions on the lower body. Light blue circle: deep circular depressions. Green dotted line: Probable abrasions.

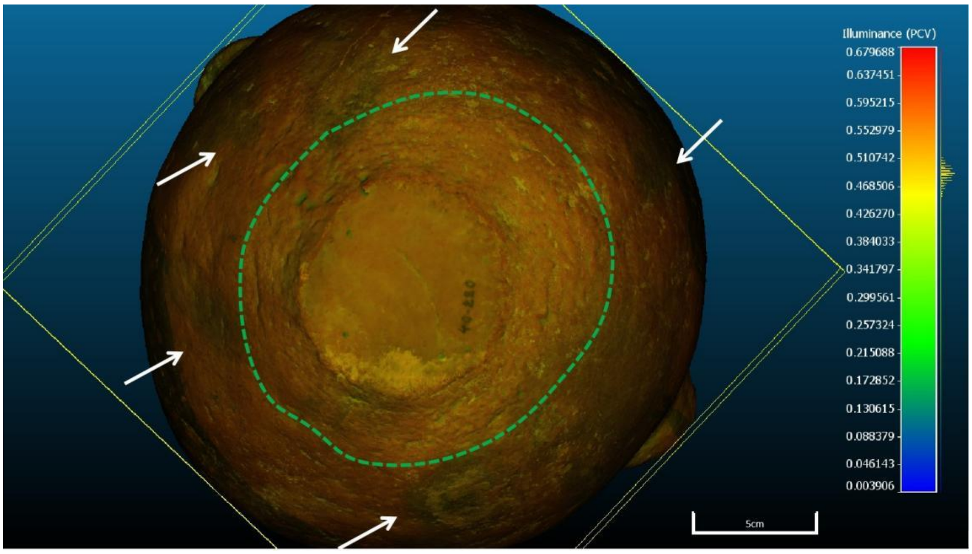


Figure 10: V-RTI visualisation of the vessel with activated texture. White arrows: Soot and oxidation marks. Green dotted line: Probable abrasion on the base.

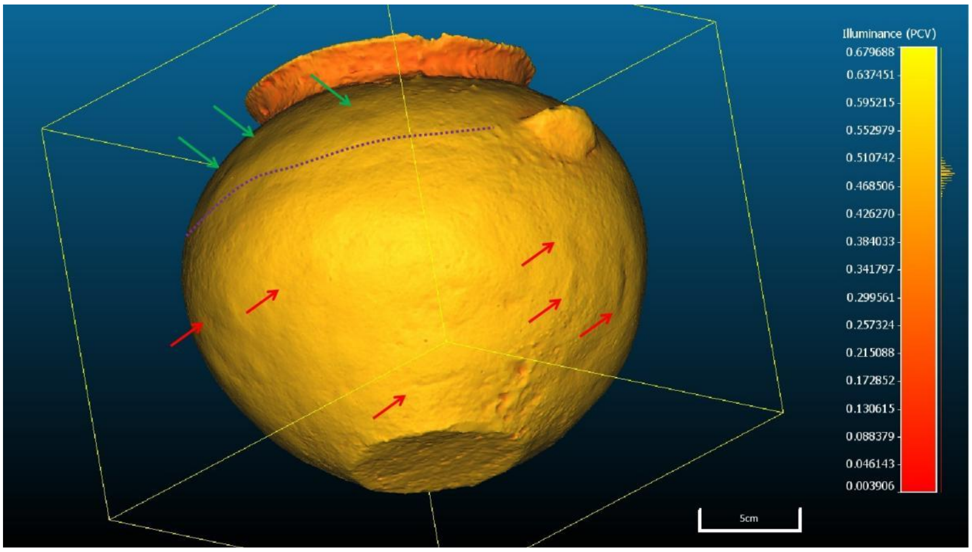


Figure 11: V-RTI visualisation of the complete vessel. Red arrows: sub-circular depressions in the lower body. Purple dotted line: overlap of the upper body. Green arrows: depressions in the upper body.

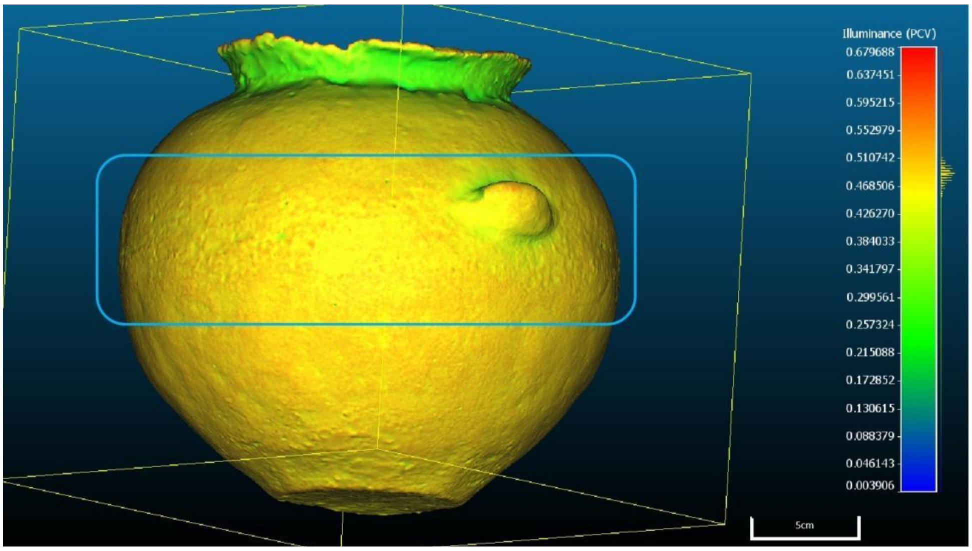


Figure 12: V-RTI visualisation of the complete vessel. Presence of micro-pull-outs in the maximum diameter of the vessel.

6. Discussion

In this paper, the use of MRM analysis and V-RTI visualisation for the identification of forming macro-traces was proposed. The results obtained have been extremely interesting, providing information to advance the understanding of forming techniques and possible functional traces.

Regarding the digital methods, the proposed workflow proved to be useful in the study of pottery forming techniques. Photogrammetry is a very versatile technique, and its use for documenting pottery vessels is well documented (see for example Barreau et al., 2014). Obtaining complex 3D models with high accuracy will provide the basis for diverse digital analysis.

The complementary analysis of MRM and V-RTI visualization allowed increasing the visibility of macro-traces on the pot surface, confirming the existence of percussion cupules, and revealing their position on the surface. They also made it possible to identify and describe marks that had not been registered on the traditional analysis of the pot, such as the presence of micro-pull-outs, and depressions around the handles of the vessel. These methods also revealed the presence of traces that were interpreted as use-alteration marks.

The limitations of the methods proposed in this pilot case are related to the quality of the 3D model. In this sense, the photogrammetric process is extremely important, relying on the expertise of the operators and the available hardware and software. In the case of V-RTI visualisation, the results were interesting, although they did not have the necessary level of detail for analysing smaller traces, especially those linked to use-alteration. These limitations can be addressed, with adequate equipment and photogrammetric processing. Regarding RTI, using a complete photographic method, instead of the virtual algorithm provided by software packages such as CloudCompare or MeshLab, may provide better results in registering and generating a better visualisation of diverse traces on the vessels. Currently, automatic pattern detection of forming techniques macro-traces is not available; and the interpretation of these traces continues to be held by ceramic studies specialists.

The forming technique identified in this case was defined as paddling, according to the sub-circular depressions or percussion cupules defined in (Garcia Roselló & Calvo Trías, 2013; Roux, 2016). These depressions were characterised in the initial macroscopic study of the globular pot, although their distribution and shape were not easily discernible. The use of MRM and V-RTI allowed completing the description and interpretation of macro-traces and defining the forming technique. In addition, the identification of micro-pull-outs related to percussion blows in leather-hard consistency clay, provided additional evidence to support the interpretation.

Concerning the presence of use-alteration traces, it was possible to identify abrasions in the base and lower body areas related to the location of the vessel in a hearth on a support surface with a hardness greater than that of the ceramic paste. The presence of deep circular depressions in a sector of the lower body may be the result of a specific abrasion with an element of greater hardness or continuous over time. The association of this abrasion with traces of soot and oxidation on the exterior, and carbonization on the interior would indicate the vessel had been used for firing with little water for prolonged periods (Skibo, 2013).

Some smaller abrasion marks identified in the macroscopic analysis of the vessel, thinner and shallower, are not perceptible in digital analysis. This may be due to the absence of a very complex geometry in the 3D model, despite having more than 800000 vertices. It is necessary to elaborate on more complex 3D models to test if V-RTI visualisation can be useful for a more detailed use-alteration analysis.

7. Conclusions

The workflow used to carry out the MRM and V-RTI analysis generated very promising results for the forming macro-traces study, revealing diverse patterns that were not completely visible in the macroscopic analysis of the pot. It was also possible to identify some use-alteration traces that generated modifications on the external surface of the ceramic vessel, although the necessary detail for smaller traces was not obtained.

The use of V-RTI appears as a very promising technique (Min et al., 2021) for the study of use-alteration traces in pottery (the Archaeological Computing Research Group of the University of Southampton provided very interesting examples of RTI on pottery), therefore, further studies must be conducted, using different techniques of acquisition and software. In this regard, not only testing MRM and V-RTI analyses in other archaeological vessels and sherds will allow refining digital pottery studies, but also different GIS or LiDAR tools that have provided promising results on other types of archaeological materials, such as DEM (Cabrelles, Lerma & Villaverde, 2020), hillshading, or LRM (Torregrosa-Fuentes et al., 2018), must be considered. Future studies in pottery collections from Quebrada de Humahuaca will incorporate larger samples of sherds and complete vessels, as well as other 2D and 3D digital methods.

Digital methods used in this pilot case have provided additional evidence for the possible presence of paddling as a forming technique for vessels in Quebrada de Humahuaca. This technique has not been described in the area in pre-Hispanic or colonial times, so the evidence presented in this pilot case represents a contribution to the study of ceramics in Quebrada de Humahuaca.

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