Non-invasive on-site method for thickness measurement of transparent ceramic glazes based on depth from focus

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ORIGINAL ARTICLE

Non-invasive on-site method for thickness measurement of transparent ceramic glazes based on depth from focus

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Abstract
Glazed ceramics are a common material analyzed through geochemistry, whether in the form of tableware collected during excavations or tiles observed as part of architectural features. Within the framework of these studies, measuring the thickness of the transparent glaze is one of the useful variables available for the characterization of the ceramic, contributing to searches for provenance as well as serialization. However, this task often requires invasive methods performed in the laboratory, which may not always be possible. This paper develops a non-invasive and portable on-site system for measuring the thickness of ceramic glazes. Based on the depth from focus technique, this method makes use of a classical camera, a macroscopic lens, a translation stage, and a laptop for system control. In this article, we test this method through the measurement of glaze for ten samples as compared to results obtained for sections through scanning electron microscopy.

KEYWORDS
depth from focus, glazed ceramics, non-invasive, SEM, thickness

INTRODUCTION

Glazed ceramics represent a major part of the cultural heritage visible in the archaeological record. They are relatively simple to produce and have been found throughout the world from the Mediterranean basin, to as far as China and Japan, for millennia. Due to its widespread and varied use (including dishes and other utilitarian items, both interior and exterior architecture, etc.) and its resistance to post-depositional degradation, it is one of the common material cultural items found during archaeological excavations. Initially applied to simple terracotta goods, the use of glazes first appeared in ancient Egypt. Once vitrified after firing, the glaze coating applied to ceramic surfaces serves not only to decorate the item, but also harden it and make it waterproof (Moorey, 1994; Tite et al., 2002). Although glazes were originally produced from ash, vitrification methods have evolved over time to include also the use of alkaline and lead glazes.

With a wealth of archaeometric approaches at our fingertips, ceramics are now widely studied with a variety of methods to answer an array of historical and prehistorical questions, such as questions of provenance, dating, method of manufacture, and trade, to name a few. In this regard, physiochemical techniques such as scanning electron microscopy (SEM) (Froh, 2004; Tite et al., 1982), X-ray diffraction (XRD), and particle-induced X-ray emission (PIXE) (Leon et al., 2012) are commonly used for determining numerous characteristics of glazed ceramics. One ceramic attribute that can be particularly informative is the determination of the thickness of a glaze. Traditionally, this measurement has been obtained by SEM examination of polished thick sections. As well as being time-consuming, this method requires the partial destruction of an object, to be able to take it to the laboratory and produce the required analytical sample. Furthermore, in the case of intact objects or architectural ceramics in place, it is inconceivable, if not impossible, to extract a sample. In this context, the prospect of a mobile, portable, rapid and, above all, non-invasive method has become an especially appealing alternative. Overall, however, measurement of the thickness for ceramic glazes has been sparsely exploited. As a notable exception, in some works (Galán & Bard, 2020; Tite, 2009) it was possible to observe an evolution of the thickness in relation to the chronology. In other ways, the thickness of the glaze can be used as an additional factor for characterization (Molera et al., 2001), or to discriminate between glazed ceramic production processes (Lahlil et al., 2015). Namely, it can reflect not only the chemical composition of the glaze, but also the method of application and firing protocol. The variation in the thickness of the glaze also plays an important role in the perception of the color of the glazed ceramic, as increased thickness results in greater absorption of light by the glaze. With so much information produced through the measurement of glaze thickness, and the aforementioned limitations of various methods for its measurement, the growing influence of 3D analytical techniques in archaeology provides a particularly interesting opportunity for researchers.

Recently, the techniques of computational photography and 3D acquisition have played an increasingly important role during excavations and historical research. For example, photogrammetry (Guidi et al., 2002) and 3D lasers (Boehler et al., 2002) can increase the possibilities of post-excavation observations. Quick to install and portable, only requiring a camera and associated equipment, these methods have the advantage of providing valuable information relatively easily. Consequently, the development of techniques based on computational photography is a particularly compelling approach for the study of glazed ceramics. Further suggesting the potential of this method, the advanced state of the art in this field also makes it possible to obtain depth information (i.e., thickness) from photographs. Specifically, an acquisition method such as depth from focus (DfF; Grossmann, 1987) strives to recover 2.5D depth information from an image stack by estimating, for each pixel, the depth of the focus plane for each pixel. In this regard, DfF is particularly appealing due to its ability to recover discrete depth information with high accuracy (Blayvas et al., 2007). Consequently, this simple and global measurement of the average thickness of the transparent glaze can then be easily associated with physicochemical techniques, and may therefore be an excellent option for the on-site study of ceramics.

The aim of the following research is twofold: (1) We develop a non-destructive and non-invasive method for the on-site analysis of glazed ceramic tiles. This is achieved by measuring in a simple, fast, and inexpensive way the thickness of the glaze while generating a clear surface image at the macroscopic scale (based on DfF). (2) We compare the results of measurements from different types of ceramics to assess the reliability of the method and to determine any limitations and drawbacks. For this second goal, fragments of various origins have been chosen.

METHOD

As mentioned above, the technique used is based on the DfF algorithm. This technique uses only a single camera with a lens system, a ring light, and a tripod to obtain 2.5D profiles of scenes in the form of a depth map in a monoscopic way (Grossmann, 1987). Particularly interesting on a macroscopic and microscopic scale, this system makes it possible to obtain profiles with better depth precision than even photogrammetry, at less than 10 μm (Blayvas et al., 2007). For this depth blur reconstruction, a focal stack (a sequence of images taken for different focal planes) is taken by moving the camera along a translation unit. Each point of the scene is in focus only on its focal plan, which means it is sharp in only one slice. As a result, an all-in-focus image and discrete depth map can be reconstructed by knowing the sharpest pixel for each direction in the scene and its respective focal plane. By working on focus measures (Sun et al., 2004) and depth estimations, it is therefore possible to increase the precision to a scale much smaller than the distance between two consecutive focal planes (Sakurikar & Narayanan, 2017).

This technique has certain limitations, however. Focus measures are based upon variations in the grey level of the image. It is therefore necessary to have details present on the image. It is indeed necessary to obtain sharp areas on the image so that texture may allow a clearly recognizable depth for each area. In addition, transparent materials cannot be accurately modeled in 3D. It is simply not possible to focus on a perfectly transparent surface without adding removable paint on the whole surface of the glaze. However, depth measurement is done on the focal plane. Consequently, the depth detection can take place on top of a transparent surface if it has defects that generate a slight local opacity, or the bottom if it is fully transparent in the given direction.

Glazed ceramics present one germane example of the impossibility of precision for 3D acquisition because they have a transparent glazed thickness on the surface. In the case of old ceramics in particular, these glazes are often scratched, chipped, etc. These effects generate a surface that is almost transparent but with roughness. The depth map obtained by DfF is therefore heavily altered in these cases. The clear zones will sometimes appear on the surface of the glaze and at other times below, directly on the bottom. In our case, we have used the defaults of this method to get results. Obtaining depths over and under the glaze in such a way can nevertheless allow for non-invasive glaze thickness measurements. Specifically, two levels of depth were obtained by taking the measurement above opaque areas (stripes, lines made with a felt tip marker, etc.), which can then be extracted and processed to obtain a thickness of the glaze.

Acquisition set-up

The analytical protocol requires a level of precision to just a few micrometers to enable precise measurements of thickness of the glaze. To accomplish this, it is necessary to reduce the depth of field as much as possible to optimize the precision. The full apparatus set-up can be seen in Figure 1. Specifically, we have used a Canon EOS 5D II camera (Figure 1a). The camera has a body sensor of 20 megapixels (pixel size, 6 × 6 μm) and was mounted on a motorized rail on a macroscopic scale which can be controlled either by computer or by hand (Figure 1b). This allows for an incremental movement of 10 cm with steps that can go as small as 2 μm, so that images can easily be stacked at the desired scales. The optical capacity has a great influence on the precision of the acquisition of data (Blayvas et al., 2007). As we require a set of lenses allowing ×2 magnification and reduced depth of field, we used a 100 mm lens and an inverted 50 mm lens for close-ups (Figure 1c). Both were fully opened (respectively 1:2.8 and 1:1.4). A light-ring was attached to the end of the lens as a light source, allowing diffuse and grazing illumination at a working distance of <1 cm, while not occluding the lens (Figure 1d). The focal stack was acquired by connecting the motorized rail to a Helicon Remote for automating the method. Finally, we precisely aligned the photos using Enfuse software for a precise alignment, while limiting the degradation of the image.

Determining the thickness

After aligning the stacked images, the region of interest (Figure 2a) was clipped out, (i.e., the area containing texture and stripes or felt on the surface), followed by application of the DfF algorithm (the only treatment made on MATLAB). We first made an initial very coarse depth map for measuring the tilt of the ceramic with respect to our device (fitting with a polynomial surface of degree 1). If the sample was not flat, we could then further determine its shape (fitting with a polynomial surface of degree 2). We then produced a second depth map. High levels of precision are necessary for this second map so that information on both sides of the glaze may be detected. Using the surface shape established with the coarse depth map (untilting for a flat ceramic, correction of the volume otherwise), we then transformed our depth map and obtained the planes above and under the glaze at constant depth (Figure 2b). Although the depth map obtained is often quite noisy, the two levels of detection are in fact visible.

By displaying the histogram of the values of depths of the map, two distinct peaks are evident (Figure 2c). These peaks correspond to the two depth levels above and below the glaze. The peaks are wide for two reasons: the variability of the measurement and the fact that the ancient ceramics are hand-made and therefore have variations in depth (which can be seen in Figure 2f). By subtracting the two peak values, one can obtain a thickness value d', corresponding to the advance of the camera. However, this value does not by itself reflect the thickness of the glaze. Rather, as shown in Figure 3, it is necessary to consider the refractive

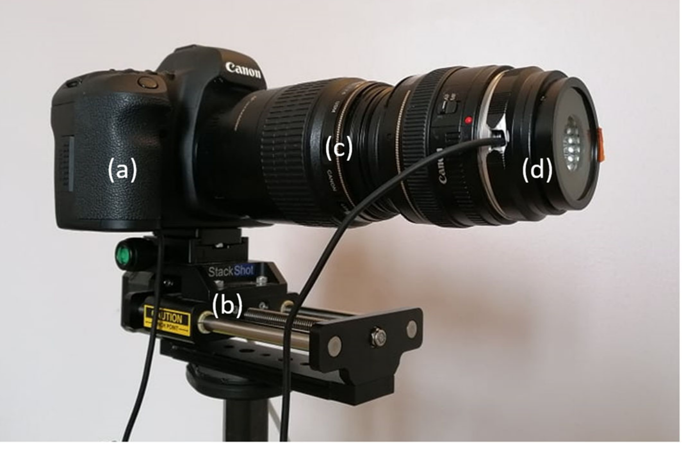


FIGURE 1 Acquisition device: (a) Canon EOS 5D II camera; (b) motorized rail; (c) optical system using a 100 mm lens and an inverted 50 mm lens; (d) light ring with diffuse filter

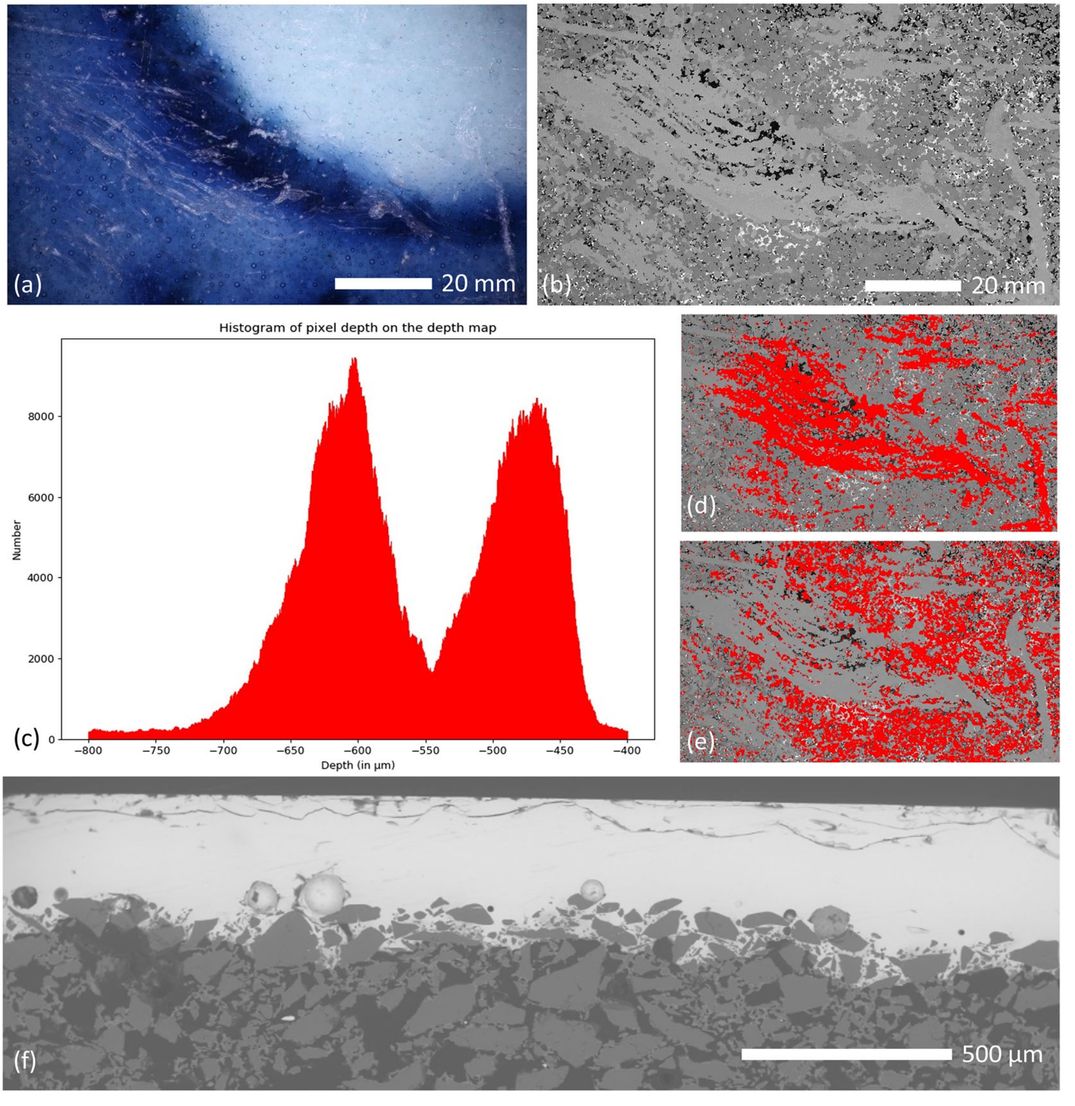


FIGURE 2 (a) Macroscopic photo of the surface reconstructed after DfF on the Iznik tile Bdx 6502; (b) obtained depth map and (c) its depth histogram for the detection of the two levels: depth underlined in red on the depth map (d) at −601 µm and (e) at −467 µm; part (f) is a section backscattered electron image made by SEM for comparing the method.

index of the glaze to obtain the thickness $d = d'n'$. Given this, the method therefore requires having an a priori knowledge of the refractive index. An example will be given in Section 3.

Using these values, we can obtain an absolute value of the thickness of the glaze in a non-invasive way and determine the overall uncertainty from the uncertainties $\Delta n'$ and $\Delta d'$ (respectively the uncertainty on the refractive index n' and the uncertainty on the depth values d' at the top of the peaks) according to the following formula:

$$\Delta d = d\sqrt{\left(\frac{\Delta n'}{n'}\right)^2 + \left(\frac{\Delta d'}{d'}\right)^2}.$$

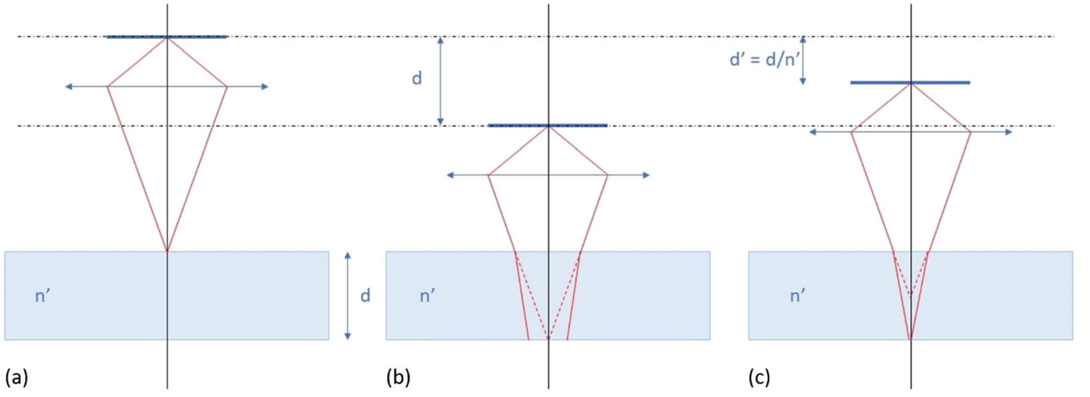


FIGURE 3 Optical diagram of the camera on the glaze, showing that the advancement of a distance d does not correspond to the measurement of a thickness d of the glaze, and the need to take into account the refractive index n'. Advancing the camera between (a) and (b) by the distance d does not provide a clear image of the bottom of the glaze. While advancing the camera the distance d' between (a) and (c) allows focusing at the two desired levels

In the following, we present the result as

$$d \pm \Delta d\,(\mu\mathrm{m}).$$

The result is therefore the thickness with approximation of the transparent glaze. However, this thickness is not a localized measurement but a global measurement for the region of interest studied. It is an average measurement on a sample that can reach more than 1 cm^2.

Finally, Python is used to code all the presented processing. For the entire process, the time required for thickness measurement is very short. Once the equipment is installed, it takes no more than 5 min to create the image stack. The processing of the DfF on MATLAB and subsequent Python coding (Cou & Guennebaud, 2022) can then be done within 15 min after setting the parameters using our non-optimized implementation.

SAMPLES

These measurements were carried out on several ceramics reflecting differing cultural origins, uses, and eras to highlight the precision and the limits of the method. Commonalities between all samples studied include a Mediterranean basin origin and the presence of a transparent glaze allowing for thickness measurement by DfF. All the glazes of the samples studied are transparent lead glaze with PbO between 23 and 57 wt% (Ben Amara, 2002; Ben Amara et al., 2005, 2006, 2001; Bauer et al., 2019; Beauvoit et al., 2021), the predominant method of the 2nd millennium CE around the Mediterranean Sea. While conventional glass tends to have a refractive index of approximately 1.5, the inclusion of lead in glass tends to significantly increase the refractive index of glass (Newton & Davison, 1989). As a result, we estimated that the refractive index at 1.75 ± 0.25 (Newton & Davison, 1989) for all the samples was due to their common high lead component. The different glazed ceramics are presented in Table 1.

Each sample has specificities making it possible to observe the use of DfF in various cases. First, Iznik ceramic presents a simple case: the glaze is flat and transparent and has sharp cracks that easily allow two levels of depth to be achieved. Like the Iznik ceramics, the Maiolica sample (Bdx 2591) is flat, but the white color of the ceramic on which the red-brown and yellow decorations have been applied (before being completely covered by a colorless transparent

TABLE 1 Description of different glazed ceramics studied

Style and object type	Inventory number	Glaze color	Decoration[b]	Provenance	Date (century CE)	References
Iznik tile	Bdx 6493 Bdx 6501 Bdx 6502	Blue-green	B, Bl, G, RB	Tunis, Tunisia	17th	Ben Mami (2000), Ben Amara et al. (2006)
House stove tile	Bdx 16621	Green		Berg Armo, France	16th	Bauer et al. (2019)
Maiolica dish	Bdx 2591	Colorless[a]	B, G, RB, Y, Be	Ravello, Italy	16th	Peduto (1996), Ben Amara et al. (2005)
Zellij (ceramic mosaic)	Bdx 6522 Bdx 6524	Green Blue		Meknes, Morocco	14th	Ben Amara (2002)
"Green and brown decoration" dish	Bdx 5502	Honey	Br, G	Raqqada, Tunisia	9th - 10th	Daoulatli (1980), Ben Amara et al. (2001)
Earthenware	Bdx 21066 Bdx 22625	Colorless	Bl R	Bordeaux, France	19th	Beauvoit et al. (2020)

[a]This glaze covers the decorations and a white glaze opacified with tin oxide.
[b], blue; Be, beige; Bl, black; Br, brown; G, green; R, red; RB, red-brown; Y, yellow.

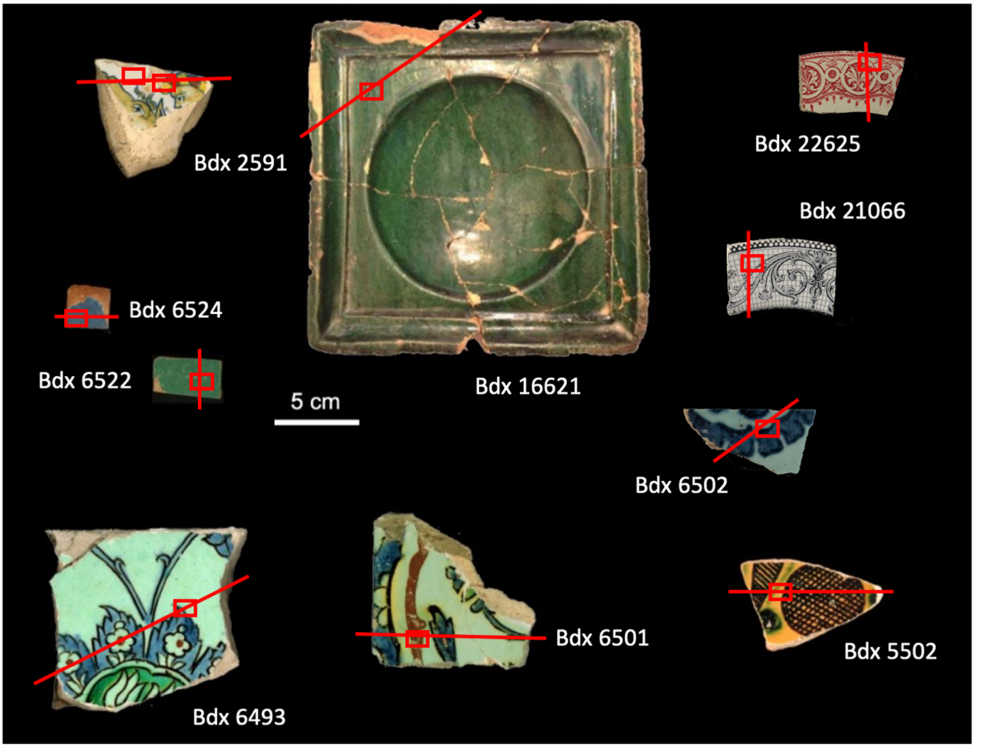
glaze) exhibits little detail and texture, making depth harder to detect by DfF. The house stove tiles in our sample are all engobed and covered with a green glaze of varying tones. Like the other studied samples, transparent glazes found on these tiles are strongly lead-bearing (47–66% in PbO) (Bauer et al., 2019) and have many cracks on the surface. Nonetheless, we focused on a flat area for our measurement. The Zellijes samples, on the other hand, have no surface defects and are a good example to assess the methodological limitations in cases where fragments are without surface defects. For our purposes, the Raqqada fragment features yet another advantage when compared to the others, in that it is not perfectly flat. Specifically, these are pieces of curved ceramic (probably dishes). This fact makes the measurement of the thickness of the glaze more complex and sheds light on possible additional limits of the DfF. To round out our sample, the study of white earthenware by DfF is by far the most complicated case presented here. Indeed, earthenware has three limiting characteristics for our method: a very specific body due to its whiteness, which makes it very difficult to detect texture; a relatively thin glaze thickness; and a non-planar shape as in the case of the sample Bdx 5502.

RESULTS AND DISCUSSION

To assess the reliability of our method, we tested the DfF on fragments of glazed ceramics in the laboratory. We then observed these sections by SEM (JEOL JSM-6460) and compared the values obtained. On each section, we realized a minimum of 15 depth measurements to obtain an average glaze thickness.

Depth from focus

For the DfF methodology, we first measured the thickness of the different tiles using our set-up; we then made sections for the SEM observation for the aforementioned reliability



Sample	Depth (μm)	
	SEM	DfF
Iznik tiles		
Bdx 6493	215±38	199±49
Bdx 6501 (glaze to red)	167±11	156±27
Bdx 6502	265±64	233±55
House stove tiles		
Bdx 16621	72±16	58±26
Maiolica dish		
Bdx 2591 (yellow part)	36±7	29±10
Bdx 2591 (white part)	99±6	86±21
Zellijs		
Bdx 6522	352±24	267±48
Bdx 6524	255±15	306±49
Raqqada ceramics		
Bdx 5502	113±7	102±38
Earthenware		
Bdx 21066	51±3	57±18
Bdx 22625	75±2	69±15

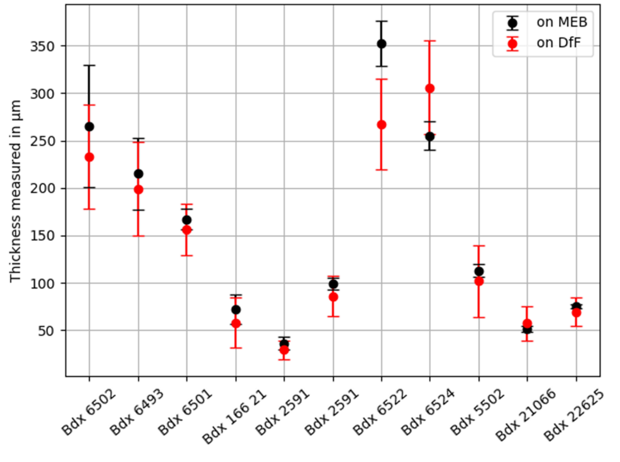


FIGURE 4 Image of the fragments measured by DfF as part of the method validation (top). Analyzed areas are represented on the samples by red lines (sections made for SEM) and red rectangles (measured areas by DfF). Numerical results (bottom left) and visual comparison (bottom right) of measured depth by SEM and by DfF on samples illustrated in the image. In numerical results are the distance between the exterior surface of the glaze and the surface of the body, except when we define "glaze to red." In this context, we measure the distance between the exterior surface of the glaze and the upper surface of the red pigment.

assessment. Iznik's tile samples present the ideal case for this test. In addition to presenting very clear scratches on the surface and details in depth, the thickness of the glaze is important. As detailed in Section 2, we measured 233 ± 55 μm for Bdx 6502, 199 ± 49 μm for Bdx 6493 and 156 ± 27 μm for Bdx 6501 (the results are visible in Figure 4). Regarding these samples, the depth histogram is clear in this case (see Figure 2c): the two peaks are readily identifiable.

The study becomes more complicated for the Berg Armo house stove, however. This case is illustrated in Figure 5. The scratches are in fact clear and easy to identify on the depth map (Figure 5b). But the thickness is much thinner than in the case of Iznik ceramics. Consequently, the two peaks on the histogram mix to form a single, larger peak (Figure 5c). It is necessary to develop a visualization highlighting in red on the depth map the pixels for a chosen depth (Figure 5d,e). By combining the depth histogram and the visualization, we may then obtain an exploitable depth of 58 ± 26 μm for the sample Bdx 16621. We estimate that for less than approximately 150 μm it becomes harder to measure the glaze thickness from the histogram. The Raqqada ceramics present a similar situation. With these, a complicating factor for performing the measurements is that the samples are not flat. Using the volume correction (Section 2) we measured a glaze of 102 ± 38 μm for this sample.

To determine the thickness of the yellow pigment of Ravello maiolica Bdx 2591, we made measurements at two points: the glaze-yellow and glaze-white thicknesses. As with the Berg Armo ceramic, the glaze thickness is quite thin, and is observable with the histogram coupled with the visualization. Specifically, the measurement for the glaze-yellow thickness is just 29 ± 10 μm. However, the absence of scratches or degradation on the surface above the white part creates difficulties for measurement. To combat this, we drew a red dot on the surface with an erasable marker. The contours of this red point on the surface of the glaze were then measured as being on the surface of the glaze. Using the above visualization, we achieved a thickness value of 86 ± 21 μm.

Zellijes from Meknes features the same disadvantage as the maiolica because the surface does not include any defects. For this sample, we again employed the red dot technique. In this case, measurements revealed a very thick glaze and, as such, the histogram is sufficient without further visualization, despite the fact that the Zellij glaze includes many bubbles and unmelted crystals. Due to these imperfections, the main peak of the bottom is very wide, and a lot of noise is visible on the histogram. We nonetheless measured a thickness of 267 ± 48 μm for Bdx 6522 and 306 ± 49 μm for Bdx 6524.

Finally, the Bordeaux earthenware is the most complicated case yet, given that it features the complicating factors of all the previous fragments: very fine glaze, no alterations on the surface of the glaze, no details on the white background (only the patterns can be measured) and a non-planar volume. Using our methods, however, we were able to overcome these difficulties and yet measure a thickness value by using the red mark on the surface and by coupling the histogram and the visualization after correcting for volume. The glaze was thus estimated to be 57 ± 18 μm for Bdx 21066 and at 69 ± 15 μm for Bdx 22625.

Comparison with SEM

The values measured by SEM are visible in Figure 4. Overall, the results are very consistent with those obtained through the DfF method. Ten of the 11 values measured by SEM are within the thickness uncertainty interval obtained by DfF. Only the measurement results for one Zellij does not match. For this sample, Bdx 6522, we suspect that the large presence of unmelted inclusions and bubbles in the glaze may be reducing the value of the measurement. On the other hand, it is also possible that the assumptions about the refractive index are incorrect. However, the orders of magnitude of the Zellijes nevertheless give a thickness scale of 200–400 μm.

Notably, we obtained similar estimations of thickness, as indicated by the overlapping intervals (Figure 4), by reducing the thickness to 30 μm despite the difficulty in reading the histogram and the need for visualization. In the end, the resulting interval of thickness is quite broad, which can be explained by the large uncertainty in the refractive index, but also by wide thickness variation within the sample we observed through SEM.

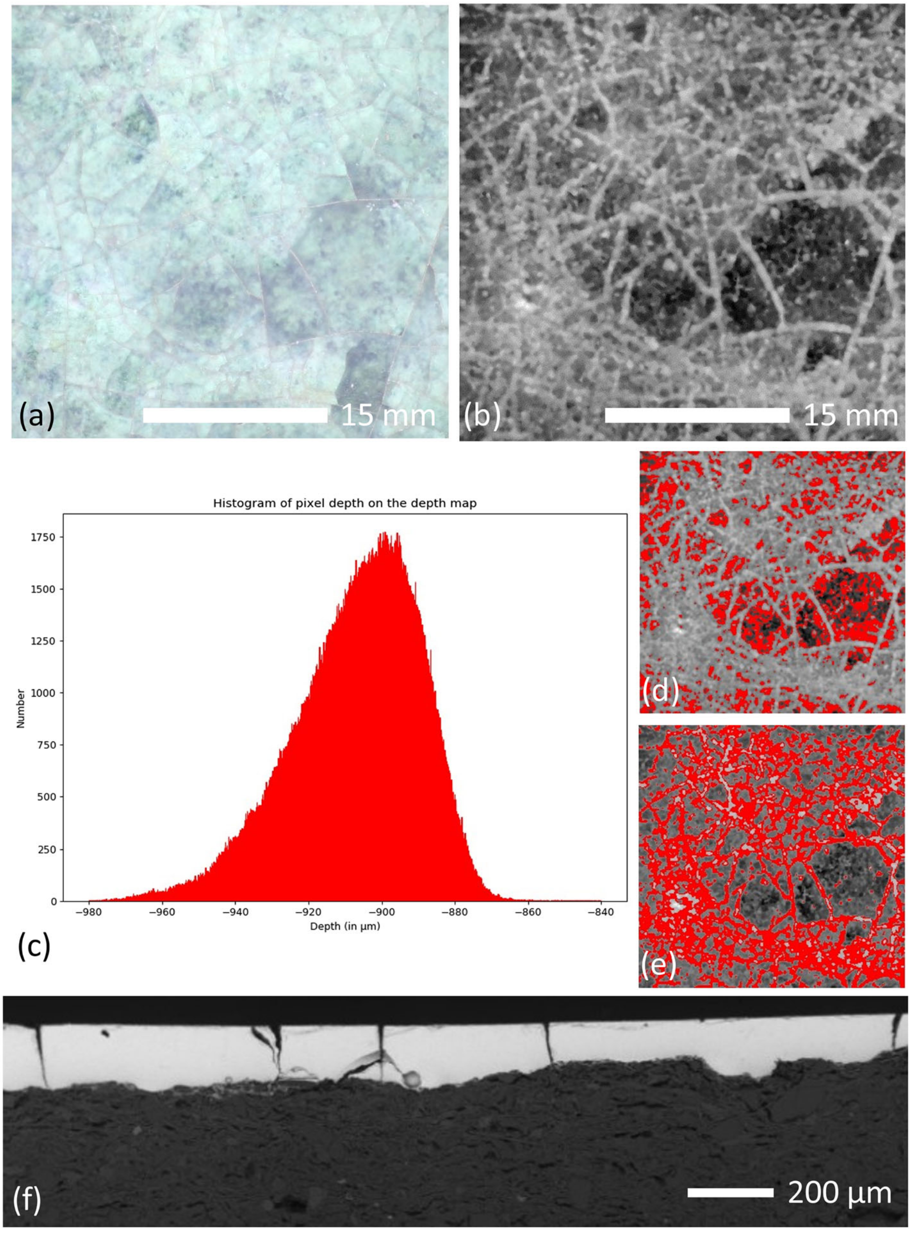


FIGURE 5 (a) Macroscopic photo of the surface reconstructed after DfF on the house stove tile from Berg Armo Bdx 16621; (b) depth map and (c) its depth histogram for the detection. As we can see, the two peaks blend. It is therefore necessary to use visualization by depth to obtain the depth (d) under the glaze at −925 µm and (e) over the glaze at −892 µm. Part (f) is one of the SEM backscattered electron images made for comparison.

CONCLUSIONS

Through comparison of our measurements to those acquired through SEM, we have demonstrated that an acquisition of a focal stack using a simple camera is an effective and accurate method for measuring the thickness of a transparent ceramic glaze. Furthermore, the advantages of this method are numerous. First, there are the non-invasive and ultra-portable aspects of the DfF method and the possibility of measuring directly on site without any contact with the ceramic. Moreover, the method is also comparatively fast to complete and does not require significant equipment. Our analyses using different types of ceramic also demonstrate that it is possible to adapt the method according to sample-specific factors, including the shape of the sample, the tint of the transparent glaze, the state of preservation of the glaze (i.e., presence or absence of deterioration), and the sample's thickness. This is all critical, as the variability in the thickness of the glaze effectively influences the perception of the color of the transparent glaze. Finally, the DfF has the advantage of giving an average measurement over a larger area than that observed by SEM (which is constrained in terms of analysis area).

The DfF glaze measurement method nonetheless has certain limitations. It requires strong a priori assumptions, such as those regarding the type of glaze. As such, it is most useful as a complement to the overall study of the sample, rather than a wholesale replacement of the SEM. The DfF, for its part, offers a different visualization from the microscopy, with a frontal view (and not in section). This does not allow for as clear a view of the state of the glaze itself. In addition, unlike SEM, the DfF cannot provide information regarding the components of ceramic materials. Finally, although methods for correction are available as discussed above, measurements regarding the thickness and state of the glaze can yet be difficult to obtain, regarding the thickness and the state of the glaze. In the ideal case (as on the Iznik tiles), the measurement can be quite simple, and apparent through the histogram. But below 150 μm it requires a more intensive analysis to locate the depth of the two planes. In certain cases, such as when the glaze is not completely transparent (i.e., in the case of the Zellijes), it can become downright impossible to obtain a perfect result. Yet, despite any difficulties or limitations, the use of the DfF method for measuring glaze thickness remains encouraging.

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PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/arcm.12813.

DATA AVAILABILITY STATEMENT

The data example and programming code that support the findings of this study are openly available in Software Heritage at [https://archive.softwareheritage.org/swh:1:rev:4b2bc2d14e7c7c54013df72330c23dd513090302].

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REFERENCES

Bauer, D., Ben Amara, A., & Cantin, N. (2019). La céramique de poêle du site Berg Armo (XVI s., Sainte-Marie-aux-Mines, France): matériaux et techniques de fabrication. *ArcheoSciences*, *43*(2), 275–286. https://doi.org/10.4000/archeosciences.6901

Beauvoit, E., Amara, A. B., Cantin, N., Lemasson, Q., Sireix, C., Marache, V., & Chapoulie, R. (2020). Technological investigation on ceramic bodies of 19th century French white earthenware from the Bordeaux region. *Journal of Archaeological Science: Reports*, *31*, 102314. https://doi.org/10.1016/j.jasrep.2020.102314

Beauvoit, E., Ben, A. A., Tessier-Doyen, N., Frugier, C., Lemasson, Q., Moignard, B., Pacheco, C., Pichon, L., Chapoulie, R., & Gratuze, B. (2021). Chemical and mechanical characterisation of white earthenware glazes from the Johnston-Vieillard manufactory (France, 19th century). *Archaeometry*, *63*(5), 941–959. https://doi.org/10.1111/arcm.12656

Ben Amara, A. (2002). Céramiques glaçurées de l'espace méditerranéen (IXe-XVIIe siècles): matériaux, techniques et altération (Doctoral dissertation, Thèse de doctorat, Université de Bordeaux 3, France).

Ben Amara, A., Schvoerer, M., Daoulatli, A., & Rammah, M. (2001). "Jaune de Raqqada" et autres couleurs de céramiques glaçurées aghlabides de Tunisie (IXe - Xe siècles). *Revue d'Archéométrie*, *25*, 179–186. https://doi.org/10.3406/arsci.2001.1013

Ben Amara, A., Cuin, M., Schvoerer, M., & Peduto, P. (2005). Voyage en majolique - Texture, composition et couleurs d'une céramique glaçurée trouvée à Ravello (XVIe siècle, Italie), Décor de lustre métallique et céramique glaçurée, Actes du séminaire, Ravello, 11-12 octobre 1998, eds Schvoerer M., Ney C. et Peduto P., collection Scienze e Materiali del patrimonio culturale, 7, CUEBC-Edipuglia, Bari, 57-70. (ISBN: 978-8872283981).

Ben Amara, A., Schvoerer, M., Cuin, M., Ben Mami, M. B. (2006). An investigation of the ceramic technology of a late Iznik ceramic production (XVIIth century AD), 34th international symposium on Archaeometry, 3-7 may 2004, Zaragoza, Spain, Ed. Institución Fernando el Católico, 393-398. (ISBN 84-7820-848-8).

Ben Mami, M. B. (2000). La Mosquée M'Hammed Bey - Un exemple de la présence architecturale et artistique ottomane dans la médina de Tunis. *Africa, Série Art et Traditions Populaires*, *12*, 1–22.

Blayvas, I., Kimmel, R., & Rivlin, E. (2007). Role of optics in the accuracy of depth-from-defocus systems. *JOSA a*, *24*(4), 967–972. https://doi.org/10.1364/JOSAA.24.000967

Boehler, W., Heinz, G., & Marbs, A. (2002). The potential of non-contact close range laser scanners for cultural heritage recording. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, *34*(5/C7), 430–436.

Cou, C., Guennebaud, G., 2022, Depth from focus using windowed linear least-squares regressions. https://archive.softwareheritage.org/swh:1:rev:4b2bc2d14e7c7c54013df72330c23dd513090302

Daoulatli A. (1980). La céramique ifriqiyenne du IXe au XVe siècle, La céramique médiévale en Méditerranée Occidentale, Colloques Internationaux C.N.R.S., N°584, Valbonne, 11–14 septembre 1978, éd. C.N.R.S., 197–201.

Froh, J. (2004). Archaeological ceramics studied by scanning electron microscopy. *Hyperfine Interactions*, *154*(1), 159–176. https://doi.org/10.1023/B:HYPE.0000032074.98045.cc

Galán, M. R., & Bard, R. S. (2020). Studies in Archaeometry: Proceedings of the Archaeometry symposium at NORM 2019, June 16-19, Portland, Oregon, Portland State University. Dedicated to the rev. H. Richard Rutherford, CSC, Ph. D. Archaeopress Publishing Ltd.

Grossmann, P. (1987). Depth from focus. *Pattern Recognition Letters*, *5*(1), 63–69. https://doi.org/10.1016/0167-8655(87)90026-2

Guidi, G., Tucci, G., Beraldin, J. A., Ciofi, S., Ostuni, D., Costantini, F., & El-Hakim, S. (2002). Multiscale archaeological survey based on the integration of 3D scanning and photogrammetry. In Proc. Int. Workshop on Scanning for Cultural Heritage Recording, Corfu, Greece (pp. 58–64).

Lahlil, S., Xu, J., & Li, W. (2015). Influence of manufacturing parameters on the crackling process of ancient Chinese glazed ceramics. *Journal of Cultural Heritage*, *16*(4), 401–412. https://doi.org/10.1016/j.culher.2014.10.003

Leon, Y., Sciau, P., Bouquillon, A., Pichon, L., & de Parseval, P. (2012). PIXE (particle induced X-ray emission): A non-destructive analysis method adapted to the thin decorative coatings of antique ceramics. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *291*, 45–52. https://doi.org/10.1016/j.nimb.2012.09.010

Molera, J., Vendrell-Saz, M., & Pérez-Arantegui, J. (2001). Chemical and textural characterization of tin glazes in Islamic ceramics from eastern Spain. *Journal of Archaeological Science*, *28*(3), 331–340. https://doi.org/10.1006/jasc.2000.0606

Moorey, P. R. S. (1994). *Ancient Mesopotamian materials and industries: The archaeological evidence*. Clarendon Press.

Newton, R. G., & Davison, S. (1989). Conservation of Glass.

Peduto, P. (1996). *Un giardino-palazzo islamico del secolo XIII: l'artificio di villa Rufolo a Ravello* (pp. 57–72). Apollo.

Sakurikar, P., &Narayanan, P. J. (2017). Composite focus measure for high quality depth maps. In Proceedings of the IEEE International Conference on Computer Vision (pp. 1614–1622).

Sun, Y., Duthaler, S., & Nelson, B. J. (2004). Autofocusing in computer microscopy: Selecting the optimal focus algorithm. *Microscopy Research and Technique*, *65*(3), 139–149. https://doi.org/10.1002/jemt.20118

Tite, M. S. (2009). The production technology of Italian maiolica: A reassessment. *Journal of Archaeological Science*, *36*(10), 2065–2080. https://doi.org/10.1016/j.jas.2009.07.006

Tite, M. S., Freestone, I. C., Meeks, N. D., & Bimson, M. (1982). The use of scanning electron microscopy in the technological examination of ancient ceramics. In Archaeological ceramics.

Tite, M. S., Shortland, A., & Paynter, S. (2002). The beginnings of vitreous materials in the near east and Egypt. *Accounts of Chemical Research*, *35*(8), 585–593. https://doi.org/10.1021/ar000204k

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