

Application of 3D Ultrasonic Tomography in Cultural Heritage: The Case of the Ustica Sculpture

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Abstract – This study investigates the structural integrity and authenticity of a small volcanic tuff sculpture discovered on May 21, 1991, at the Middle Bronze Age site of Faraglioni Village on the island of Ustica. The artifact, a stylized female figure found in two fragments by archaeologists R.R. Holloway and S.S. Lukesh, was proposed as the earliest example of Bronze Age sculpture in Sicily. However, a 1993 letter suggested that modern fabrication had induced a dispute over its authenticity. To evaluate this claim, a high-resolution 3D Ultrasonic Tomography (UST) analysis was performed. The measured ultrasonic wave velocities are 1-2 km/s, consistent with those of porous, low-density pyroclastic rocks, such as volcanic tuffs. These values are significantly lower than those of compact lavas, supporting the identification of the material as tuff. The UST results confirm material coherence between the two fragments and suggest the sculpture is consistent with volcanic stone, verifying its authenticity.

1. INTRODUCTION

Ustica is a small volcanic island (8.6 km²) located in the southern Tyrrhenian Sea, approximately 65 km north of Palermo, Sicily (Fig. 1). Its geological formation dates back to the Middle Pleistocene, around one million years ago, when tectonic activity related to the expansion of the Tyrrhenian basin caused magma to rise and led to the emergence of a volcanic seamount off the northwestern coast of Sicily. On the island's northern shore lies the Faraglioni Village, a Middle Bronze Age settlement strategically situated on a coastal terrace bordered by steep coastal cliffs and defended inland by a substantial arched wall with reinforced construction. The site extends over an

area of about 7.000 m² and includes numerous dry-stone structures aligned along a narrow passageway. Archaeological investigations since the 1970s have revealed a complex spatial organization and produced a rich assemblage of domestic ceramics and other well-preserved artifacts [1].



Fig. 1. Map of the island of Ustica (Sicily, Italy) showing the location of the Faraglioni Village (in green).

Over the years, several excavations have taken place at the site, including a particularly significant one on May 21, 1991. During this excavation, a small tuff sculpture, fragmented into two pieces and measuring 22 × 19 × 2.5

cm, was recovered (Fig. 2a). The artifact, representing a stylized female figure, was interpreted by R.R. Holloway as a ritual object potentially associated with an altar. He further proposed it as the earliest example of Bronze Age sculpture documented in Sicily [2]. An anonymous letter and a series of photographs, presumably depicting the statue during its supposed modern creation in 1993, posed questions about its authenticity and generated an extensive scientific debate that has continued for over three decades.

This study aims to evaluate the internal condition and authenticity of the sculpture through 3D Ultrasonic Tomography (UST). This method is used to assess the structural integrity of the artifact by detecting and localizing subsurface anomalies—such as internal fractures, delaminations, decay zones, or inclusions—through measurements of elastic wave propagation velocities and estimates of mechanical parameters, such as the elastic modulus. The goal is to reconstruct a tomographic image of the statue’s internal structure and produce a 3D velocity map that highlights variations in its mechanical properties.

2. ULTRASONIC TOMOGRAPHY ANALYSIS

Ultrasonic tomography (UST) is a non-destructive testing (NDT) technique that employs high-frequency mechanical waves—ultrasonic waves—to investigate the internal structure of materials [3–5]. These elastic vibrations typically range from above 20 kHz to over 200 MHz. Ultrasonic waves can be classified into pressure (longitudinal) and shear (transverse) types, each with distinct propagation characteristics. Higher frequencies provide greater resolution but reduced penetration depth, as their ability to travel through materials decreases with increasing frequency. Penetration efficiency also depends on the material’s physical properties, such as elasticity, density, and internal structure.

Ultrasonic waves propagate effectively through homogeneous solids and liquids, maintaining coherence over considerable distances, although they are less efficient in gases like air. When encountering internal discontinuities—such as cracks, voids, inclusions, or interfaces—these waves undergo partial reflection, refraction, or scattering. The nature of these interactions provides valuable information about the internal condition of the investigated object. In the context of artworks and archaeological artifacts, UST offers high sensitivity and spatial resolution, allowing for the detection of subsurface features, provided they are larger than the wavelength of the signal used. The technique is especially suitable for assessing the conservation state of marble and other fine-grained stone materials. However, several challenges persist. Differences in ultrasonic velocity between materials can be minimal, resulting in low contrast that complicates the identification of subtle features.

Additionally, the geometric complexity and material heterogeneity of cultural heritage objects - such as sculptures with intricate details or composite construction - can hinder accurate data interpretation.

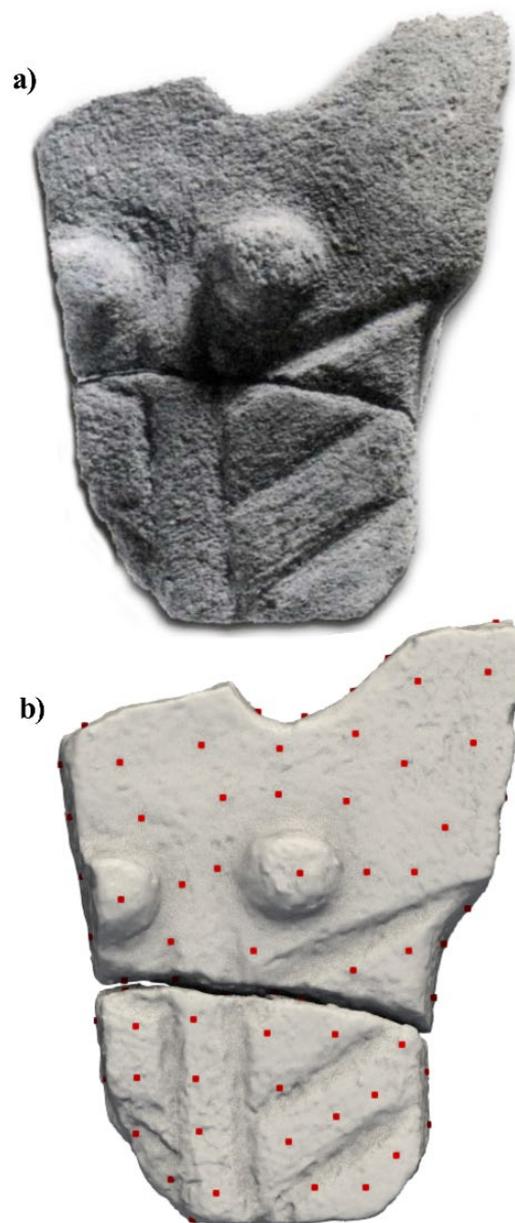


Fig. 2. a) Photograph of the sculpture discovered by archaeologists R.R. Holloway and S.S. Lukesh during excavation [6]; b) 3D digital reconstruction of the two statue fragments (front view), with measurement points in red.

The data acquisition was performed using the TDAS 16

system developed by Boviari S.r.l. This multichannel instrument, equipped with 16 input channels, enables the acquisition of signals from four channels simultaneously via an electronic switching mechanism, with a maximum sampling rate of 1.25 MHz. Both the transmitting and receiving probes operated at a central frequency of 55 kHz. The sensors (both transducers and receivers) are conical in shape to achieve better positioning precision and reduce the contact surface, with a diameter of approximately 3-6 cm and a height of approximately 4-8 cm. A total of 81 measuring points (Fig. 2b) were chosen, 50 in the upper fragment and 31 in the lower fragment of the statue. The chosen points covered the entire surface and identified the best locations for locating the transducers, which alternated between transmitting and receiving ultrasonic waves. A total of 474 signals were acquired and processed, identifying the time of first arrival of the elastic waves.

To enhance the spatial interpretation of velocity data, a 3D scan of the statue was integrated into the analysis. The 3D model was created using RealityScan, a mobile application that facilitates the creation of digital models of real-world objects through photogrammetry guided by augmented reality (AR) technology. Multiple images of the statue were captured from various angles to ensure comprehensive coverage of its surface. The AR-based interface enables users to achieve optimal image distribution, minimizing occlusions or blind spots during data acquisition. Following image capture, the application applies photogrammetric algorithms to reconstruct the object's geometry by identifying matching key points across the image set. This process generates a dense point cloud, which is then converted into a polygonal mesh optimized for digital visualization and analysis.

3. RESULTS AND DISCUSSION

were determined through a manual picking procedure, allowing for precise identification of the first arrivals. The graph in Figure 3, which plots travel time (ms) against ray path distance (mm), illustrates the distribution of acquired data from both fragments of the sculpture. The two portions, identified as the upper fragment ("A") and the lower fragment ("B"), exhibit comparable apparent wave velocity patterns, with green diamonds and blue squares marking the respective data points. The consistency in travel time behaviour across both fragments suggests that the material properties and structural composition of the statue are largely homogeneous. A coherent trend in wave propagation velocity is observed, with an average velocity of approximately 1500 m/s. This value decays within the expected range for low-density pyroclastic rocks, such as volcanic tuff, supporting the lithological classification of the artifact based on prior visual and petrographic observations.

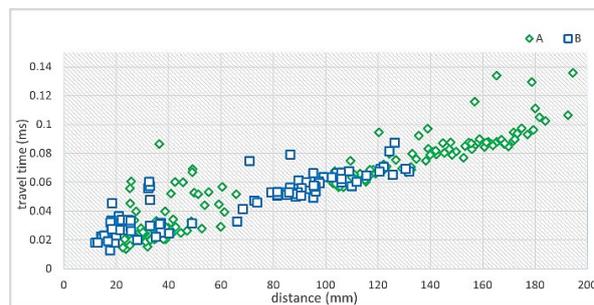


Fig. 3. Travel time plot for ultrasonic signals. Green diamonds represent data from the upper fragment (A), while blue squares correspond to the lower fragment (B).

To further explore the internal characteristics of the statue, the results were rendered into a 3D volumetric model (Figure 4), which visualizes the spatial distribution of ultrasonic wave velocities throughout the object. This reconstruction confirms the previously observed homogeneity, as it reveals a globally consistent velocity field across the two fragments. The continuity of this velocity distribution, particularly across the break interface, is of relevance. It strongly supports the hypothesis that the two fragments originally belonged to a single, unified artifact, rather than having been artificially assembled from unrelated pieces. Such evidence contributes significantly to the ongoing discussion regarding the authenticity and historical coherence of the sculpture.

Despite the overall homogeneity, the model also highlights localized low-velocity anomalies, primarily along the margins of the lower fragment, where values drop to between 500 and 700 m/s. These regions, rendered in red in the 3D visualization, likely correspond to zones of internal weakness, possibly resulting from fractures, elevated porosity, or material degradation. Given the natural heterogeneity of volcanic tuff—which often contains vesicles, voids, and secondary mineral phases—such anomalies are not unexpected. However, their identification is important, particularly from a conservation standpoint.

The estimated range of wave velocities (500–2500 m/s) aligns well with literature values for porous pyroclastic lithologies, reinforcing the interpretation of the statue's composition and supporting the effectiveness of UST in characterizing materials of this nature. Furthermore, the ability of UST to detect subtle variations in material cohesion and integrity underscores its utility in heritage science, where non-invasive techniques are essential to preserve the physical and historical integrity of valuable artifacts.

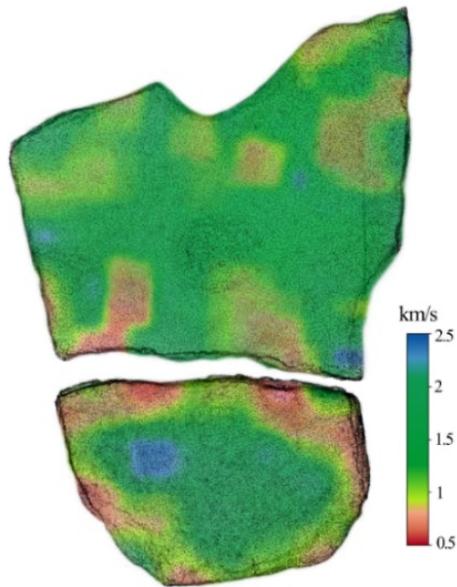


Fig. 4. 3D rendering of the statue's internal velocity model. Red zones correspond to areas with ultrasonic velocities below 1000 m/s.

In conclusion, the results of this study demonstrate the reliability and sensitivity of ultrasonic tomography in evaluating both the structural condition and material consistency of cultural heritage objects. In the case of the Ustica statue, UST has provided key insights not only into the physical state of preservation but also into its historical authenticity. The observed internal continuity across fragments, coupled with the identification of potential zones of degradation, illustrates the method's potential as a diagnostic and conservation planning tool for similar

lithic artifacts. Future studies could benefit from integrating these results with complementary techniques, such as micro-CT scanning, infrared thermography, or 3D photogrammetry, to further enhance diagnostic resolution and conservation strategies.

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