

Original research or treatment paper

Evaluation of the relief line and the contour line on Greek red-figure vases using reflectance transformation imaging and three-dimensional laser scanning confocal microscopy

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The relief and contour lines on a group of ancient Greek red-figure vases and vase fragments in the collection of the Harvard Art Museums and the Worcester Art Museum were examined using two surface examination methods – reflectance transformation imaging and three-dimensional laser scanning confocal microscopy. These methods helped characterize the lines and answer questions regarding tools, techniques, and production sequence used by Greek vase painters. This research also incorporated fabricated mock-ups to gain a better understanding of the ancient technology and in so doing confirmed that the relief lines were not produced by an extruded method, but with a brush made with only a few hairs, termed *linierhaar* as first proposed by Gérard Seiterle in 1976. Furthermore, it was discovered that not one but two distinct types of relief lines exist on these ancient vases: the laid line (proposed by Seiterle) which has a characteristic ridged profile, and the pulled line (proposed in a previous publication by the authors) which has a furrowed profile. It was also determined that the relief line used to outline figures was applied prior to the contour line in Attic vase decoration, although variations in this sequence occur in vases from South Italy. Based on observations made during this research, the authors propose a likely evolution for the techniques used to produce decorative features throughout the period of red-figure vase production.

Keywords: Red-figure vase, Vase painting, Attic pottery, Greek vase, Relief line, Contour line, Magna Graecia, Reflectance transformation imaging (RTI), 3D laser scanning confocal microscopy

Introduction

Greek Attic pottery production began around the first half of the sixth century BCE and lasted until about 331 BCE (Boardman, 2001, pp. 48 and 105). The black-figure technique defines the first part of the Attic pottery production period, which later gives way to the red-figure technique around 525 BCE with an overlap of about 30 years (Boardman, 2001, p. 66). The main periods of red-figure Attic ware production are the Late Archaic (500–480 BCE), the Classical (480–430 BCE), and Late Classical (430–360 BCE) periods (Oakley, 2001). The technical knowledge for producing red-figure vases traveled from Greece to the Greek colonies in South Italy (Magna Graecia), with Attic emigrants leaving Greece in the late fifth century (Mayo, 1982, p. 10; Giuliani, 1995, p. 13).

The South Italian production of vases developed into its own unique style and lasted to the early third century BCE.

The ingenious method used to produce the distinctive red and black color of ancient Greek vases is a milestone in the history of ceramic technology. According to this ceramic tradition, the black sections on the vessels are painted. The ‘paint’ used is technically a glaze (also referred to as ‘glossy black glaze,’ ‘black glaze,’ or ‘black gloss’), which consists of dilute clay containing silicon, iron, oxygen, aluminium, potassium, and lesser amounts of sodium, magnesium, calcium, and titanium (Aloupi-Siotis, 2008; Newman, 2008, p. 106). The unpainted portions of the vessels reveal the red color of the fired clay body. Once decorated, the vessels undergo a firing process involving a sequence of three firing environments – first oxidation, then reduction, and finally re-oxidation – to achieve the distinctive red and black colors. This process was

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replicated and described in detail in 1942 by the German chemist Theodor Schumann (Schumann, 1942). Today scholars agree that the vessels were fired in three different firing environments to produce the distinct red and black colors, although some scholars like Aloupi-Siotis who oversees a modern workshop that produces Greek vase replicas propose that the vases were possibly subject to a pre-firing or multiple firings rather than just one as proposed by Schumann. Aloupi-Siotis (2008, pp. 121–5) writes that since breakage of green ware is so common, vases were possibly pre-fired before they were decorated to make the production of pots more cost efficient.

Debates continue among scholars over multiple aspects relating to the production of Greek vases. One such debate centers on what tools and methods were used to create certain decorative features such as the relief lines on the red-figure ware. There are also conflicting opinions as to the sequence of the applied decoration, in particular which came first – the relief line or the contour line surrounding the red figures. In 2011, the authors published an article describing their research on a stamnos by the Tyszkiewicz Painter that depicts the sea goddess Thetis and her female companions struggling against the advances of Peleus in the collection of the Worcester Art Museum (Fig. 1) (Artal-Isbrand *et al.*, 2011). A step-by-step description was given of the decorative process on this vessel, followed by a topographic study of the relief lines on the stamnos using reflectance transformation imaging (RTI) and a three-dimensional (3D) measuring laser microscope. These examination methods allowed for the lines to be characterized more fully and ultimately helped determine what tools and techniques were used to produce them. Since then, further investigations have tested if the findings made regarding the Worcester stamnos are applicable to Greek red-figure vases



Figure 1 Stamnos attributed to the Tyszkiewicz Painter, c. 480 BCE (Worcester Art Museum 1953.92).

more broadly. An overview of these investigations is presented here.

Ten vases or fragments thereof were examined with RTI and a 3D measuring laser microscope as part of this research. These works were carefully selected to cover as broad a time span of the red-figure production period as possible using only dated works (c. 510 to c. 330 BCE). Although none of the works are signed, all of them except two have been attributed by scholars. Among them are eight fragments generously made available from the collection of the Harvard Art Museums and the remainder are in the collection of the Worcester Art Museum. In addition, a black-figure vessel from the late sixth century BCE and a red-figure vessel from South Italy also from Worcester were examined, and visual examinations were made of two vessels from South Italy on display at the British Museum.

An integral part of this research was the fabrication of mock-ups to test the tools that Greek painters may have used to produce the relief line and to better understand application techniques. The working properties for each method were assessed and the morphology of the fabricated lines were compared and evaluated against relief lines on ancient works.

Instrumentation

Two complimentary surface examination methods, both relatively new in the field of art conservation, were used for this research: RTI (Malzbender *et al.*, 2001; Padfield *et al.*, 2005; Mudge *et al.*, 2006) and 3D laser scanning confocal microscopy (Artal-Isbrand *et al.*, 2011).

The RTI instrument used for this project includes 40 fixed lights arrayed in a dome-like configuration and a high-resolution Canon EOS-1 Mark III digital camera mounted on an adjustable stand (Fig. 2). To generate an RTI file, 40 individual digital images are taken of the same surface detail as it appears under the various angles of illumination provided by the fixed light array. Fitting software combines the 40 images into one interactive file, resulting in a high-resolution, 2D representation of an object's intricate 3D surface. The method enables viewers to control the angle of illumination through the computer mouse to optimize the conditions for viewing surface topography. In addition, various transformation algorithms can be applied in order to visualize features otherwise difficult to see. For example, the specular enhancement feature of the viewing software determines the surface normal for each pixel in the image and generates an interactive view of the surface as it would appear if completely reflective. Relevant still-captures from RTI investigations are included throughout this publication. Fig. 3 illustrates how topographical features – such as preliminary sketch lines, the broad contour line



Figure 2 The Worcester Art Museum's portable fixed-light array RTI dome (photo by Marlin Lum, Cultural Heritage Imaging).

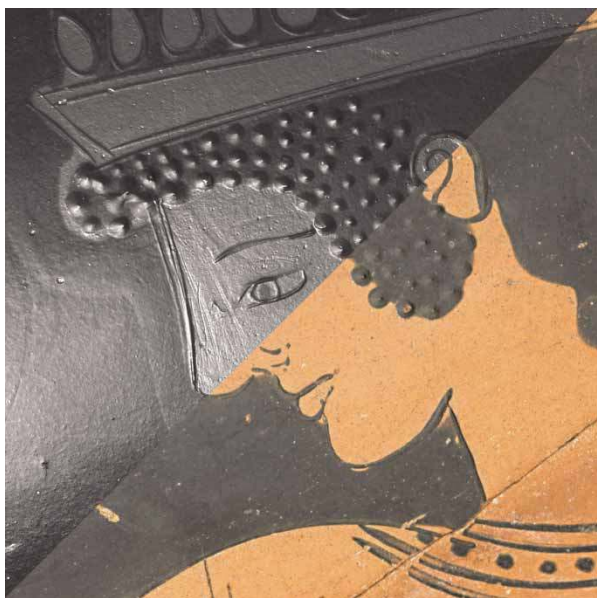


Figure 3 Split-image detail of Thetis' head depicted on the stamnos in Fig. 1. The image shows RTI still-captures of the detail, one with specular enhancement (upper left) and the other under normal illumination (lower right).

surrounding the figures, and relief lines used to outline the figures and to describe shapes like ears and eyes – are more readily discerned using RTI.

In addition to RTI, a LEXT OLS4000 3D measuring laser microscope manufactured by Olympus was used for nanometer-level imaging and 3D topographical measurements of the surfaces examined (Fig. 4). The instrument, which features a dual confocal system and utilizes a 405-nm laser, is capable of a magnification range of $\times 108$ – $\times 17\,280$. The surface



Figure 4 LEXT OLS4000 3D measuring laser microscope manufactured by Olympus. Pictured on the instrument stage is the lid from the *Pyxis* by the Eretria Painter, c. 430 BCE (WAM 1935.148), which was part of this research.

measurements can be presented in a number of modes including real-color 3D dual confocal images and 3D elevation maps. In its standard configuration, the microscope is equipped with $\times 20$, $\times 50$, and $\times 100$ objectives with stand-off distances of 1.0, 0.35, and 0.35 mm, respectively. The instrument can also be used with a long working distance $\times 50$ objective, which has a fixed working distance of 10.6 mm. The microscope is integrated to a remote-controlled stage that allows for precise positioning; however, the manufacturer's standard stage configuration limits the size of the object that can be examined and for this reason mostly pottery fragments were chosen for this study.

Terminology, techniques, and observations

The relief line

The type of line used for outlining figures and for painting details like eyes, mouths, hair, body parts, and folds in garments is called a relief line. These lines consist of black glaze material, which – as their name suggests – exist in relief and have a 3D quality. They occur in a relatively wide range of lengths. While longer lines like those typically used in garments are continuous, dynamic, and fluid, shorter lines are less fluid, can be quite thick, and are typically in higher relief. During examination of the Tyszkiewicz stamnos it was noticed that some relief lines have a profile characterized by a single peaked ridge,

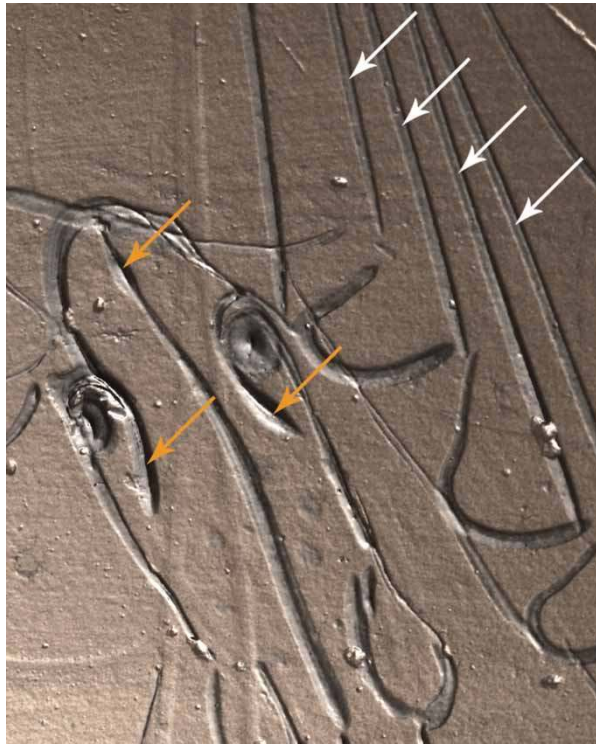


Figure 5 RTI still-capture of a detail of the stamnos in Fig. 1. Examples of ridged lines are indicated with orange arrows, and furrowed lines with white arrows.

whereas other relief lines have a distinctly furrowed profile (Fig. 5).

Debate remains as to what tools were used to produce the relief lines. Tools that have been suggested include a reed pen (Winter, 1978, p. 58) or a metal pen, a quill (Winter, 1978, p. 58), the tip of a feather (Hartwig, 1887), a thin brush (Boardman, 2001, p. 286), a brush with only a few hairs (Seiterle, 1976, p. 6; Giuliani, 1995, p. 67; Boix, 2010, p. 31), and a syringe-like instrument made from a feather quill and animal intestine or bladder used to extrude the glaze (Adams, 1849, p. 819; Noble, 1988, pp. 119–20). Today there is consensus that reed or metal pens could not have produced the relief line because the thick glaze material cannot travel through the narrow pen channel, which functions by capillary action (Seiterle, 1976, p. 4).

Mock-ups were prepared using the proposed tools and techniques to determine if they could indeed create relief lines with the same topographical features observed on the ancient stamnos. For the mock-ups an extra-fine clay-based gilding bole with a thick and pasty consistency was used as the painting medium in order to create relief lines that retained their shape similar to that of ancient relief lines. Mock-ups were not fired, as the extent of alteration to the general shape of the line upon firing is considered insignificant for this investigation. The substrate for the mock-ups was hard-press cardboard or Masonite®.

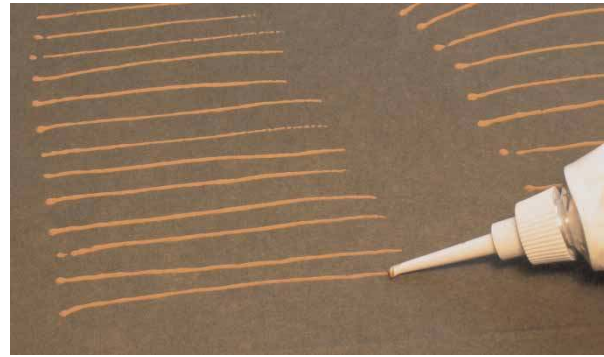


Figure 6 Modern tin tube with a plastic tip simulating an ancient syringe was used to make extruded lines on a Masonite® substrate.

To test the extrusion theory a tin tube was filled with clay bole and lines were drawn by extruding the bole through a plastic tip to replicate an ancient syringe (Fig. 6). This method could produce thin lines but typically made a disproportionately large deposit of medium at the beginning of each line that was not observed on the ancient vases. In addition, none of the modern extruded lines displayed the characteristic features that were observed on the ancient works. Topographic examination of these extruded lines with the confocal microscope confirmed that they differed fundamentally from the lines observed on the stamnos (Fig. 7). The extrusion method did not produce lines with the ridged or furrowed profiles observed in the ancient works.

When testing a feather tip and fine conventional brushes it was found that the clay bole did not flow or easily transfer to the substrate when used at the consistency necessary to produce relief lines, and when the fluidity of the bole was increased the line lacked the unique relief quality. Furthermore, when using a feather or brush it was not possible to create the type of short lines with sharp turns present on the ancient vase.

The type of brush first proposed by scholar of Greek art Gérard Seiterle in 1976 was tested next. Referred to as a *linierhaar*, such a brush consists of very few hairs. *Linierhaar* translates from the German as ‘hair that produces lines’. For this research, a series of brushes with two or more hairs of different lengths, thicknesses, and consistencies were constructed using cat whiskers, horse mane hair, horse tail hair, pig bristles, and human hair. Empirical evidence showed that a single hair brush lacked the necessary capillary action to pick up enough glaze to produce a line. According to Seiterle, the *linierhaar* was dipped into the glaze, laid down onto the surface of the vessel, and then lifted straight up to create a relief line (Fig. 8). This technique allows for a range of line lengths, but none longer than the length of the brush hair. A distinctive feature of

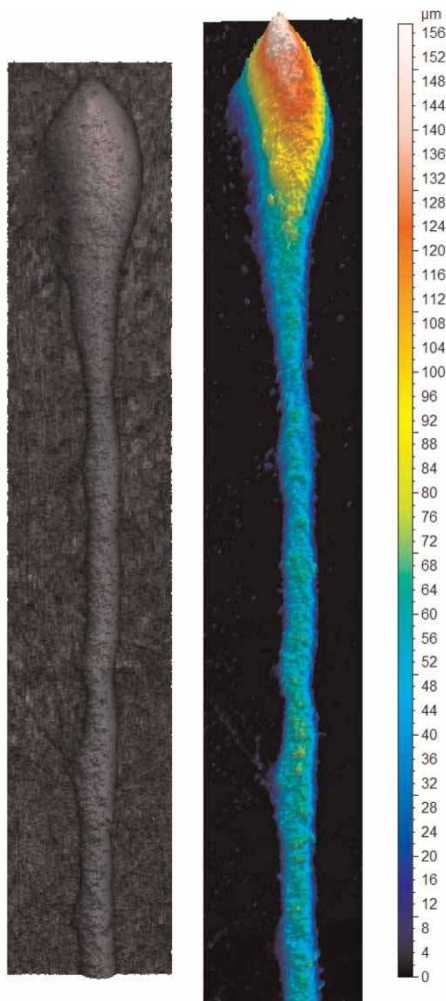


Figure 7 3D confocal image of modern extruded line (left) and as a 3D elevation map with the threshold setting adjusted to remove measurements associated with the Masonite® substrate (right). The large deposit at the beginning of the line is obvious and a rounded profile is maintained down the length of the line. The elevation map indicates that the height of the line at the beginning is close to 150 µm, whereas the height of the rest of the line averages around 60 µm. The length of the line is 7.5 mm.

lines produced in this fashion is a raised ridge in the middle of the line created by the action of lifting away the brush hair. The term *laid line* has been proposed by the authors to describe this line type and derives from Seiterle’s description of the brush action that produces such a line ‘die Linien wurden aufgelegt’ (the lines were laid) (Seiterle, 1976, p. 6; Artal-Isbrand *et al.*, 2011).

Lines with similar profiles are evident on the Worcester stamnos. For example, the eye consists of lines with a central ridged profile like that produced using the laid line technique (Fig. 9). The lines that define the outline of the eye were painted first, followed by those that outline the iris. Both the real-color confocal image and the 3D elevation map clearly show an additive effect where the lines overlap. In contrast, the pupil was painted with a more dilute application, probably with a conventional brush. A preliminary sketch of the eye inscribed into the surface with a hard tool is also discernible just above the eye.

An especially soft and short brush is needed to create small loop-shaped lines such as the ones in the headdress of Thetis (Fig. 10). Ancient and modern loops (Fig. 11) were examined with the confocal microscope, and their close resemblance suggests that Seiterle’s proposed tool and technique for producing these curved lines with tight turns is correct. The laying-down and lifting-up motion creates the resulting ridged topography of the laid line. Both ancient and modern loops are characterized by a curved line with a central ridge running the length of the line that is narrow and pointed at the beginning where the brush hair first touches the substrate, and then becomes wider and higher at the end. There is also a characteristic widening that occurs in the area where the line turns, likely resulting from a slight shift of the hairs across the surface during application.

In contrast to the laid lines described above, the authors proposed that long fluid lines with a distinctive

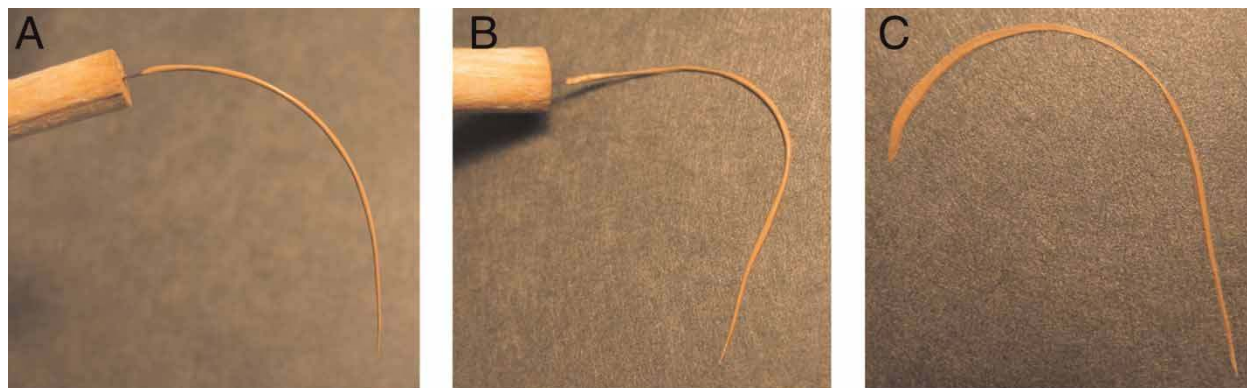


Figure 8 A *linierhaar* loaded with clay bole (A) and used to produce a laid relief line (B); detail view of the resulting laid relief line with characteristic central ridge (C).

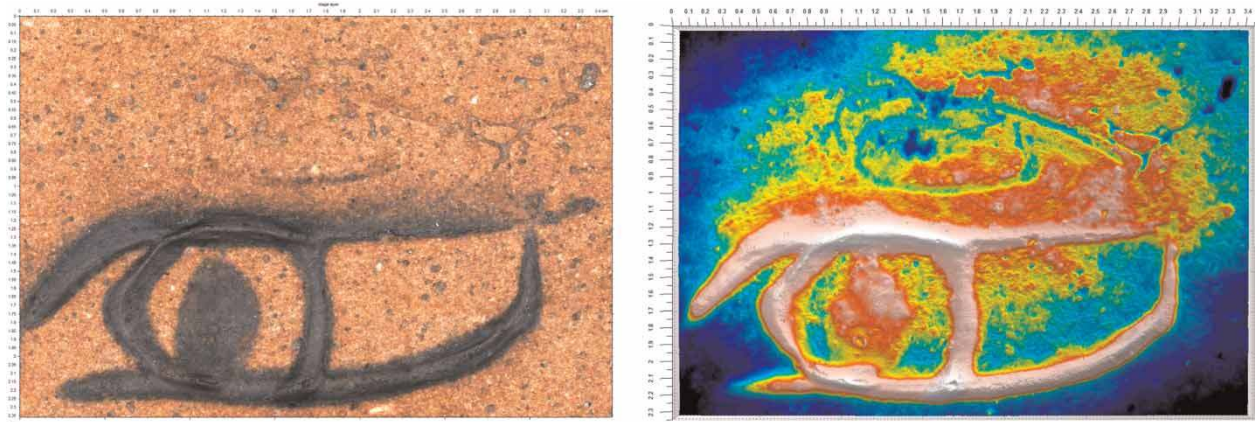


Figure 9 Real-color confocal image (left) and the corresponding 3D elevation map (right) of Thetis' proper left eye in Fig. 3 on the Worcester stamnos. The relief lines exhibit the central ridged profile characteristic of laid lines. Evidence of a preliminary inscribed sketch is visible in the surface directly above the eye. The dimensions of each image are 3.45×2.35 mm and the images were stitched from 32 individual area scans taken with a $\times 50$ objective. The distance from the substrate surface to the highest elevation on the lines is $40 \mu\text{m}$.

furrow running down the middle were produced by setting down the tip of the *linierhaar* and – while leaving all or some of the hair in contact with the vessel – pulling the brush across the surface (Artal-Isbrand *et al.*, 2011). The action of the brush hair as it is pulled through the medium across the surface produces the characteristic furrowed profile of the line

which the authors termed *pulled line* (Fig. 12). Although Seiterle mentions that some ancient lines have a bifurcation in the beginning of the line (he includes an illustration of such lines in his article) and that sometimes a furrow can be observed in the middle of a line instead of a ridge, he asserts that all relief lines were made with the laid line technique and ‘not by *pulling* the brush along the surface as one would with a traditional brush’ (Seiterle, 1976, p. 6). He writes that ‘the occasional bifurcation at the beginning of the line is due to the action of the brush touching down onto the surface of the vase. A furrow half way in the middle of the line can be explained by the lack of glaze medium in the brush’ (Seiterle, 1976, p. 6).

However, research conducted at the Worcester Art Museum found that such lines were indeed produced in the same fashion as a line formed with a traditional brush. This pulled method also enables the maker to produce lines that are longer than the length of the brush hair. Profile comparisons of ancient and modern pulled lines were made using the OLS4000 3D measuring laser microscope, and the resemblance was striking (Fig. 13).

Averaged profiles of the two proposed line types were generated from topography maps of representative sections of ancient relief lines and compared. Despite the wear from almost 2500 years of age, the line measurements still produced distinctly different profiles (Fig. 14).

It is important to mention that not all lines on Greek vessels strictly exhibit the characteristic features of either the pulled or laid lines. For instance, hybrid lines were observed with both characteristic furrowed and peaked profiles, whereas other lines lack either features. Empirical evidence from mock-up preparation indicates that hybrid lines result when a line started as a pulled line



Figure 10 Confocal image of a looped line in the headdress of Thetis. The field of view is about 4.0×2.2 mm and the image was stitched from eight individual area scans taken with a 5x objective.

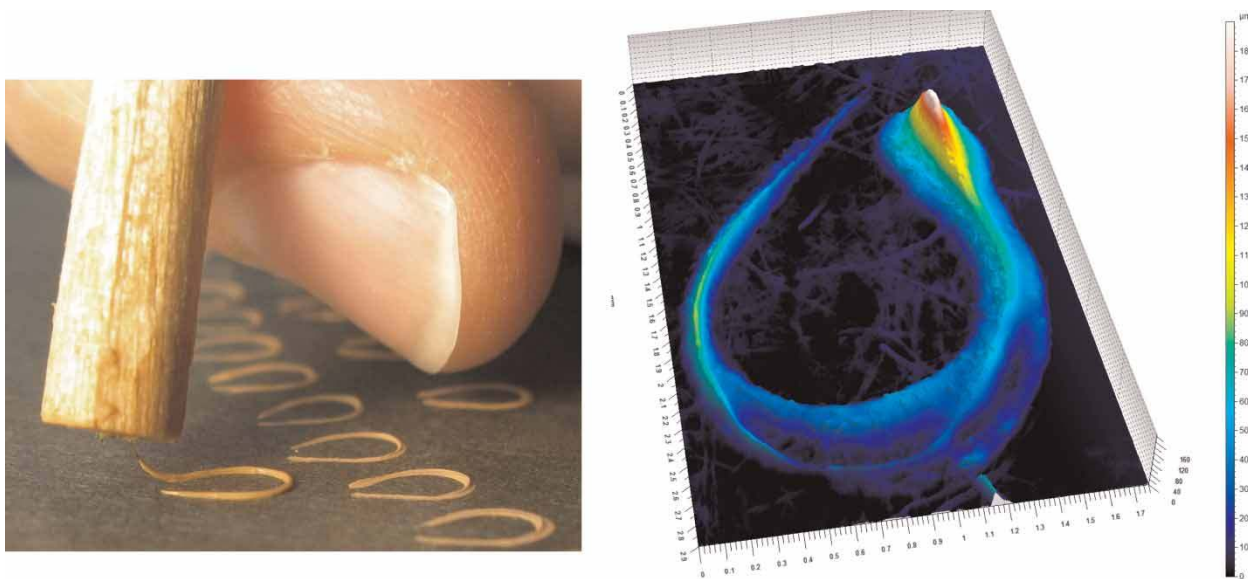


Figure 11 A *linierhaar* made of human hair is used to produce looped laid lines similar to that seen in Fig. 10 (left) (photo by Kari Kipper). A 3D elevation map of one such fabricated looped line displays topographical features distinctly similar to the ancient looped line (right). The threshold setting in the elevation map was adjusted to remove the majority of measurements associated with the cardboard substrate. The dimensions of the elevation map are 1.73 × 2.9 mm. The elevation scale bar is in μm .

is then lifted up in the midst of the action. Whereas featureless lines may result when the medium is too wet subsequently causing the line profile to level out. In addition, a line with more than one furrow can result when the brush hairs are too stiff, or when inclusions in the glaze material are dragged along with the brush hair.

The Museum of Fine Arts Boston has in its collection a fragmentary kylix attributed to the Antiphon Painter from c. 480 BCE and a favorite among scholars interested in understanding the fabrication process of Attic pottery (Fig. 15). The fragment depicts a male figure seated on a chair holding a kylix in his left hand and a stylus-like tool in his right. When examined under magnification with raking light, a single relief line connecting the tool and the surface of the vessel is discernible and can convincingly be argued to depict a *linierhaar*, as Seiterle observed (Seiterle, 1976, p. 9). The figure on the fragment also holds a small pointy implement

between his left thumb and index finger, which the authors believe could be a reservoir of glaze.

The contour line

In addition to the relief line, another decorative feature of interest in this research is the study of the contour line, a wide line forming part of the black background that often surrounds the figures on red-figure vases (Fig. 16). The black background was painted in two stages with glaze more dilute than that of the relief lines, using a wider, more traditional type of brush. The contour line was applied with the purpose of creating a safe margin around the silhouettes of the figures to protect them from being disrupted by the broadly applied brush strokes of the background glaze, an action probably executed at a relatively fast pace.

One question considered in this study is which came first, the relief line or the contour line. Scholars

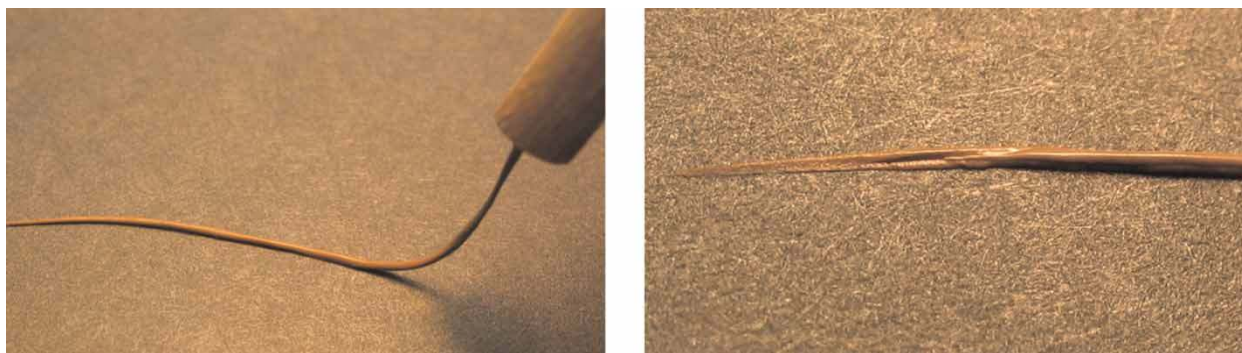


Figure 12 A *linierhaar* being used to produce a pulled line (left) and the characteristic furrowed profile produced as the brush is pulled across the surface (right).

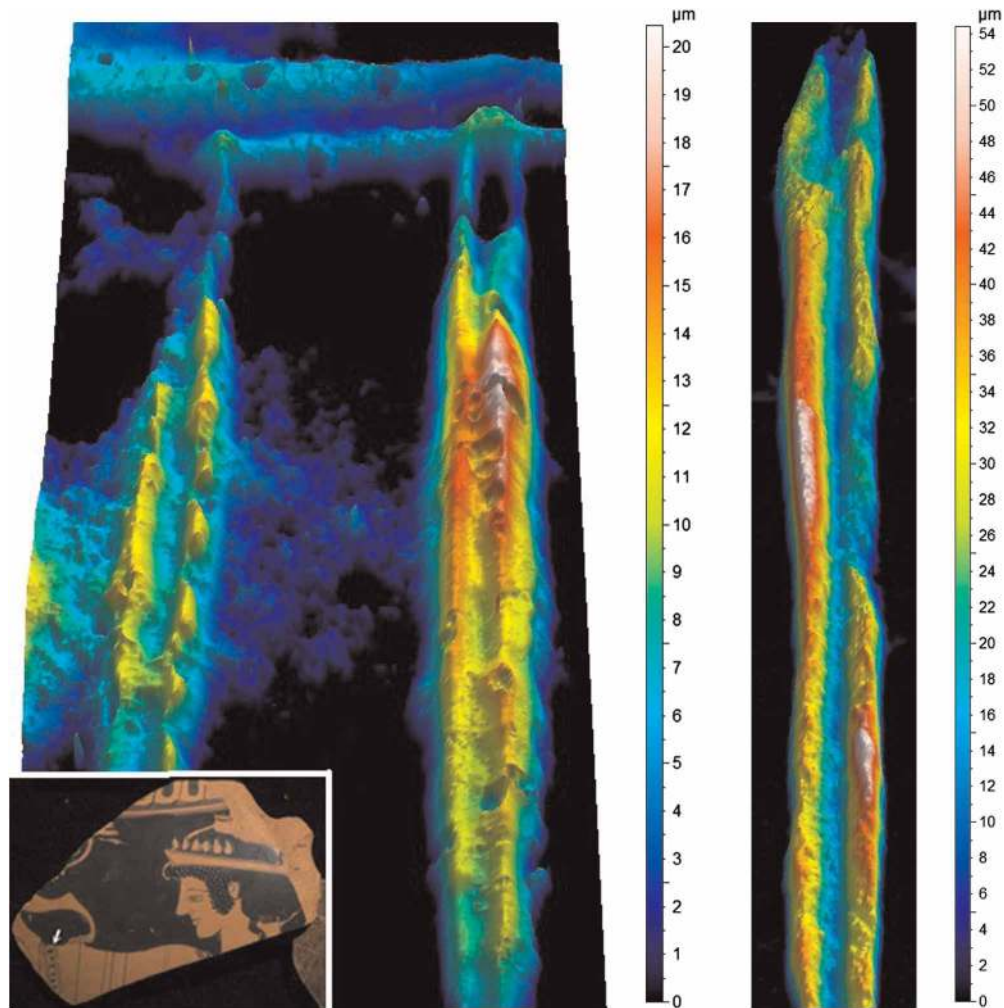


Figure 13 3D elevation maps of three ancient pulled lines from the stamnos (see photo inset for location) (left) and a modern pulled line (right). The map on the left was stitched from six scans and the map on the right from 16 scans, each using a $\times 20$ objective. The average length of the ancient lines is about 2.7 mm, the length shown of the mock-up line is 3.1 mm. The furrowed profile of the ancient and modern lines are clearly similar. The threshold setting in both images was adjusted to remove the majority of measurements associated with the substrate.

have conflicting opinions regarding the application sequence of these two line types. While Greek vase scholars Norbert Kunisch (1994, pp. 84–90) and Beth Cohen (2006, p. 151) suggest that the relief lines outlining the figures preceded the application of the contour line, other vase experts like Joseph V. Noble (1988, pp. 105–7) and Alexander Boix (2010, p. 30) propose

a reverse sequence, though Boix claims that there are exceptions. The sequence proposed by Kunisch and Cohen was observed on Worcester’s Tyszkiewicz stamnos where the overlap of the contour line on the relief lines extending into the background at the nape of the figure’s neck, results in a softer, more rounded appearance of the otherwise crisp lines (Fig. 16). In

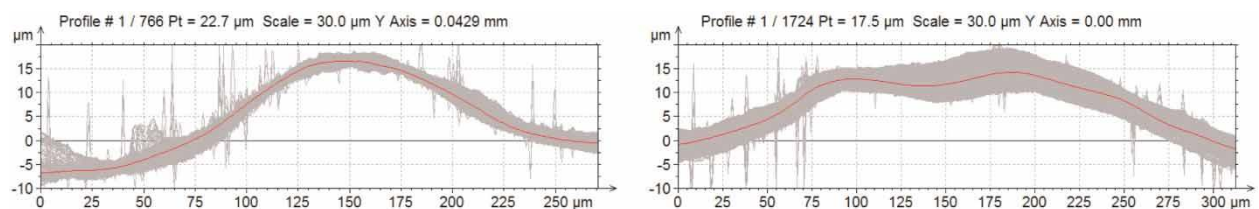


Figure 14 Profile measurements for selected sections of ancient relief lines. The red line in each graph represents the mean extracted profile from 766 profile measurements along the length of the line (17.38 mm) used for the left graph and 1724 measurements of the line (30.17 mm) used for the right graph. The left graph clearly illustrates the ridged profile of a laid line, and the right graph illustrates the furrowed profile of a pulled line.



Figure 15 Kylix fragment attributed to the Antiphon Painter, c. 480 BCE (left) (MFA 01.8073) and a detail (right) of the fragment showing what is likely a *linierhaar* in the painter's right hand and possibly a reservoir for the glaze in his left (photos by Abigail Hykin).

his research on South Italian vases Giuliani (1995, p. 68) asserts that the application sequence entailed an initial placement of a dilute contour line, followed by a thicker overall glaze to the background that also covers the contour line, and finally the application of the relief line decoration.

Study samples and observations


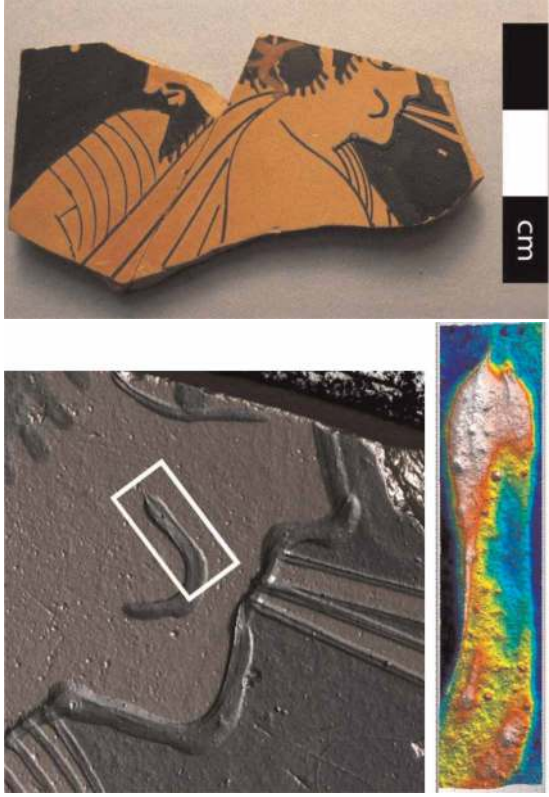
In order to determine whether the observations first made on Worcester's Tyszkiewicz stamnos were consistent for a broader range of red-figure vases, a group of nine Attic vases or fragments of vases spanning the red-figure period (c. 510 to c. 330 BCE),

were studied using RTI and the LEXT OLS4000 3D measuring laser microscope. Of this group, eight were lent by the Harvard Art Museums (HAM). In addition, three fourth-century South Italian vases, two on view at the British Museum, were also part of this research. The latter two were examined visually only. Finally, an Attic black-figure vessel from the late sixth century BCE surprisingly featuring relief lines was also studied. The vessels and fragments are dated, and all except two are attributed to specific painters. The observations made during this study are presented in Table 1 and summarized in Table 2.



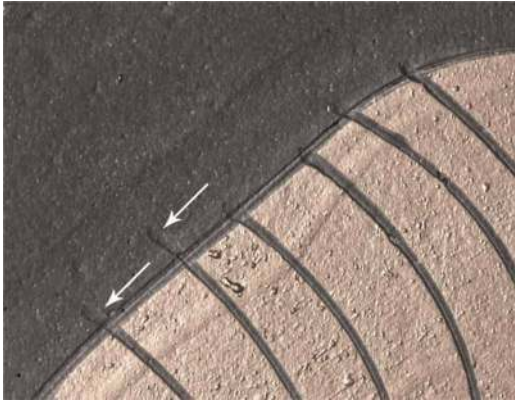


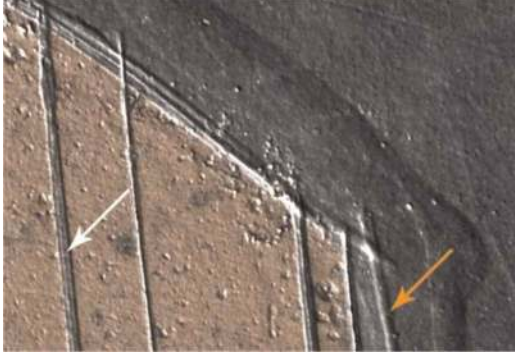
Figure 16 RTI still-capture with specular enhancement showing the use of a wide contour line around the head of a female attendant depicted on the stamnos in Fig. 1 and the broadly applied background glaze. The white circle in the more magnified detail on the right illustrates how the contour line overlaps the ends of the relief lines that extend into the background area, indicating that the application of the relief lines preceded the contour line.

Table 1 Observations regarding the decorative features on vases and vase fragments, with an emphasis on relief and contour lines. The works are listed in chronological order. Overall images of each object are normal illumination photographs, and all detail images are RTI still-captures unless otherwise noted.

Object-related information	Overall and detail images	Observations
<p>Black-figure kylix, unattributed, Attic, last quarter of the sixth century BCE (WAM 1912.37)</p>	 <p>The top image shows a black-figure kylix with a dark interior and exterior, decorated with a pattern of looped lines. A scale bar is visible in the bottom left. The bottom image is a detail of a relief line, showing a white arrow pointing to a characteristic ridge running through the middle of the line.</p>	<p>The exterior sides of the vessel depict men mounted on mules. A repeating pattern of looped lines, possibly depicting grape vines, are between the horses and riders. Traces of a white colorant are visible in selected areas.</p> <p>The looped lines appear to be laid relief lines (white arrow) with the characteristic ridge running through the middle. The technique used to produce these lines may be an early precursor of the laid relief line technique later used in red-figure ware.</p>
<p>Kylix fragment (interior), Nicosthenic Painter, Attic, 510–500 BCE (HAM 1995.18.9, Fragment B)</p>	 <p>The top image shows a fragment of a kylix with a black-figure design. A scale bar labeled 'cm' is visible on the right. The bottom left image is a detail of a relief line, outlined in white. The bottom right image is an elevation map of the detail, showing the distinctive furrowed profile of a pulled line.</p>	<p>The fragment depicts a bearded male figure (left) and a youth playing a double flute (right). The youth's wreath is painted with a red colorant. The figures are surrounded by relief and contour lines.</p> <p>The painter used the pulled line technique not only for the long straight lines of the flutes and the drapery, but also for the shorter lines of the cheek, eye, and face profile. There is however a difference in the quality of the lines: the long ones are very regular in width and height whereas the short ones are quite irregular, suggesting a less fluid execution. The detail outlined in white is shown as an elevation map (right) depicting the distinctive furrowed profile of a pulled line. The area shown in the elevation map is 0.634 × 2.94 mm. The distance from the substrate surface to the highest elevation on the line is about 30 μm.</p>

Continued

Table 1 Continued

Object-related information	Overall and detail images	Observations
<p>Kylix fragment (interior), Triptolemos Painter, Attic, 500 BCE (HAM 1995.18.103)</p>		<p>The contour line goes over the ends of the relief lines that extend into the background (white arrows), softening their otherwise crisp appearance, and providing additional evidence that the contour line was applied after the figures were fully drawn with the relief lines.</p>
		<p>The fragment depicts a bearded male figure, wearing a wreath and a himation, to the right is a staff, on the top right a partial border, and on the bottom right a section of another wreath. A partial inscription visible in the black background reads HOP. The wreaths and inscription are painted with a red colorant. The figure, the second wreath and the staff are surrounded by relief and contour lines, with the exception of the hair, which is not surrounded by a relief line.</p>
		<p>All relief lines on this fragment are pulled, including the short ones in the face making up the eyebrow and eye. There are no laid lines.</p>
		<p>The contour line goes over the ends of the relief lines that extend into the background, thereby softening their appearance. Furthermore, the relief line at the bottom right (orange arrow) is entirely covered by the contour line. The line on the far left (white arrow) displays multiple furrows. This effect may be the result of either a brush with several stiff hairs or inclusions in the glaze medium that create the furrows when dragged across the surface.</p>

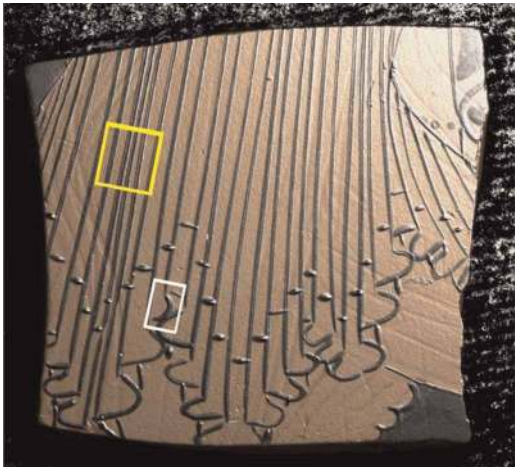
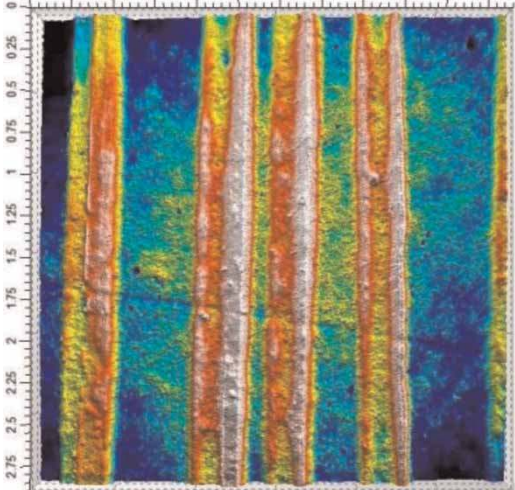
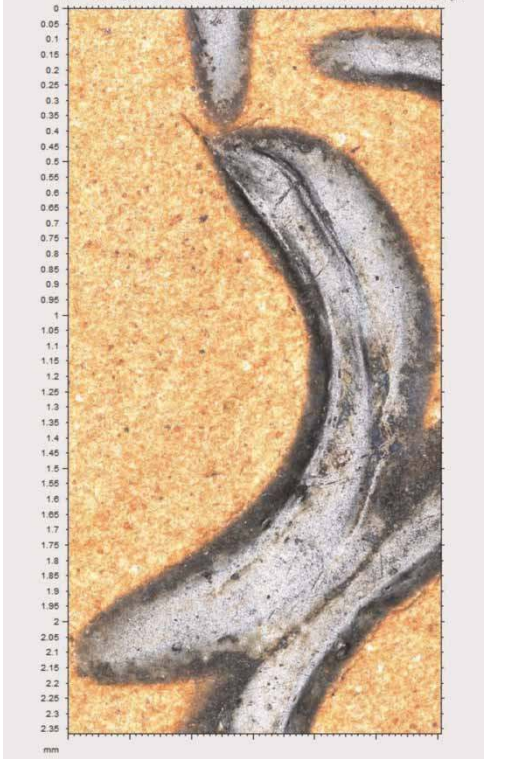
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Table 1 Continued

Object-related information	Overall and detail images	Observations
<p>Kylix fragment (interior), unattributed, Attic, c. 490 BCE (HAM 1995.839)</p>		<p>The fragment depicts the lower part of a male figure wearing a himation and leaning on a staff. On the right is a small section of another figure and on the left the leg of a stool. The red-figure portions are surrounded with relief and contour lines.</p> <p>Both pulled and laid lines are present. The pulled line technique was used for long lines (black arrow). The laid line technique was used for short and relatively straight lines (white arrows) and possibly for longer curved lines on the bottom borders of the garment, though it was not clear from the images. The lines with tight curves that make up the tips and bottom contour of the fingers show both profiles and therefore are examples of hybrid lines (red arrows).</p> <p>The contour line overlaps sections of the outlining relief line (black arrows).</p>
<p>Kylix fragment (interior), Brygos Painter, Attic, 480 BCE (HAM 1995.18.53)</p>		<p>The fragment depicts the lower part of a himation. Wherever the black background is visible a relief outline is present. While the background area showing in the upper left corner is too small to detect the entire width of a contour line, a contour line is visible on the bottom right corner of the fragment.</p>



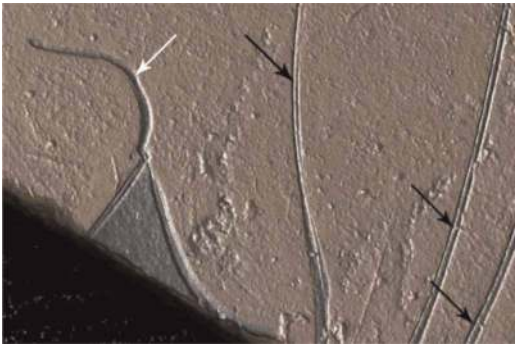
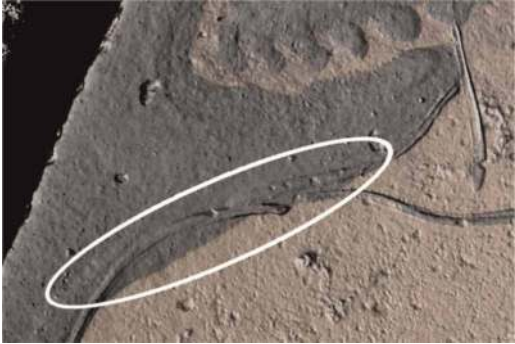

Continued

Table 1 Continued

Object-related information	Overall and detail images	Observations
		<p>All relief lines on this fragment are pulled lines. The very short lines that bridge the long lines near the bottom of the garment were produced by a dash-like touch of the brush to the surface of the vessel.</p>
		<p>This elevation map corresponds with the lines within the yellow box above and shows the characteristic furrowed profiles of long pulled lines. The area of the elevation map is 2.90 mm². The distance from the substrate surface to the highest elevation on the lines ranges from about 15–20 μm.</p>
		<p>The Brygos painter also produced the short, curved lines using the pulled line technique shown in this confocal image that corresponds with the area outlined above in white showing a magnified view of a short curved line with a furrow running through the line indicative of the pulled technique.</p>

Continued

Table 1 Continued

Object-related information	Overall and detail images	Observations
<p>Kylix fragment (interior), Antiphon, Attic, 480 BCE (HAM 1995.18.145)</p>		<p>The contour line overlaps the outlining relief line (white arrow) indicating that it was applied after the relief lines were painted.</p>
		<p>The fragment depicts the torso of a bearded male partially covered in a himation with the proper right arm extended. The figure is surrounded with relief (except for the beard) and contour lines.</p>
		<p>Both pulled (black arrows) and laid lines (white arrow) are visible.</p>
<p>Kylix fragment (interior), Makron, Attic, c. 480 BCE (HAM 1995.18.88)</p>		<p>A clear overlap of the contour line on the relief line is visible on the figure's shoulder.</p>
		<p>The fragment depicts parts of both legs of a male figure wearing a himation. The figure is outlined with relief and contour lines.</p>

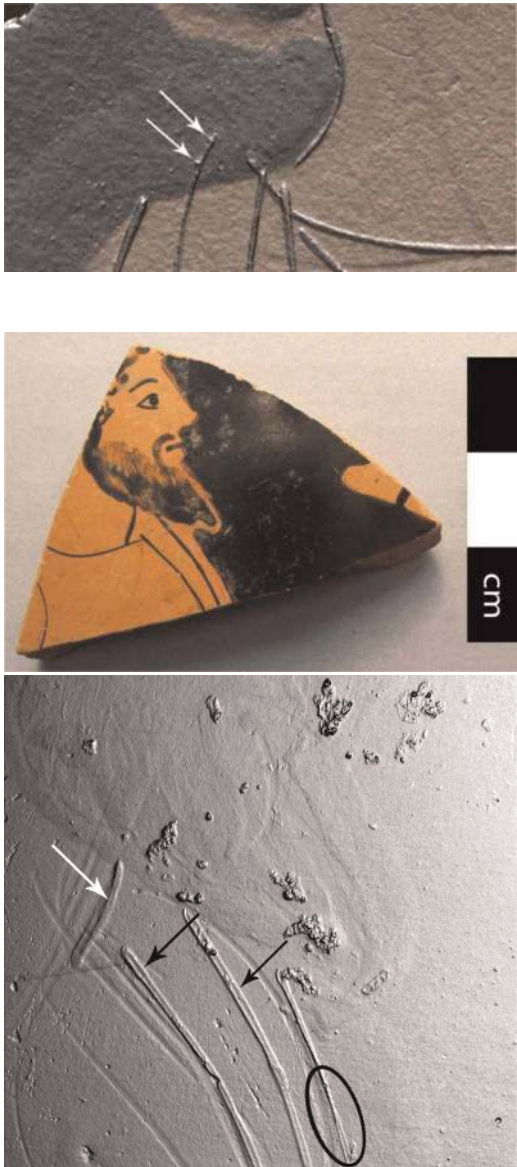

Continued

Table 1 Continued

Object-related information	Overall and detail images	Observations
Kylix fragment (interior), Akestorides Painter, Attic, 470–460 BCE (HAM 1995.18.4)		This RTI still capture detail with specular enhancement clearly shows both pulled (black arrow) and laid lines (white arrow).
		The contour line overlaps the outlining relief lines (black arrow).
		This fragment depicts a woman wearing a chiton, and a second figure to the right holding out her arms. To the left is a section of a chair with a cushion lying on it. The red-figure portions are only partially outlined with the relief line, whereas the contour line is visible throughout.
		Pulled lines (black arrows) and laid lines (white box) are visible throughout. The white arrow at an area where the contour line overlaps the outlining relief line.
	The elevation map of the detail outlined in white in the preceding image depicts two laid lines with the characteristic ridged profile. The area shown is 0.637 mm × 2.94 mm. The distance from the substrate surface to the highest elevation on the line is about 20 μm.	


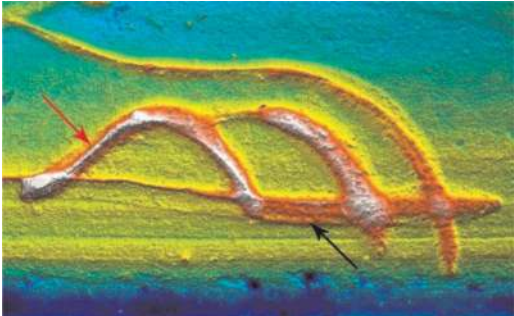
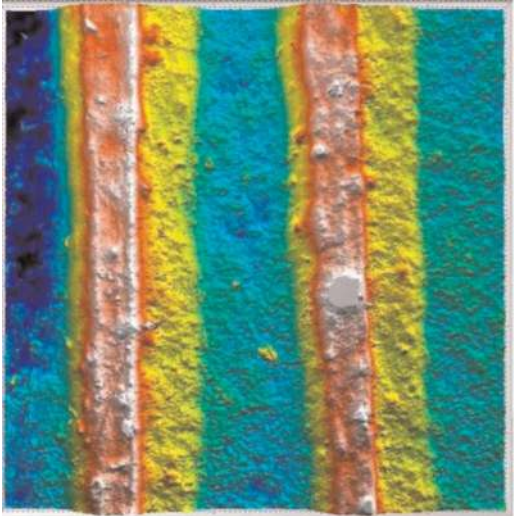
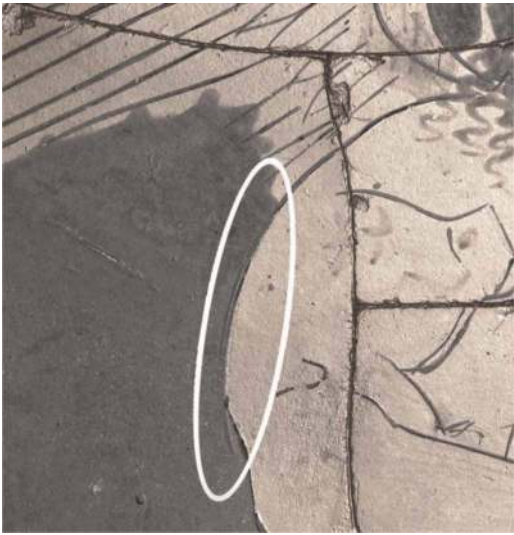
Continued

Table 1 Continued

Object-related information	Overall and detail images	Observations
<p>Skyphos fragment (exterior), near the Penthesilea Painter, Attic, 460–450 BCE (HAM 1995.18.12)</p>		<p>The contour line overlaps the relief lines that extend into the background indicating that the contour line was applied after the relief lines. The glaze contains inclusions, which are clearly visible next to the relief lines extending into the background (white arrows). This detail also provides information regarding directionality of the application of the glaze. The two inclusions were stopped by the relief line when the painter's brush went over it from left to right.</p> <p>This fragment depicts a partial head and torso of a bearded male figure. On the right is an unidentified compositional element. Relief line outlines are visible on the body portion but not around the head or on the element to the right, whereas the contour line is visible around all red-figure portions on this fragment.</p> <p>This RTI still capture detail with specular enhancement shows both pulled (black arrows) and laid (white arrow) lines. The contour line overlaps portions of the outlining relief line (circled).</p>
<p>Pyxis, Eretria Painter, Attic, c. 430 BCE (WAM 1935.148)</p>		<p>This cosmetics container depicts three women with their servants, and on the lid (knob handle is lost) two pairs of erotes are shown with roosters and rabbits. The underside of the lid depicts myrtle berries painted in white. The red-figure portions are only partially outlined with relief lines. The contour lines are partial as well.</p>

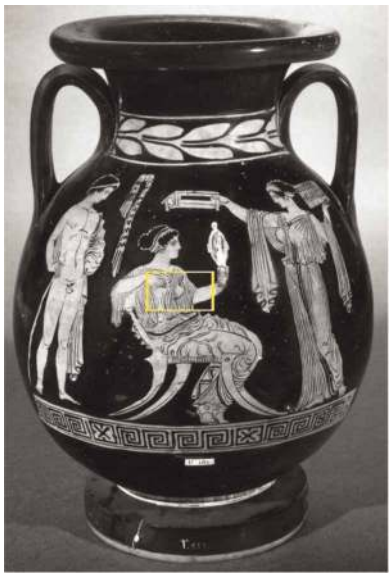


Continued

Table 1 Continued

Object-related information	Overall and detail images	Observations
		<p>An RTI still capture with specular enhancement showing a detail of a rabbit with an area outlined in white that corresponds to the elevation map below. In addition to details done with relief lines like eyes, ears, and feet, the rabbit's fur was painted with a dilute glaze most likely using a conventional brush.</p>
		<p>An elevation map of the rabbit's rear foot shows both pulled (black arrow) and laid (red arrow) lines. The area shown is 3.5 mm x 2.3 mm. The distance from the substrate surface to the highest elevation on the line is about 30 μm. The pulled line is an example of a line with multiple furrows.</p>
		<p>An elevation map of other relief lines on the lid that show multiple furrows. In this case the cause of the multi-furrowed profile appears to be inclusions in the glaze medium that were dragged across the surface as the lines were drawn. The area shown is 0.96 mm². The distance from the substrate surface to the highest elevation on the line is about 15 μm.</p>
		<p>This detail of the back of one erote shows the absence of contour lines and how the background glaze overlaps the relief line on the figure's back (white circle). The absence of both contour and relief lines around the wing results in an irregular flow line of the glaze at the end of the feathers. Here the glaze not only functions to fill in the background but to help describe the compositional elements as well.</p>

Continued

Table 1 Continued

Object-related information	Overall and detail images	Observations
<p>Pelike, Brooklyn-Budapest Painter, Lucania, South Italy 390–370 BCE (British Museum 1814,0704.553). Size: 32.8 cm × 24.3 cm</p>	 <p>(photo: ©Trustees of the British Museum)</p>	<p>This vessel depicts two women and a youth. A white colorant was used for decorative elements such as jewelry. A full contour line is visible. Relief lines occur mostly within the figural sections to depict facial features and details in garments, but are also present as partial outlines of the figures.</p>
		<p>This detail (outlined in yellow in the overall image above) is not an RTI still capture, but a photograph taken through a gallery case. The ability to observe topography was therefore limited; however, visual inspection suggests that the relief lines are laid lines. The relief line describing the bottom edge of the arm (white arrow) appears to be overlapped by the shiny contour line.</p>
<p>Hydria, South Italy (Apulia), unattributed, 350–320 BCE (WAM 1941.70)</p>		<p>This water vessel depicts a seated female figure dressed in a chiton holding a large box with her right hand and a wreath with her left. Some parts of the design are painted in white. No outlining relief lines but partial contour lines are present.</p>

Continued

Table 1 Continued

Object-related information	Overall and detail images	Observations
<p>Amphora, Patera Painter, North Apulia, South Italy, c. 340–330 BCE (British Museum 1867, 0508.1334). Dimensions: 89 cm x 40 cm</p>		<p>This image is a detail of the sitter's waist outlined in yellow above. Both relief line techniques were used on this vessel. The laid line was used to produce the looped line with an exceptionally high ridge (white arrow). The pulled line (red arrows) was used for long fluid lines and for relatively short lines in the area of the waist in the garment.</p>
		<p>This detail (outlined in white in the overall image above) shows that a relief line passing through the black background area (black arrow) remains crisp, suggesting that it goes over the background.</p>
		<p>This elaborate and highly decorated vessel depicts in the central tier a scene in Hades with a seated Pluto holding out a phiale and a scepter (detail below). A bejeweled Persephone stands in front of Pluto. On the tier below is a busy toilet scene. Many parts of this vessel are painted in white.</p>

(photo: ©Trustees of the British Museum)

Continued

Table 1 Continued

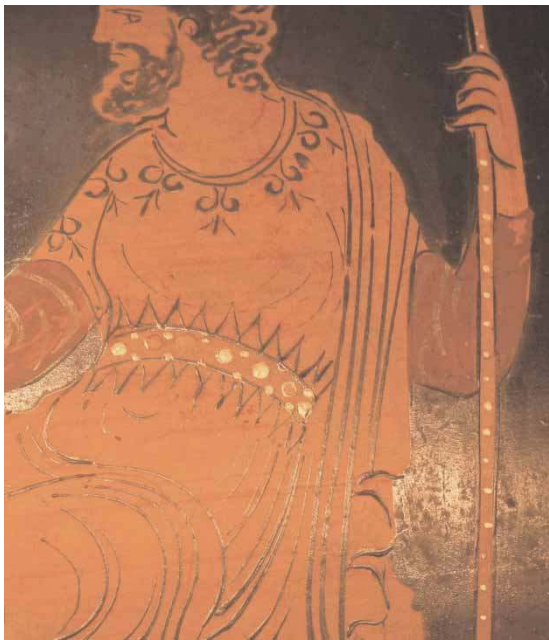
Object-related information	Overall and detail images	Observations
		<p>The red-figure portions are partially outlined with the relief line. No contour line surrounds the red-figure portions. Both relief line types, pulled and laid, are used for decorative elements, folds in the garments, and for eyes, mouths, and fingers. They are applied boldly so that they are clearly discernible with the unaided eye. This image is not an RTI still capture but a photograph taken through a gallery case.</p>

Table 2 Observations made in this study (includes Tyszkiewicz stamnos published in 2011) and techniques encountered

Object (where not specified the origin is Attic)	Pulled lines	Laid lines	Outlining relief line (not including hair and beard portions)	Contour line	Overlap of relief line by contour line or background
Unattributed, last quarter of the sixth century BCE (WAM 1912.37)	No	Yes (early precursor)	n/a	n/a	n/a
Nicosthenic, 510–500 BCE (HAM 1995.18.9)	Yes	No	Full	Full	Yes
Triptolemos, 500 BCE (HAM 995.18.103)	Yes	No	Full	Full	Yes
Unattributed, c. 490 BCE (HAM 1995.839)	Yes	Yes (for short straight lines only)	Full	Full	Yes
Brygos Painter, 480 BCE (HAM 1995.18.53)	Yes	No	Full	Full	Yes
Antiphon, 480 BCE (HAM 1995.18.145)	Yes	Yes	Full	Full	Yes
Makron, c. 480 BCE (HAM 1995.18.88)	Yes	Yes	Full	Full	Yes
Tyszkiewicz Painter, 480 BCE (WAM 1953.92)	Yes	Yes	Full	Full	Yes
Akestorides Painter, 470–460 BCE (HAM 1995.19.4)	Yes	Yes	Partial	Full	Yes
Near Penthesilea Painter, 460–450 BCE (HAM 1995.18.12)	Yes	n/a	Partial	Full	Yes
Eretria Painter, 430–425 BCE (WAM1935.148)	Yes	Yes	Partial	Partial	Yes
Brooklyn-Budapest Painter, South Italy (Lucania), 390–370 BCE, (BM 1814,0704.553)	No	Yes	Partial	Full	Yes
Unattributed, South Italy (Apulia), 350–320 BCE (WAM 1941.70)	Yes	Yes	No	Partial	No (relief line over background)
Patera Painter, South Italy (North Apulia), 340–330 BCE (BM 1867,0508.1334)	Yes (very few)	Yes	Partial	No	Could not be determined

Summary of observations

The following observations were made during the examination with RTI and laser scanning confocal microscopy of the group of Greek vases and vase fragments:

- A series of long, looped laid lines were observed on a black-figure kylix dating to the last quarter of the sixth century BCE. Not typical for black figure ware, as already noted by Kunisch (1994, p. 84) and Boix (2010, p. 31), this can be seen as a precursor of the

laid line technique which is used later by red-figure vase painters in a wide variety of lengths and shapes.

- There is evidence of the pulled line technique on every red-figure item examined during this research except on one South Italian pelike from the British Museum, which was only viewed in an exhibition case without magnification. In the early red-figure period, which seems to coincide with the Archaic Period, painters appear to have used the pulled line

technique exclusively. The sole reliance on the pulled line method limited the painter's ability to produce continuous lines with intricate turns. This is evident in the irregular and discontinuous quality of the lines that painters such as the Nicosthenic Painter produced for the flute player's cheek line and profile on the Harvard kylix fragment. However, the Brygos Painter, for example, was skilled at producing clean and even pulled lines with turns in them, apparently using a brush well charged with glaze material.

- The laid line technique appears later during the Classical Period, when the painters seem to be familiar with both line types and intentionally choose one over the other depending on the shape of line they want to produce.
- On every Attic piece examined in this study, overlaps of the contour line or background glaze were observed on the relief lines outlining the figures and those that extend into the background, which means that the figures were first outlined and features within the red-figure portions were drawn with the relief lines prior to the background application.
- During the Archaic Period the relief line appears to consistently define the outline of the figures with the exception of hair and beard portions. Later during the Classical Period it seems to become increasingly common not to fully outline the red-figures on Attic vessels with relief lines, but rather to use the contour line or the background glaze to help define the edges of the figural composition. Kunisch (1994, p. 89) also makes this observation.
- Vase painters in South Italy used both relief line types, the pulled and the laid lines, supporting the idea that Attic vase painting techniques were indeed brought by the Greeks to their colonies on the Italian peninsula. In fourth-century South Italian vase painting the lines are applied boldly, with a high reliance on the laid line technique. The authors assert that rather than being an example of the extrusion theory as maintained by Noble (1988, p. 121), the face and hair on the Apulian krater fragment in his book is instead an excellent example of the mastery of the laid line technique by the painters of South Italy.
- On South Italian vases the relief line is used only partially or not at all to outline the figures. The contour line was observed as a full or a partial line on some vases, and on others it was non-existent.
- On the South Italian vases that were examined, two scenarios were observed, rather than just one as described by Giuliani; on one vase the relief lines reaching into the background seem to be overlapped by the contour line, and on another they were painted over the background (no contour line present). In addition, a contour line was observed fully on one vase, partially on the second, and there was none on the third.

Conclusions

The use of RTI and 3D laser scanning confocal microscopy, two complementary surface examination methods not previously used together in the study of ceramics, led to new insights in the study of Greek vases.

These non-destructive, non-invasive methods enable researchers to examine surface topography more in depth by providing qualitative (RTI) and quantitative (3D laser scanning confocal microscopy) data. This combination will likely prove useful in future investigations where surface examination is central, not only to determine fabrication methods but also to evaluate the impact of conservation treatments, as well as to examine and document surface degradation, and much more.

In this research, two types of relief lines identified by the authors in an earlier publication were observed throughout: the *laid line* – characterized by a ridged profile, and the *pulled line* – characterized by a furrowed profile. Both line types were reproduced with brushes made with only a few hairs, as first proposed by Seiterle. Two different application techniques were used to produce the two types of lines. As the name indicates, laid lines are produced by laying the glaze-dipped hairs of the *linierhaar* down onto the surface of the vessel followed by lifting the brush straight up, creating the distinctive ridged profile of the line. The resulting line is typically no longer than the length of the brush hair. In contrast, the *pulled line* is created by setting down all or part of the brush, and while leaving the hair in contact with the vessel, the brush is pulled across the surface creating a characteristic furrowed profile as the tip of the brush drags through the medium producing lines that are longer than the length of the brush hair.

While the pulled line technique was used on all Attic red-figure vases, the laid line technique seems to become more prevalent as a second line type later during the Classical Period. Before then the painters – probably unaware of the laid line technique – made short lines with turns in them using the pulled line technique. The result is that these lines are often truncated and of varying thickness compared with the more even and controlled lines produced later with the laid line technique. Vase painters of South Italy (c. 390–320 BCE) used both line types in their red-figure pottery production, further linking the migration of Attic vase painting techniques to the Italian colonies. The unique painting style of South Italian red-figure ware can be characterized by bolder, more dynamic brush strokes. This makes it easier for the viewer to discern each line type, sometimes even without the need of magnification. This is especially true for the laid line technique, which was predominantly used and mastered by the South Italian painters. These lines have pronounced profiles and stand well above the surface.

This study also gives insight into the production sequence used by red-figure painters. During the process of surface decoration by Attic painters, relief lines were applied first to describe the general outline of the red-figure portions of the composition as well as features like the arms, legs, eyes, ears, and folds and other details in the garments. The next step consisted of painting in the background using contour lines around the

figures to create a safe margin and prevent the broadly applied background glaze from disrupting the edges of the figures. RTI examination of the areas where relief and contour lines meet revealed that on every Attic piece in this study the contour line overlaps the relief lines confirming that the contour line was painted after the relief line as Kunisch and Cohen propose. On the other hand, the three South Italian ceramics examined showed variation in the application sequence of the relief line: in one instance it overlaps the background, in another it is overlapped by the background.

This research also suggests a general transition from an uninterrupted relief outline during the Archaic Period in Attic red-figure painting (with the exception of hair and beard portions) to a partial relief outline starting in the Classical Period, confirming what scholars like Kunisch had observed. In South Italy the presence of the relief outline and contour line on vases is not consistent. This observation as well as the variation in the application sequence, suggest that the South Italian painters worked more freely, without rigid adherence to established rules of production.

As a final note, the authors acknowledge that this study is based on the examination of a limited number of works. The hope behind this study is that as a greater number of works are examined the findings presented here will inform future research and will lead to a clearer understanding of the materials, techniques, and development of ancient red-figure ceramics.

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List of suppliers

Charbonnel yellow extra-fine gilder's clay base – Talas, 330 Morgan Ave., Brooklyn, NY 11211, USA, <http://www.talasonline.com/>

Tin tubes – Unipac Supply Co., PO Box 98026, Pittsburgh, PA 15227, USA (no longer in business).

'Sta-Wet Handy Palette' with acrylic paper – Masterson Art Products, Inc., PO Box 10775, Glendale, AZ 85318, USA.

Windsor & Newton brushes – C.C. Lowell, 258 Park Avenue, Worcester, MA 01609-1927, USA.

References

- Adams, F. 1849. *The Genuine Works by Hippocrates*. London: Sydenham Society.
- Aloupi-Siotis, E. 2008. Recovery and Revival of Attic Vase-Decoration Techniques: What Can They Offer Archaeological Research? In: K. Lapatina, ed. *Papers on Special Techniques in Athenian Vases*. Los Angeles: Getty Publications, pp. 113–28.
- Artal-Isbrand, P., Klausmeyer, P. & Murray, W. 2011. An Evaluation of Decorative Techniques on a Red-Figure Attic Vase from the Worcester Art Museum using Reflectance Transformation Imaging (RTI) and Confocal Microscopy with a Special Focus on the 'Relief Line'. In: P. Vandiver, W. Li, J.L. Ruvalcaba Sil, C.L. Reedy & L.D. Frame, eds. *Materials Issues in Art and Archaeology IX*. New York: Cambridge University Press and Materials Research Society, vol. 1319, pp. 3–33.
- Boardman, J. 2001. *The History of Greek Vases: Potters, Painters and Pictures*. London: Thames & Hudson, pp. 48, 66, 105, 286.
- Boix, A. 2010. Rotfigurige Maltechnik. In: M. Bentz, W. Geomring & J.M. Müller, eds. *Tonart: Virtuosität Antiker Töpfertechnik*. Petersberg: Michael Imhof Verlag, pp. 30–4 [in German].
- Cohen, B. 2006. Outline as a Special Technique in Black- and Red-Figure Vase-painting. In: B. Cohen, ed. *The Colors of Clay: Special Techniques in Athenian Vases*. Los Angeles: Getty Publications, pp. 150–60.
- Giuliani, L. 1995. *Tragik, Trauer und Trost. Bilder für eine Apulische Totenfeier*. Berlin: Staatliche Museen zu Berlin-Preussischer Kulturbesitz [in German].
- Hartwig, P. 1887. Die Anwendung der Federfahne bei den Griechischen Vasenmalern. *Jahrbuch des Kaiserlichen Deutschen Archäologischen Instituts*, 14: 147–67 [in German].
- Kunisch, N. 1994. Über das rotfigurige Zeichnen. *Antike Kunst*, 37: 81–90. [in German].
- Malzbender, T., Gelb, D. & Wolters, H. 2001. Polynomial Texture Maps. In: *Siggraph 01: Proceedings of the 28th International Conference on Computer Graphics and Interactive Techniques*. New York: ACM, pp. 519–28.
- Mayo, M.E. 1982. Preface. In: M.E. Mayo & K. Hamma, eds. *The Art of South Italy: Vases from Magna Graecia*. Richmond: Museum of Fine Arts.
- Mudge, M., Malzbender, T., Schroer, C. & Lum, M. 2006. New Reflection Transformation Imaging Methods for Rock Art and Multiple-Viewpoint Display. In: M. Ioannides, D. Arnold, F. Nicolucci & K. Mania, eds. *The 7th International Symposium on Virtual Reality, Archeology and Cultural Heritage (VAST 2006)*. Nicosia, Cyprus: Eurographics, pp. 195–202.
- Newman, R. 2008. Ferrous and Ferric: A Review of Scientific Research on the Iron in Attic Greek Glazes. In: K. Lapatina, ed. *Papers on Special Techniques in Athenian Vases*. Los Angeles: Getty Publications, pp. 105–12.
- Noble, J. 1988. *The Techniques of Painted Attic Pottery*. Second revised edition. New York: Thames & Hudson.
- Oakley, J.H. 2001. Rotfigurige Vasenmalerei. In: *Der Neue Pauly* 10, col. 1141–2.
- Padfield, J., Saunders, D. & Malzbender, T. 2005. Polynomial Texture Mapping: A new Tool for examining the Surface of Paintings. In: J. Brigland, ed. *ICOM Committee for Conservation, 14th Triennial Meeting, Preprints*. The Hague: ICOM-CC, vol. I, pp. 504–10.
- Schumann, T. 1942. Oberflächenverziehung in der antiken Töpfertechnik: Terra sigillata und griechische Schwarzrotmalerei. *Berichte der Deutschen Keramischen Gesellschaft*, 23: 408–26 [in German].
- Seiterle, G. 1976. Die Zeichentechnik in der rotfigurigen Vasenmalerei. *Antike Welt*, 7(2): 2–10 [in German].
- Winter, A. 1978. *Die Antike Glanztonkeramik*. Mainz am Rhein: Verlag Philip von Zabern [in German].