Immeasurable Details: Micrometric Analysis of Reed Stylus Fiber Impressions on Cuneiform Tablets

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Abstract

In recent years, the exploration of digital methodologies within Assyriological research has significantly intensified. The advent of 3D modeling of cuneiform tablets offers numerous advantages, including the possibility to simulate various lighting conditions, thereby enhancing the visibility of morphological details. Furthermore, 3D digital copies facilitate the geometric examination of cuneiform signs, aiding in the recognition of scribal handwriting and joins. However, the fibrous impressions left by the reed stylus on the left-hand side of the wedges have been overlooked in previous studies. Despite their dimensions spanning merely a few microns, these fiber impressions have the potential to be as unique to each stylus as fingerprints are to human. This research employs the Gocator 3504, a high-resolution structured-light scanner by LMI Technologies, with a nominal resolution of 6.7 μm in XY and 0.2 μm in Z, to measure and visualize the fibrous impressions on a group of tablets from Ghent University. The examination and representation of these fibrous impressions offer a potentially new and complementary diagnostic technique for verifying joins, thereby determining whether fragments of cuneiform tablets exhibit identical fibrous patterns on their wedges. Such similarity would suggest that the fragments were impressed by the same stylus and might belong to the same tablet.

Keywords
metrological scanner, micrometric survey, multi-resolution model, cuneiform signs, fiber impressions.

3D model of the cuneiform tablet LW21.CUN.161. Elaboration by the authors.

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Introduction

Cuneiform tablets are among the earliest records of human civilization, dating back to circa 3300 BCE. For over three millennia, scribes across the ancient Near East used their styluses to impress wedge-shaped signs on wet clay, giving rise to the 'cuneiform' writing (from the Latin *cuneus* meaning wedge). These tablets were pivotal in documenting the daily activities, intellectual pursuits, and cultural practices of ancient Near Eastern societies. The dimensions of cuneiform tablets varied significantly, reflecting the diverse purposes they served, from approximately 1.5 × 1.5 cm to 36 × 33 cm, although most were conveniently small enough to fit comfortably in one's hand [Taylor 2012, pp. 9-10; Charpin 2010, p. 75]. Ancient scribes maximized the use of space on cuneiform tablets by impressing the text on the obverse, reverse, and all the edges.

On these 3D pillow-shaped artifacts, scribes impressed 3D wedges with a stylus usually fashioned from reed stalks. Impressing the stylus tip into the clay created a distinct wedge-shaped impression with three faces (fig. 1). The upper face (fig. 1.1) represents the stylus' short side, akin to the cross-section of the reed stalk; the left face (fig. 1.2), often exhibiting fiber impressions, corresponds to the inner portion of the reed stalk where it has been sliced; the right face (fig. 1.3) appears smooth due to the impression left by the glossy exterior surface of the reed [Cammarosano 2014].

The documentation and representation of cuneiform tablets for their analysis and interpretation remain a fundamental aspect of the Assyriological research, with a variety of methodologies and approaches being applied to this end [1]. The creation of 3D digital copies offers numerous advantages [Bogacz and Mara 2022; Diara 2023; Homburg et al. 2022]. A particularly notable advantage is the possibility for scholars to examine the tablet in a virtual

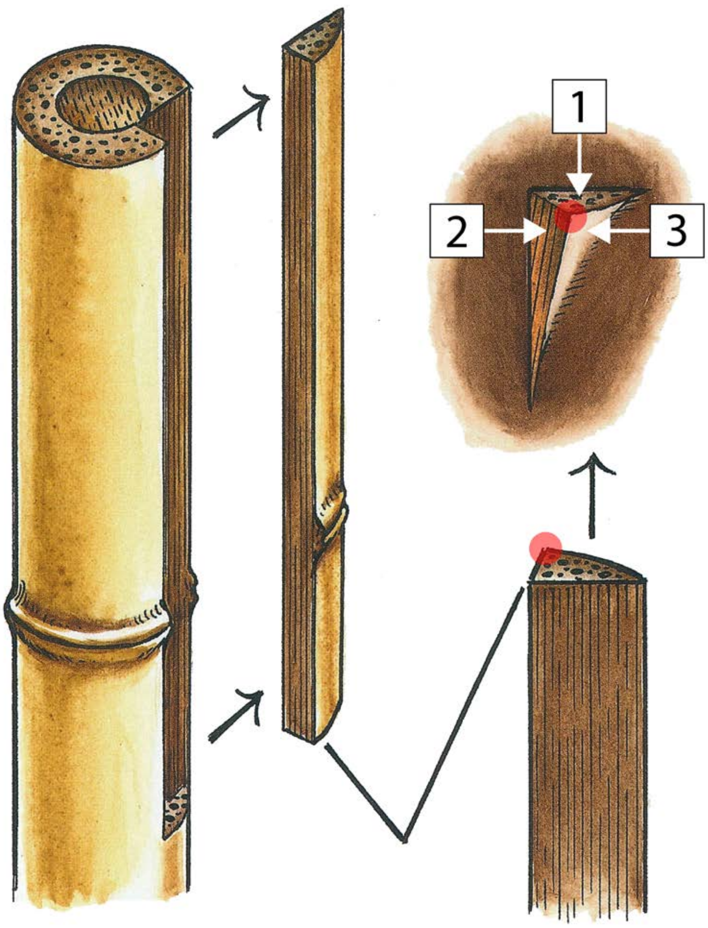


Fig. 1. The production of a stylus from a reed stalk. In the bottom part, the red circle indicates the tip of the stylus that is pressed into the clay. The upper right corner shows a cuneiform wedge: 1) upper face, 2) left face, 3) right face. The red circle shows the resulting corner impression on the clay made by the tip of the stylus [2].

environment. This virtual examination avoids the necessity for tactile interaction with the real object while still allowing for an exhaustive analysis with different light angles and zoom levels. Rotating the tablet and simulating various lighting conditions to enhance the visibility of the cuneiform signs and better examine the edges and other morphological details is crucial for correctly interpreting the text. These actions are traditionally performed by Assyriologists when handling the actual artifact. However, such manipulations are limited when working with photographs or hand copies, underscoring the value of 3D digital modeling in Assyriological research. Although 3D digitization of cuneiform tablets is increasingly being adopted, achieving high-definition 3D documentation of detailed tablet features, such as single wedges of only a few millimeters in size, remains a technological challenge [Antinozzi et al. 2023].

Measuring the micron

The collection of Ghent University comprises 306 inventory numbers (LW21.CUN.1-306), including tablets, bullae, and tags, dating from the mid-third millennium to the first millennium BCE. The entire collection of Ghent was digitized using the structured light scanner "Scan in a Box" (@2015 Open Technologies SRL) (fig. 2), which offers a nominal resolution of 0.08 mm with an accuracy of 0.04 mm and allows for the creation of a comprehensive digital model of the tablets within a reasonable timeframe. Once the instrument is calibrated and the workstation is prepared, an experienced operator can typically complete the data acquisition and processing for small to medium-sized tablets (such as the one in the case study presented below) in approximately 30 minutes. On average, 14 scans are necessary to fully digitize a medium-sized tablet: 2 nadirals of the two faces (obverse and reverse), 4 nadirals of the edges, and 8 tilted connecting ones. The final output is a geometrically complete mesh model where the wedges can be clearly examined. Furthermore, the output file has relatively modest dimensions, with individual meshes ranging from approximately 80 to 180 MB in STL file format. These files are manageable with standard computers and can be easily published online.
However, this first digital survey conducted with "Scan in a Box" has a limitation: some microscopic details fall beyond the resolution capacity of this instrument. For instance, the fiber impressions left by the reed stylus on the left face of a wedge cannot be examined within this standard 3D model (fig. 5). To overcome this challenge and perform 3D analysis on a

Fig. 2. Left: the cuneiform digital survey with the structured light scanner "Scan in a Box": 1) projector; 2 and 3) stereo cameras. Right: complete 3D model of the tablet LW21.CUN.133. Elaboration by the authors.

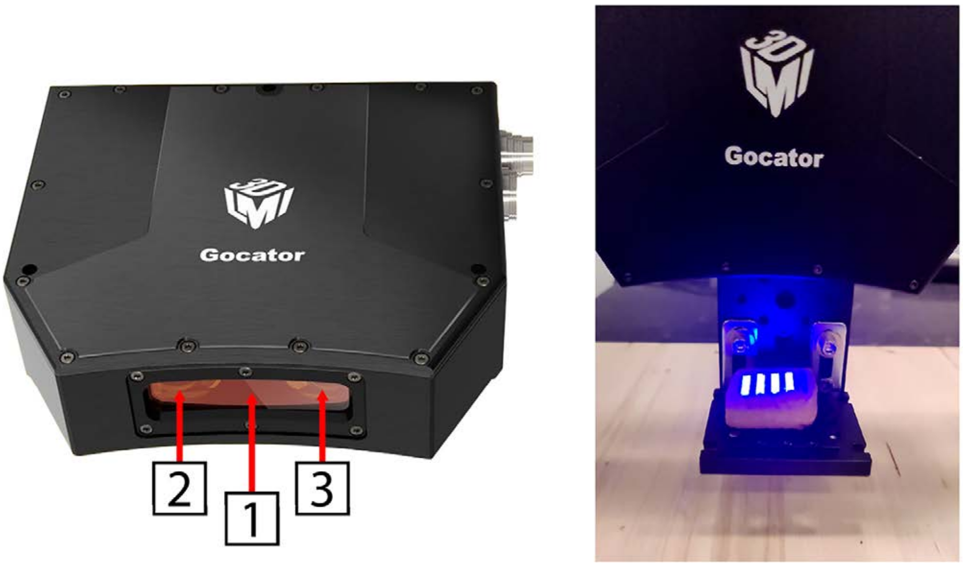


Fig. 3. The cuneiform digital survey with the industrial scanner Gocator 3504 (LMI Technologies): 1) projector; 2 and 3) stereo cameras. Elaboration by the authors.

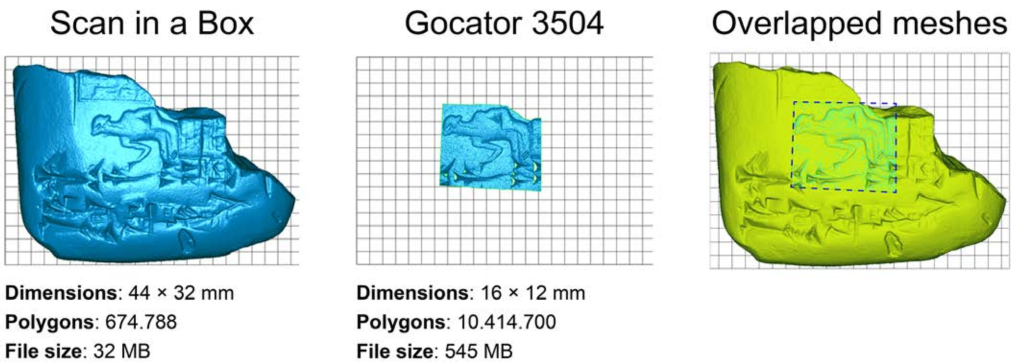


Fig. 4. Comparison between Scan in a Box and Gocator 3504 mesh models of tablet LW21.CUN.159 (reverse). The grid space is 2 mm. Elaboration by the authors.

microscopic scale, we used the Gocator 3504 by LMI Technologies, an industrial structured light scanner (fig. 3).

To the best of our knowledge, this initiative represents the first instance of such technology being specifically employed within the field of Assyriology. While the "Scan in a Box" offers a resolution of approximately a tenth of a millimeter, the Gocator achieves a 6.7 μm XY and 0.2 μm Z nominal resolution, with an accuracy of 6 microns. Nonetheless, a significant advantage of the "Scan in a Box" lies in its wide Field Of View (FOV = 100 × 75 mm^2), which allows for capturing an entire small-to-medium tablet face in just one scan (fig. 2, right). Although multiple scans from different viewpoints are required to create a complete 3D model (without shadow cones due to undercuts of the wedge-shaped geometries), registering these scans is straightforward and effective.

In contrast, the FOV provided by the Gocator is considerably more limited (13 × 15 mm^2) (fig. 4), necessitating a significantly higher number of scans to fully capture a tablet surface. Additionally, aligning these numerous scans to create a complete 3D model of one face (obverse or reverse) of the tablet poses a significant challenge, exacerbated by the large file sizes. This process is further complicated by the necessity of maintaining at least a 50% overlap between scans to ensure accurate and robust registration.

Nonetheless, the Gocator metrological scanner provides the required resolution to capture minute details of cuneiform signs and fiber impressions accurately. The comparison between the two mesh models highlights the level of detail obtained and demonstrates a clear difference in resolution (fig. 5). However, the greater resolution comes at the expense of a very small FOV, which allows for detailed acquisition of individual wedges. Additionally, the Depth

of Field (DOF) is notably small, with a Measurement Range of just 7 microns, complicating the process of taking multiple tilted shots to overlap and align the scans of the edges and faces to produce a merged 3D model. Consequently, creating a full 3D model of a tablet face using the metrological scanner requires considerable time, large file sizes, and significant computing resources.
A hybrid approach was adopted to navigate these challenges: using complete mesh models of the cuneiform tablets captured with the "Scan in a Box" as a basis on which to align high-resolution detail scans made with Gocator 3504. This method enables the creation of

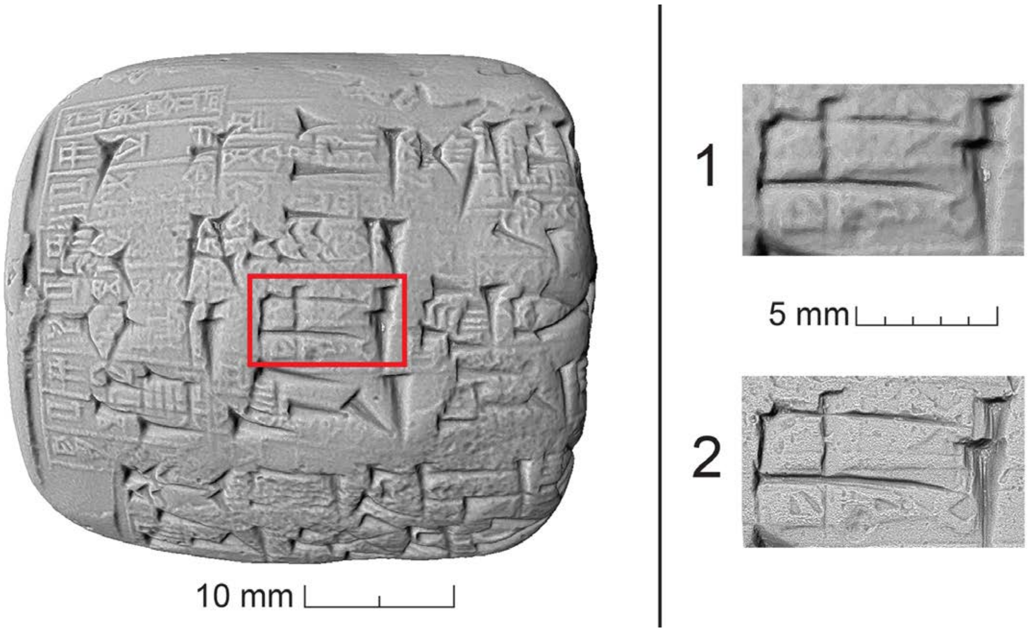


Fig. 5. Left: complete 3D model of tablet LW21. CUN.133 from "Scan in a Box" with a highlighted red detail. Right: 1) close-up of the detail made with "Scan in a Box"; 2) closeup of the same detail made with Gocator 3504. Elaboration by the authors.

a comprehensive digital model that retains the geometry of the object at a resolution of tenths of a millimeter while incorporating multiple levels of detail down to the micron (fig. 4, right). This innovative solution effectively balances the need for submillimeter precision with the practicality of managing digital representation, offering a viable pathway to detailed analysis without overwhelming technical demands.

Fiber impressions analysis: results and discussion

A 3D model facilitates the manipulation not only of the object orientation but also its lighting conditions, significantly enhancing the visibility of fiber impressions. For instance, as illustrated in the image (fig. 6), a grazing light from the left side can enhance vertical fibers (fig. 6.2), whereas lighting from below may highlight horizontal fibers, making vertical ones less discernible (fig. 6.3). Additionally, applying filters to the 3D model can further improve the visibility of details, providing a richer examination of the tablet surface features (fig. 6.4).
The examination of fiber impressions left by the reed stylus is of significant interest due to their potential uniqueness, akin to human fingerprints, which may allow the identification of individual styluses used during the writing process. Some features like short ridges, ridge endings, or bifurcations, found in human fingerprints, can also be discerned in fiber impressions (fig. 7) [3]. The analysis of these fibrous impressions could serve as a novel and supplementary diagnostic method to confirm joins, thereby determining if fragments of cuneiform tablets share the same fibrous pattern of the wedges. This consideration would indicate they were impressed with the same stylus and are possibly part of the same document. Often,

Fig. 6. Effects of grazing lights and filter on the visibility of fiber impressions on an area of tablet LW21.CUN.133 scanned with Gocator 3504. 1) Frontal light; 2) grazing light from left; 3) grazing light from below; 4) filter (Radiance Scaling in Meshlab). Elaboration by the authors.

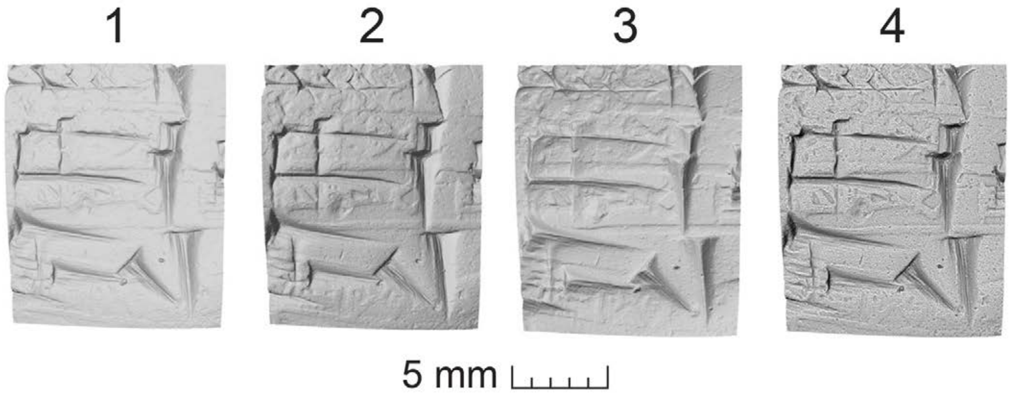
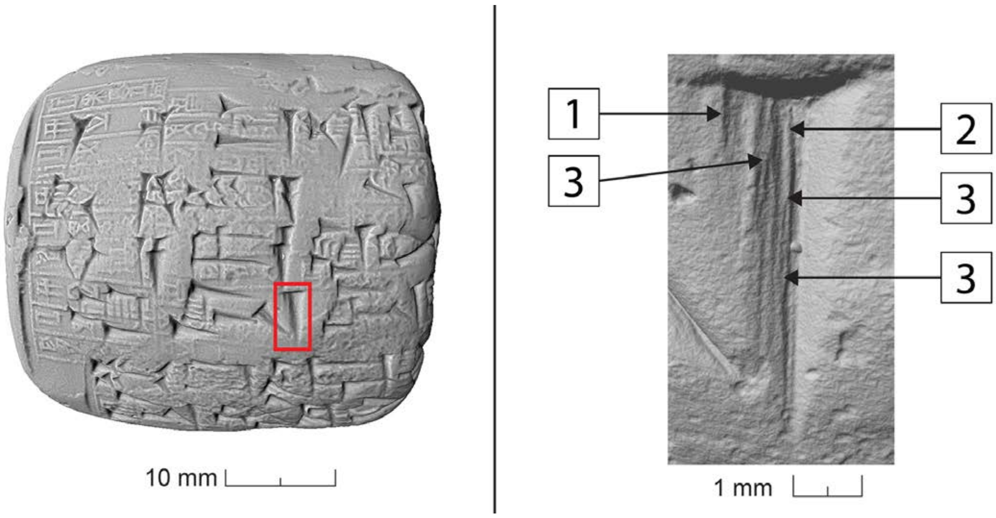
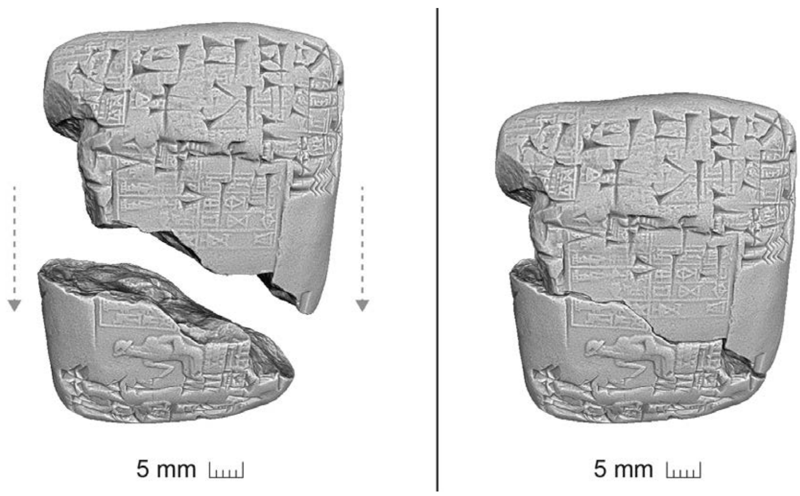


Fig. 7. Left: complete 3D model of tablet LW21.CUN.133 from "Scan in a Box" with a highlighted red detail. Right: closeup of the highlighted area made with Gocator 3504. The grazing light from the left provides better conditions to identify the features of the fiber impressions: 1) short ridge, 2) ridge ending, and 3) bifurcation. Elaboration by the authors.



a single cuneiform tablet is fragmented into several smaller pieces, and the relation of the fragments to a single document can only be ascertained based on the content of the text and, thus, relying on philological grounds. Characteristics such as the color of the clay of the tablet are not always reliable [4]. In some cases, joining fragments of cuneiform tablets is relatively straightforward, particularly when the fragments are part of the same collection

Fig. 8. Virtual joining of the 3D models LW21.CUN.159 and LW21.CUN.160. Elaboration by the authors.



and their shapes fit together seamlessly, much like puzzle pieces (fig. 8). However, there are cases where multiple fragments may not appear to interlock or correspond to each other at first glance, posing a significant challenge in ascertaining their association. In such complex scenarios, examining fiber impressions becomes an invaluable tool.
An experiment was conducted on the wedges of the same tablet, which were likely impressed with the same stylus, to validate this approach and assess its effectiveness in recognizing fiber impressions using the Gocator.
The 3D model of the tablet was digitally split into two parts. Subsequently, eight wedges - four from each part - showing clear fiber impressions were selected for comparative analysis (fig. 9). For the sake of clarity and ease of examination, the horizontal and oblique wedges (figg. 9.2-9.4, fig. 9.8) were vertically reoriented. The analysis revealed a consistent pattern of fibers, with similar features recurring across the wedges under study (see the reconstructed fiber impression drawing based on the eight samples in fig. 9, right). Thus, it was determined that examining just eight wedges is sufficient for precisely recognizing and identifying the fiber impressions left by the stylus.
Furthermore, using the Gocator scanner for wedge analysis allows for accurately measuring the different shapes of wedges impressed by the stylus into the wet clay. The impressions

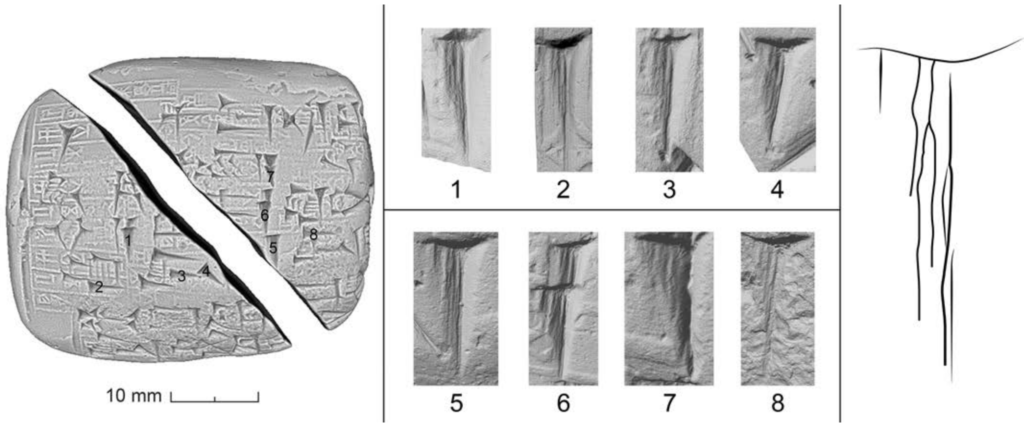


Fig. 9. Left: 3D model of tablet LW21.CUN.133 (obverse, virtually split into two parts) from "Scan in a Box" with wedges selected and numbered from 1 to 8. Middle: selected wedges for the comparison of the fiber impressions (not to scale and vertically reoriented). Right: a drawing of the reconstructed fiber impressions based on the eight selected wedges. Elaboration by the authors.

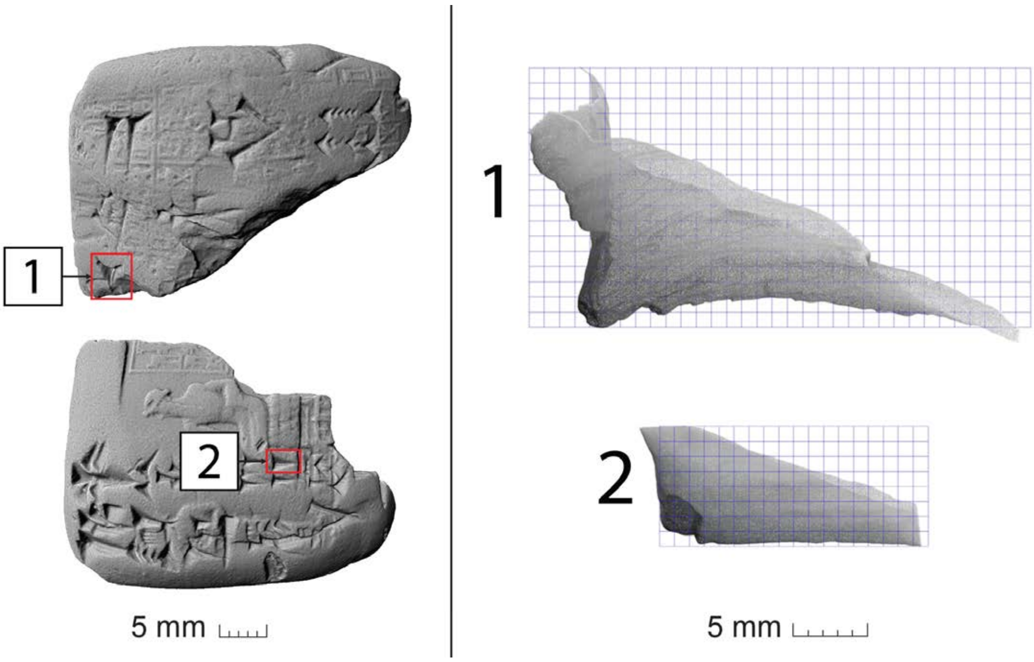


Fig. 10. Left: complete 3D model of tablet LW21.CUN.159 (obverse and reverse) from "Scan in a Box" with highlighted red details and selected wedges (nos. 1 and 2). Right: profile of wedges nos. 1 and 2, made with Gocator 3504. The grid space is 1 mm. Elaboration by the authors.

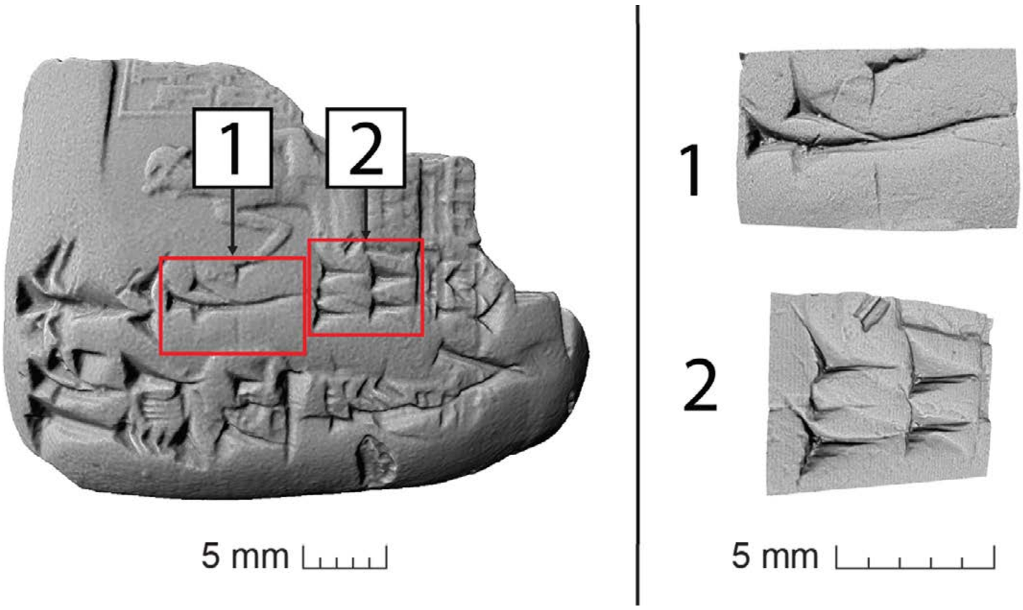


Fig. 11. Left: complete 3D model of tablet LW21.CUN.159 (reverse) from "Scan in a Box" with highlighted red details and selected areas (nos. 1 and 2). Right: areas nos. 1 and 2, made with Gocator 3504, exhibit flattened (1) and short (2) cuneiform signs. Elaboration by the authors.

left by the stylus in the clay can vary due to several factors, such as the trajectory during the impression and/or the shape of the stylus itself [Cammarosano 2015, 156-157], as is the case of the two wedges in the image (fig. 10) which have two different upper faces (one 'flat' and the other 'curved').

However, the rolling of a seal on wet clay sometimes flattened the cuneiform signs, resulting in the obliteration of the fiber impressions, as visible in the image (fig. 11.1). In other situations, short signs (fig. 11.2) may not exhibit sufficient fiber features to enable meaningful analysis.

Despite these challenges, detailed micrometric features can still be measured and digitally analysed using an industrial scanner, providing valuable data for studying the geometric features of cuneiform signs and identifying joins. Following the observations made above, we propose a preliminary four-step methodology for the analysis of wedges, and the identification of joins in cuneiform tablets::

1. Autoptic examination. A preliminary visual inspection of the tablet aims to select specific wedges for further study. This step ensures that wedges unsuitable for analysis (such as those that are too short or have been flattened by seal impressions) are not included.
2. Micrometric survey. A metrological scanner (Gocator type) enables a detailed survey of the selected wedges. The data produced from this survey can then be used to construct a multi-resolution model.
3. Geometric analysis. The analysis of the wedge geometry to determine dimensions, shape, and angles (dihedron angles generated by the three faces) [Antinozzi et al.
4. 2023].
5. Analytical recognition. Examining the 3D scans allows for the identification of structural consistencies in the fiber impressions, which can confirm existing joins or identify new ones.

Conclusions and Future Aims

This research underscores the advantages and potential of employing micrometric surveys to document, represent, and analyze cuneiform signs. However, as noted, the higher resolution results in a significant reduction in FOV and DOF, making the process of aligning multiple scans to produce a single 3D model of even a single face highly complex and time-consuming. Additionally, this model would result in a large file that is difficult to manage.

As anticipated, these limitations were resolved by devising a multi-resolution 3D model of the wedge-shaped tablet, i.e., by integrating the two surveys: the centesimal resolution model (Scan in a Box) was used as a reference and basis for the micrometer resolution scans (Gocator 3504). This approach ensures a bi-univocal correlation between the geometrically complete digital model of the cuneiform tablet and the microscopic model of one or more of the wedges examined. Finally, the study leveraged the Gocator 3504 submillimetric resolution to visualize and analyze the geometric characteristics of the wedges and the fibrous impressions left by reed styluses. These impressions could provide a novel methodology to verify whether two or more fragments belonged to the same tablet. A four-step approach is proposed to analyze the shape and dimensions of wedges and to identify joins of cuneiform tablet, consisting of 1) autoptic examination, 2) micrometric survey, 3) geometric analysis, and 4) analytical recognition.

The research is ongoing, with plans to significantly expand the dataset of acquisitions using industrial scanners to encompass a much larger sample of tablets from the Ghent University collection. These additional acquisitions can provide more data to enhance and enrich both geometric and Assyriological analyses. One experimental objective is to reconstruct the stylus shape from negative impressions. Additionally, a future goal is to explore the integration of artificial intelligence and image recognition software, akin to the tools employed by forensic experts, to facilitate the automatic identification of fiber impressions.

Notes

[1] For a summary, see [Antinozzi et al. 2022, pp. 3135-3142].

[2] Adapted from [Finkel and Taylor, 2015, p. 75, Fig. 42]

[3] For a summary of the features of fingerprints [Cummins and Midlo 1961].

[4] See, e.g., the tablet CDLI no. P346229, composed of several fragments of different colors < https://cdli.mpiwg-berlin.mpg.de/artifacts/346229>

Credits

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